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The effect of deep tillage and incorporated organic material on development of different cereal crops

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Abstract

Climate change is the most challenging factor for modern agriculture. The risk of heatwaves combined with heavy precipitation events and steady rainfall absence determines agriculture in many regions of the world. One of the key factors to mitigate these problems is a optimum soil performance.

By this adapted tillage to improve soil performance and thus, mitigate impacts of climate change is of outstanding importance. The subsoil (soil layer beneath the A-horizon) is a soil layer very rich in nutrients and carbon, and contains water reservoirs which are important during times of drought. However, this soil layer is very often compacted and soil physical properties do not allow plant roots to develop into it.

Deep soil loosening (subsoiling) can be highly beneficial to soil physical properties and improve soil structure substantially. Beneath, sustainable fertilizer application is also of outstanding importance. The combination of subsoiling and deep placed organic fertilizer can be a solution to improve soil performance and secure stable cereal crop yield at times of climate change.

The objective of this thesis is to test how deep soil loosening, and its combination with deep placed organic fertilizer affects cereal crop development. Subsoiling is undertaken stripwise and yields are monitored in two distances to the melioration. Results show that different working tools affect plant development and organic fertilizers being rich in nitrogen (biocompost) and with a dense C:N ratio are highly valuable to yield development compared to untreated control. Organic fertilizers with wider C:N ratios do not increase yield in the short-term (year 1) while for one material (chopped straw) a trend towards positive effects is recognizable on the longer term (year 2). Results at fallow land demonstrate that yields continuously decrease with distance to the melioration and an optimum strip distance of 1 m creates beneficial effects for a whole crop area.

The combined results of pre-trial and main-trial allow the conclusion that mixing of biocompost and chopped straw can substantially increase cereal crop yields at times of climate change, respectively to weather and soil conditions in the area of 'Rhineland Bonn'.

Zusammenfassung

Der Klimawandel ist einer der Hauptfaktoren, der die moderne Landwirtschaft beeinflusst. Das Risiko andauernder Hitzeperioden kombiniert, mit Starkregenereignissen bei gleichzeitig insgesamt geringen Niederschlägen, bestimmt die Landwirtschaft in weiten Teilen der Welt. Einer der Hauptfaktoren, um diesen Problemen entgegenzuwirken, ist eine optimale Bodennutzung. Angepasste Bodenbearbeitung, die die Bodenstruktur verbessert und somit dem Einfluss des Klimawandels entgegenwirkt, ist von großer Bedeutung. Der Unterboden (die Bodenschicht unterhalb des A-Horizonts) ist reich an Nährstoffen und Kohlenstoff, gleichzeitig verfügt er über tiefliegende Wasserreservoirs, die in Dürreperioden die Wasserversorgung der Nutzpflanze positiv beeinflussen. Häufig kann diese Bodenschicht jedoch nicht von Pflanzenwurzeln erschlossen werden, da sie verdichtet ist.
Tiefe Bodenbearbeitung (Unterbodenbearbeitung) kann die Bodenstruktur positiv beeinflussen und nachhaltig verbessern. Des Weiteren steht ein angepasstes Düngemanagement im Fokus der Bodenverbesserung. Eine Kombination aus Unterbodenbearbeitung und tief eingebrachtem organischen Dünger kann ein Weg zur nachhaltigen Bodenverbesserung sein und stabile Erträge in Zeiten des Klimawandels sicherstellen.
Die vorliegende Arbeit beschäftigt sich mit den Auswirkungen einer Unterbodenbearbeitung und deren Kombination mit tief eingebrachtem organischem Dünger auf die Ertragsentwicklung von Getreidepflanzen. Die Unterbodenmelioration wird hierbei streifenweise vorgenommen und die Erträge in Abstand zu dem Meliorationsstreifen bonitiert. Die Ergebnisse zeigen, dass unterschiedliche Lockerungswerkzeuge den Ertrag beeinflussen und organische Dünger, die reich an Stickstoff sind und ein enges C:N Verhältnis haben (Biokompost), den Ertrag positiv beeinflussen. Organische Dünger mit weiten C:N Verhältnissen beeinflussen den Ertrag in einem einjährigen Versuch nicht positiv. Ein Trend hin zu einer positiven Wirkung lässt sich im zweijährigen Versuch in der Variante Strohhäcksel erkennen. Die Ergebnisse des Vorversuchs auf einer Brachefläche zeigen, dass der Ertrag mit zunehmendem Abstand zum Meliorationsstreifen abnimmt und die optimale Distanz für den Streifen, mit der sich flächendeckend positive Ergebnisse erzielen lassen, bei 1 m liegt. Die Ergebnisse aus Vorversuch und Hauptversuch lassen darauf schließen, dass eine Mischung von Biokompost und Stroh ein Substrat für den Unterboden ergibt mit dem dieser sich nachhaltig verbessern lässt, in der Region 'Rheinland Bonn'.

Contents

List of Abbreviations

%	Percent
A-horizon	first 30 cm of the soil, 0-30 cm
B-horizon	subsoil, 30-60 cm
C	untreated Control treatment
C:N	Carbon-Nitrogen-Ratio
cm	centimetre
CO_2	Carbon dioxide
DL	Deep loosening treatment
DLB	Deep loosening + Biocompost treatment
ha	hectar
m	meter
N	Nitrogen
NIRS	Near-Infrared-Sensor
SB	Spring Barley
SD	Standard deviation
SM	Spader machine treatment
SMB	Spader machine + Biocompost treatment
SMCS	Spader machine + Chopped straw treatment
SMG	Spader machne + Green waste compost treatment
SMS	Spader machine + Sawdust treatment
t/ha	tonnes per hectar
TKW	Thousand Kernel weight
vol%	volumetric percent
WW	Winter Wheat

List of Figures

List of Tables

1. INTRODUCTION

1.1. Challenges in agriculture at times of climate change

Agriculture in the 21st century has to rise the challenges of climate change. These challenges accompany increasing atmospheric CO_2 concentrations, global warming, and changes in precipitation events.
Little is known about common response to these problems by crop plants and scientists all over the world aim at modelling the consequences for agriculture. However, different models and main focusses within the models, e.g. concentration of CO_2 or a certain region of the world, large differences in yield estimations occur.

The current status of climate change only allows the statement that weather extremes increase. By this, the risk of heatwaves and heavy precipitation events will become more frequently (Asseng et al., 2013; Seneviratne et al., 2006). The results of Christensen (2001) indicate that a trend towards drier summer conditions and severe flooding events will increase. These results confirm the general weather shift through climate change. Granier et al. (2007) adds that especially the Northern hemisphere will be affected by drought. However, Olesen and Bindi (2002) identify results of climate change also as a chance for the Northern hemisphere. Their state that warming will allow the introduction of new species and varieties, crop production may increase as the suitable area for crop cultivation will expand. Though they also state that growing period for determinate crops will reduce, while it will increase for intermediate crops.
Concerning the global scale Lobell and Field (2007) state that warming has improved yields, if classified as food production per unit of land area, in some areas, reduced in others or the impact is negligible in further other areas. Even though impacts on yield are site-specific, all sectors will be affected by soil moisture deficits (Lal, 2004) and the distribution of precipitation throughout the year will change (Iglesias and Garrote, 2015). As soils are one of the key drivers for agricultural production and also a sink-source for atmospheric CO_2 (Alcantara et al., 2016) adaption strategies are of major interest.

First consequences of climate change and drought could be seen in Europe during the extreme summers 2003 and 2018. Both summers were characterized by extreme drought caused by high temperatures and rainfall deficits, resulting in reductions of yields. The adaption of agricultural systems and ecosystems to this phenomena is predominant in current agricultural research. Howden et al. (2007) summarize that an investment in technological solutions to adapt towards soil moisture deficits and water management as pioneering. Furthermore, precision agriculture (in all sectors from pest management to variety selection and adaption of tillage to changing conditions) and improving climate forecast should always be considered.

1.2. Development of deep tillage in agriculture

The use of deep tillage in agriculture is not very widespread and commonly accepted, although it is known that it can sufficiently decrease bulk density and penetration resistance of soils. To mitigate the impacts of climate change, No-till is designated to be the common solution. Investigations to the impact of deep tillage, so-called subsoiling, were mainly undertaken from the 1980s-1990s. After that, there is a lack in research studies on this field up to the beginning of the 2000's (Schneider et al., 2017).
According to the meta-analysis of Schneider et al. (2017) the definition of subsoiling comes along with several uncertainties and what it exactly refers to. The depth of tillage operations, that are named subsoiling ranges from working depths of 10 cm up to 100 cm. Furthermore, there is a huge variety of machinery used for this. Subsoiling is undertaken by either deep ploughing, moldboard ploughing, disc ploughing, deep chiseling, deep ripping, rotary spader machines or in the combination of this machinery. Thus, the exact definition of subsoiling varies from study to study which hampers clear interpretations and comparability of studies. Nonetheless, all studies have in common that they evaluate effects concerning yield development, bulk density development, and very often root development. Ellington (1986) examined very early trials who combined deep ripening with gypsum application at soil depths of 20 cm and 40 cm. They could demonstrate that effects strongly depend on the soil type and increases wheat yield under very acid and compacted soil conditions. Blackwell et al. (1990) used a trench digger for deep loosening and gypsum application at a soil depth of 40 cm. Gypsum was applied in slots of 15 - 20 cm width and caused faster and deeper wetting in heavy clay soils which are associated with improved aeration and increased crop yields. Ide et al. (1987) and Ross (1986) simply subsoiled soils up to a depth of 60 cm on sugar beets and potatoes. The yield of sugar beets was significantly increased,

which was associated with increased nutrient uptake and water availability, while for potatoes, this effect was only present under arid conditions. Trouse (1983) demonstrated that subsoiling has beneficial effects on yield development in the long term of 15-years. Subsoiling up to 60 cm was undertaken by Rolf (1991) and resulted in reduced bulk densities and penetration resistance, which lead to increased pore volume and air-filled porosity of the soil. On the 3-year scale, limitations could be seen for clayey soils. Martínez et al. (2012) and Sun et al. (2017) focussed on alternating No-till/subsoiling concepts. Both studies promoted positive effects on soil quality and root development on such alternating concepts. However, the effects of subsoiling decrease over time, and special focus has to be given to the frequency of subsoiling. Besides single subsoiling, the use of a chisel plough for deep soil loosening is also studied. Cai et al. (2014) and Ghosh et al. (2006) used a chisel plough at soil depths of 30 cm and 50 cm. Cai et al. (2014) studies resulted in increased grain yield and biomass of 12.8% and 14.6% on average compared to the control. Ghosh et al. (2006) could observe 20% increase in yield of soybeans. Both attributed this to increased root development, which increased nutrient accumulation and improved water storage within the soil.

Besides deep chisel ploughing, effects of single deep ploughing are also investigated in numerous studies. Deep ploughing decreases the bulk density and penetration resistance (Baumhardt et al., 2008), increases root length density and nitrogen uptake (Guaman et al., 2016) and changes root distribution and soil pH positively (Madeira et al., 1989).

Fabio Pezzi (2005) compared the effect of various machines for deep soil loosening (plough, spader machine, and rotary chisel) and states that the use of rotary spader machine creates favorable soil biopores and thus improves soil quality

1.3. Use of organic fertilizers in agriculture

The use of organic materials in agriculture as a fertilizer is a common practice, and it is documented that its application can increase the soil organic carbon content (SOC, Abiven et al. (2009); Diacono and Montemurro (2010)). However, depending on the material and application rate effects on yield development of crop plants can vary.

A review by Diacono and Montemurro (2010) concluded that the addition of organic residues from the compost would increase soil natural fertility and crop yields may increase up to 250% by long-term application of organic waste compost in high rates. The soil organic nitrogen content can increase up to 90% from perennial compost application.

Erhart et al. (2005) evaluated the effect of biocompost application on the long-term scale (10 years). They state that its use can reduce the input of mineral fertilizers to conventional agriculture and ensure a proper nutrient supply to organic farming systems. The yield increase under biocompost application was on average, 10% in 10 years. The effect of biocompost application developed over time with shallow effects at the beginning and slightly increasing effects during the experimental duration. Main reasons were attributed to arid climatic conditions and C:N ratio of 23:1.

The effect of biocompost applied in same total quantities in different doses and intervals in a 5-year field trial with permanent rye was evaluated by Hartl et al. (2003). Their results indicated that biocompost should be applied preferably in a 2-year interval as this treatment resulted in slightly higher yields than all other treatments. Evanylo et al. (2008) also examined the effects of different application rates testing the effects of a mixed poultry litter-yard waste compost with a traditional organic fertilizer (poultry litter) and inorganic fertilizer. On a 3-year duration, crop yields could not benefit from low compost rates, but improvements in bulk density and soil porosity imply beneficial effects on the long term even in low application rates.

Annabi et al. (2011) and Khalilian et al. (2000) emphasized effects of municipal solid waste compost. Khalilian et al. (2000) pointed out that the application method of compost is of minor interest as their results showed surface application or injection of this compost has no effect on yield development. Annabi et al. (2011) focussed the effects on soil parameters and furthermore tested effects of green waste, wood chips, and biowaste compost. All organic amendments tended to increase the resistance of soil aggregates to water effects compared to the control, and thus, soil degradation was improved. All materials were disk ploughed into the soil up to a soil depth of 10 cm. Debosz et al. (2002) also examined the effects of various compost combinations (single soil, soil mixed with compost and sewage sludge mixed with shredded straw) in an 11-month incubation experiment. Results promote positive effects of waste amendments. Compared to the dynamics observed in an unamended soil, effects are moderate and mainly occur in the first weeks after application.

Besides the application of different composts, the application of sawdust is on interest in the studies of Olayinka and Adebayo (1985). They tested whether there is a difference in sawdust being applied to the surface layer of the soil or incorporated into the soil under greenhouse conditions on maize growth. The surface application significantly decreased yield, while the incorporation of sawdust leads to a significant increase compared to the control. Following the results of Webster (1961) the application of sawdust and straw can conserve soil moisture and lead to increased yields.

1.4. Knowledge of combined deep tillage with introduced organic fertilizers

The current knowledge of combined deep tillage with introduced organic fertilizers is not far-reaching. First studies are found during the 1960s by Larson et al. (1960). They investigated single subsoiling and subsoiling combined with the deep placement of fertilizer (concentrated superphosphate) on a silty loam at soil depths from 40 cm - 60 cm. The response of corn yield to tillage was site-specific and ranged from significant reductions to increases. However, the overall response to fertilizer application was positive. The studies of Marks and Soane (1987); Soane et al. (1987) during the late 1980s concentrated on the results of subsoiling and deeply incorporated phosphorus and potassium fertilizer at various locations. Subsoiling increased yields of spring crops on sandy soils at severe drought conditions, while for silty soils under wet conditions yield decrease was predominant. No significant benefit from fertilizer introduction could be observed.

Mullins et al. (1994, 1997) concluded that cotton responds with highly increased yields to subsoiling combined with deeply placed potassium fertilizer. Gajri et al. (1994) established contributions of maize to different deep placed fertilizers (straw mulching and farmyard manure). Overall, all treatments increased yields, and specific effects could be noticed for each treatment. Single deep loosening resulted in reduced soil strength and allowed deeper rooting, and straw mulching kept the surface layer wetter thus improving root growth. Improved root growth was also detected under farmyard manure.

Recent studies from the 21st century were only established by Gill et al. (2008) and Leskiw et al. (2012). Gill et al. (2008) could demonstrate that deep placed organic material doubled biomass production, grain yield was increased by 1.7 times, and 60% more ears were produced compared to the untreated control. This effect was linked to an increase in plant-available water at the subsoil and supply of nitrogen and other nutrients. Leskiw et al. (2012) combined subsoiling with the injection of organic pellets. Their results promoted positive structural changes in subsoil structure, thus allowing better rooting. Nutrient availability increased, and crops responded with higher yields. A review by Hamza and Anderson (2005) pointed out that mixing of organic materials and soil seems to be useful to improve soil bulk density and porosity, which are two key factors for good soil performance.

1.5. Aim and limitations of work

The following thesis has developed as a part of the BonaRes Soil[3] project.

The project has the aim to evaluate the effects of subsoiling on the soil and cereal crop development. The sub-project of the Institute of Agricultural Engineering Bonn covers the entire investigation of the field trial from installation up to harvest and plant observations.
This implies the invention of a practical subsoiling concept to common field trials. The identification of available machines and equipment involves a detailed literature analysis to evaluate past subsoiling concepts and their effects. However, the construction and design of the subsoiling concept and machinery is not of primary focus and belongs to the project working packages of Dr. Oliver Schmittmann - Institute of Agricultural Engineering. Thus, results about this will not be discussed, and the complete melioration technique is of intellectual property of Mr. Schmittmann.
To combine subsoiling with the incorporation of organic material and consequently meliorate the subsoil, organic materials needed to be identified. Following the project outline of Soil^3 organic materials were identified that are of practical focus for farmers.

The effect of subsoiling and subsoiling with the introduction of organic material on the growth of cereal crops is of primary focus within this thesis. By this, the two-year effects are evaluated concerning crop development, which implies an evaluation of yield and grain parameters. The effects are evaluated at the part of the melioration and in the distance to it for the crops Spring barley (*Hordeum vulgare*, 2017) and Winter wheat (*Triticum aestivum*, 2018)

The following scientific issues are discussed within this work:

- Do different subsoiling tools (machinery) influence yield and yield parameter development?
- Are there any differences between single subsoiling and subsoiling combined with different organic materials?
- What is the optimum melioration distance and material for subsoiling?

An outlook gives closing of this thesis to recently arising questions during the fieldwork process and development of machinery.

2. MATERIALS AND METHODS

2.1. Concept of deep tillage

The general idea of deep tillage and deep tillage combined with intermixing of organic material is shown in Figure 2.1. The concept proposes a strip-wise implementation of deep tillage into the field. Within this strip, the a-horizon of the soil (classified as 0-30 cm) remains undisturbed, while the b-horizon (classified as 30-60 cm) is meliorated. The term 'melioration' is now used to describe the deep tillage operation in single or in combination with intermixed organic material.
The melioration of the soil creates an upgraded b-horizon through its loosening and the introduction of organic material. Thus, the attractiveness of this soil layer is increased, resulting in increased biomass development above the stripe. The expected growth of biomass will decrease with increasing distance to the strip.

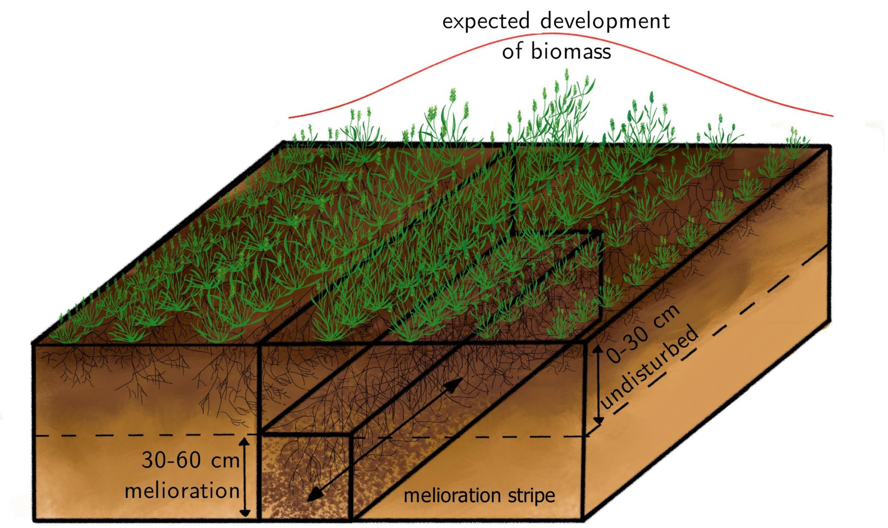

Figure 2.1.: Concept of deep tillage and expected development of biomass

2.2. Description of Incorporation materials

The different incorporation materials were chosen based on their availability and possible economic options for farmers.
Table 2.1 gives an overview of the different materials. Biocompost and green waste compost come from the composting plant 'KRS KompostWerke Rhein-Sieg GmbH & Co.KG'. The basic material for the biocompst is biological household waste, while the basis for green waste compost is cuttings from parks and bushes. For chopped straw wheat straw was used, and sawdust stems from customary animal bedding (Raiffeisen Hobelspäne 'Profi').
The sieving analysis was undertaken following Kromer and Schmittmann (1999). The composition of ingredients and C:N ratio for the two composts are based on regular internal analysis of the composting plant. For chopped straw and sawdust an external lab (JenaBios GmbH) was assigned with this analysis.

Table 2.1.: Analysis of incorporation materials. Values, except for C:N ratio, are in given in percentage (%)

		Incorporation material			
		Biocompost	Green waste compost	Sawdust	Chopped straw
Classification of particle sizes	<3 mm	71,17	58,41	14,90	4,62
	3-6 mm	11,19	14,17	19,72	9,77
	6-10 mm	7,41	11,60	61,76	7,41
	10-15 mm	6,61	8,20	2,19	4,90
	15-20 mm	1,67	3,51	0,48	2,56
	20-25 mm	1,58	2,94	0,48	1,78
	>25 mm	0,37	1,18	0,48	68,95
Ingredients	Total C	41,80	48,00	50,32	42,84
	Total N	1,92	1,17	0,13	0,55
	Total P	0,75	0,44	0,01	0,22
	Total K	1,50	0,92	0,06	1,30
C:N ratio		13:1	24:1	370:1	78:1

2.3. Design of field trial and implementation of deep tillage

The field trial was investigated at the 'Campus Klein-Altendorf' experimental research station (50°37'.51 N;6°59'.32 E), University of Bonn, Germany. According to the FAO (2015) standard, the soil can be classified as a Luvisol derived from loess.

Weather data

The climate is characterized by a mean annual air temperature of 9.4℃ and annual precipitation of 603.4 mm. The weather data was collected from the weather station of the Campus Klein-Altendorf and its development during the experimental period is shown in Figure 2.2.

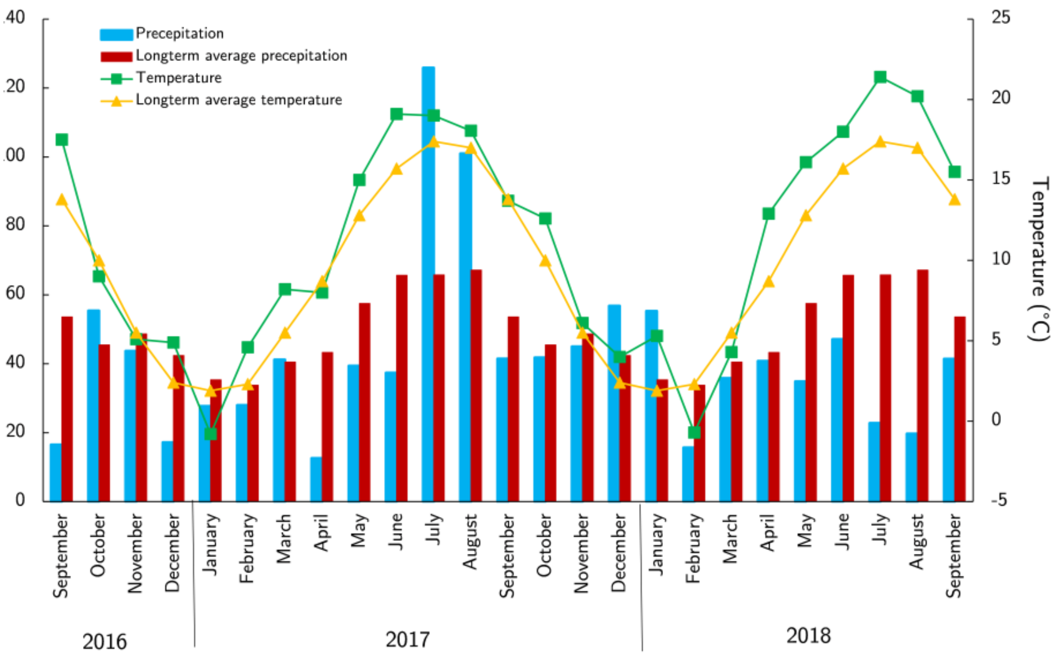

Figure 2.2.: Weather data during experimental period

Plot design and treatment overview

The field trial covers control plots, deep tilled plots, and deep tilled plots with incorporated organic material. In total, the experiment consists of eight treatments in a threefold repetition. The eight treatments are the result of a combination of different tools for melioration and their combination with organic materials. An overview of all treatments is shown in Table 2.2.

Table 2.2.: Treatment overview, Materials were mixed into the B-horizon in a quantitative proportion of 20vol%

Treatment	Melioration tool	Incorporation material	Treatment combination
C	-	-	Control treatment
DL	Tine	-	Deep loosening
DLB	Tine	Biocompost	Deep loosening + Bicompost
SM	Spader machine	-	Deep intermixing
SMB	Spader machine	Biocompost	Deep intermixing + Biocompost
SMG	Spader machine	Green waste compost	Deep intermixing + Green waste compost
SMS	Spader machine	Sawdust	Deep intermixing + Sawdust
SMCS	Spader machine	Chopped straw	Deep intermixing + Chopped straw

Melioration was implemented in all plots except for the control during fall 2016. The plots have a size of 15 m x 3 m (length x width), and melioration was conducted centered within each plot. Figure 2.3 covers the five steps of melioration. Step two was conducted in treatments with organic material (see Table 2.2). Melioration starts with the creation of a centred furrow (15 m x 0.3 m x 0.3 m; length x width x depth) using a one ploughshare (step one, see Figure 2.1 and Figure 2.3). By this, the a-horizon is uncovered and laid aside without disturbing it. The placement of organic material is done using a fodder mixer (step two). The usage of the fodder mixer furthermore allows homogenization of the material. The compliance of the quantitative proportion from 20vol% was secured through the regulation of the forward speed of the tractor and the number of rotations within the fodder mixer (data was calculated and evaluated as a part of Master Thesis P. Odenhausen, 2017, unpublished). In a third step, the b-horizon (30 cm - 60 cm) of the soil is either deep loosened (treatments DL and SM) or organic material is intermixed into the b-horizon using the deep working tine and spader machine. During the fourth step, the soil was recompacted using a depth wheel, and the a-horizon was placed back onto the furrow using a pushing shovel (step five). After this regular field operations for seedbed preparation followed (rotary harrow)

Melioration technique

1: Creation of a furrow

Creation of a 30 cm x 30 cm (width x depth) furrow using a one plough share

Creation of one furrow within 3 m width, a-horizon remains uncovered

2: Deposition of material (Treatments DLB, SMB, SMG, SMS and SMCS)

Homogenization of material using the fodder mixer; sample: chopped straw

Deposition of material using the fodder mixer; sample: biocompost

Deposed materials (at the front: sawdust, at the back: biocompost)

3: Deep loosening and deep loosening with mixing of material

Deep working tine

Deep loosening of the soil (DL)

Deep loosening of the soil and mixing with biocompost (DLB)

Spader machine with 3 (visible 2) rotating spates

Spader machine mixing soil and green waste compost (SMG)

4: Recompaction of the a-horizon

The b-horizon is recompacted using a depth wheel

5: Return of the a-horizon

The a-horizon is returned using a pushing shovel

Figure 2.3.: Melioration technique of the field trial

2.4. Plant analysis

To evaluate the effect of the concept on plant development plant observations that follow the German standard plant observation system was undertaken (Bundessortenamt, 2000). The standard plant observations for cereals include the continuous observation of 1-meter growing plants. The guidelines of the system were adapted and optimized to generate a representative amount of plant observations. A sketch of the plant observation system is shown in Figure 2.4 and includes that plants were observed at the part of the melioration and in the distance to it. Within the melioration, two meters with an offset of one plant row (plant row 12 & 13) were observed and in 50 cm distance to it one meter left (plant row 8) from the melioration and one right (plant row 17) was used.
The following parameters were observed during the growth period of spring barley and winter wheat:

- number of plants
- number of ears
- maximum plant height
- yield, separated into grain and straw yield

After harvest, the grains were analyzed for protein and starch content using NIRS-technology.

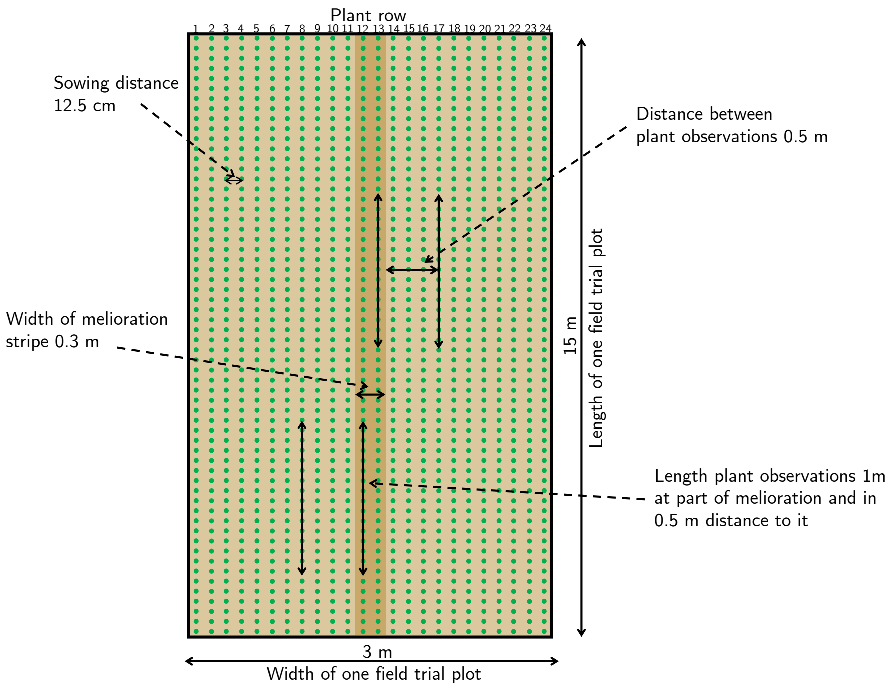

Figure 2.4.: Design of one field trial plot and plant observation scheme

3. RESULTS AND DISCUSSION

Deep soil loosening and its combination with the introduction of organic material affects crop plant development at all stages. However, depending on the treatment, effects are either positive or negative towards the untreated control (see Figure 3.1 and Table 3.1). The yields observed in the distance to the melioration also vary among the treatments.

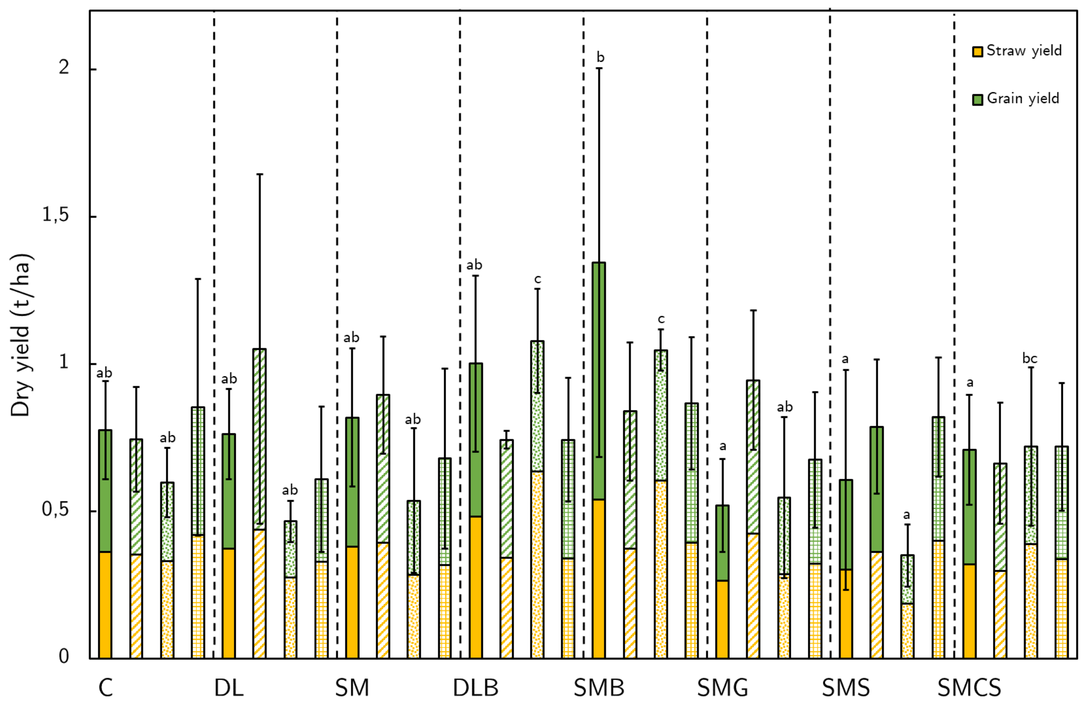

Figure 3.1.: Yield development of different cereal crops grown under different deep tillage conditions. filled: spring barley melioration (year 1); diagonal striped: spring barley 50 cm distance (year 1); dotted: winter wheat melioration (year 2); checked: winter wheat 50 cm distance (year 2); C: control; DL: deep loosening tine; SM: deep loosening spader machine; DLB: tine + biocompost; SMB: spader machine + biocompost; SMG: spader machine + green waste compost; SMS: spader machine + sawdust; SMCS: spader machine + chopped straw; error bars represent +/- standard deviation of dry yield; letters indicate significant differences between dry yields of the treatments in each year and observation row at Tukey's Test $p<0.05$

3.1. Influence of different working tools for subsoiling

The influence of various working tools on cereal crop development is shown within the results of the treatments DL and SM. Treatments DL and SM have developed differently. Thus it can be concluded that the type of deep working tool influenced crop development.

Table 3.1.: Results of grain quality parameters. SB: spring barley melioration (year 1); SB50: spring barley 50 cm distance (year 1); WW: winter wheat melioration (year 2); WW50: winter wheat 50 cm distance (year 2); DL: deep loosening; SM: spader machine; DLB: deep loosening biocompost; SMB: spader machine biocompost; SMG: spader machine green waste compost; SMS: spader machine sawdust; SMCS: spader machine chopped straw, Letters indicate signifcant differces between the treatments at Tukey's Test $p<0.05$

		C	**DL**	**DLB**	**SM**	**SMB**	**SMG**	**SMS**	**SMCS**
Number of plants / m₂	SB	143	147	140	123	152	143	129	143
	SB50	144	161	129	147	144	149	119	156
	WW	255	229	263	267	243	207	244	229
	WW50	224	253	240	225	235	204	249	217
Number of Grains / m₂	SB	551a	897ab	708ab	801ab	1123b	564a	548a	576a
	SB50	637	912	623	747	715	793	611	557
	WW	301abc	263a	425bc	288ab	444c	268a	267a	311abc
	WW50	365	345	373	359	391	324	369	349
maximum plant height	SB	73cd	76de	80f	74cd	78ef	67b	63a	70bc
	SB50	72	74	74	73	74	70	70	70
	WW	54a	56a	67b	54a	68b	52a	50a	52a
	WW50	57	54	60	53	57	55	55	57
TKG	SB	48,3bc	49,0bc	45,0abc	45,3abc	49,5c	41,7a	43,5ab	45,5abc
	SB50	47,8ab	49,5b	44,3a	47,0ab	45,8ab	44,5ab	46,3ab	45,8ab
	WW	28,7	27,2	29,0	27,7	29,0	28,2	25,3	29,5
	WW50	29,8	26,8	29,2	27,5	28,2	28,7	28,5	28,5
Protein (%)	SB	11,1ab	12,8c	14,6a	11,1b	14,2cd	9,7a	9,8ab	10,2ab
	SB50	11,6abc	12,1bc	12,3bc	11,4ab	12,7c	10,7a	10,7a	11,5abc
	WW	9,8a	10,2ab	12,2bc	10,5abc	13,0c	10,5a	10,3ab	9,8a
	WW50	10,2	11,2	10,8	11,5	11,7	10,7	10,5	10,5
Starch /(%)	SB	54,7abc	54,4ab	54,0a	55,2bcd	53,9a	55,7cd	55,8d	55,9d
	SB50	54,6	54,8	55,1	55,2	54,7	55,3	55,6	55,4
	WW	74,3	74,0	73,2	73,7	72,7	74,0	73,5	74,0
	WW50	74,5	73,5	73,7	73,3	73,5	74,0	73,5	74,0

3.2. Effect of different organic materials

The four different incorporation materials are all classified as organic fertilizers while their raw materials differ. The analysis of incorporation materials (see Table

2.1) shows that materials differ in structure (sieving analysis), ingredients, and C:N ratio. Especially the C:N ratio is of major responsibility for slow or fast implementation of the materials and the usability of N introduced by the materials. According to Abiven et al. (2009) easily decomposable products have a powerful and transient effect while more recalcitrant products have a lower but longer-term effect. Ros et al. (2006) adds that micro-organisms introduced by compost have a direct effect on soil fertility. Of all materials, biocompost is the only one which significantly increases dry yield development compared to C in both years. The introduction of green waste compost, sawdust, and chopped straw lead to decreased dry yields in year 1. In year 2 the chopped straw increased yield at part of melioration. Dry yields and grain quality parameters in 50 cm distance vary positive and negative from C, but significant differences are only present at SB 50 for TKG. The effect of biocompost is positive but differs for DLB and SMB as a consequence of different machinery used. As the effect of biocompost in DLB is increasing in year 2 (see Table 3.2 dry yield +29.2% year 1 and +80,4% year 2) the effect of SMB remains stable in both years (dry yield +73.5% year 1 and +75.2% year 2). Diacono and Montemurro (2010) state that materials with similar C:N ratios may mineralize different amounts of N and thus different amounts of N are directly available to the crop.

Even though the number of plants slightly differs for all years and treatments (see Table 3.1) none of these differences are significant. Different results for SMS and SMCS could be expected as Procházková et al. (2003) and Webster (1961) state that the application of sawdust and straw can have a detrimental effect on plant establishment due to the lack of nitrates, physical and biochemical effects (e.g. water consumption for decomposition). Since the material was incorporated into the subsoil and not applied at the soil surface effects came into acount after plant establishment. The yields of SMG, SMS, and SMCS year 1 are lower than C; however, this decrease is not significant. Even though yields and yield parameters for SMG, SMS, and SMCS decreased compared to C, the yields of SMCS are nearly stable around the experimental period. The introduction of these materials with a large C:N ratio might have led to a competition of N by plants and microbial community, thus immobilizing it (Diacono and Montemurro, 2010; Döring et al., 2005; Olayinka and Adebayo, 1985). The development of grain quality parameters reinforces the negative effect of these materials on crop development.

Table 3.2.: Percentage variance of each treatment towards the control treatment for yield and grain quality parameters. SB: spring barley melioration (year 1); SB50: spring barley 50 cm distance (year 1); WW: winter wheat melioration (year 2); WW50: winter wheat 50 cm distance (year 2); DL: deep loosening; SM: spader machine; DLB: deep loosening biocompost; SMB: spader machine biocompost; SMG: spader machine green waste compost; SMS: spader machine sawdust; SMCS: spader machine chopped straw

		DL	SM	DLB	SMB	SMG	SMS	SMCS
Dry yield	SB	-1,7	5,7	29,2	73,5	-32,8	-21,8	-8,4
	SB50	41,0	20,3	-0,3	12,5	26,8	5,7	-10,9
	WW	-21,9	-10,2	80,4	75,2	-8,5	-41,5	20,4
	WW50	-28,7	-20,5	-13,0	1,4	-21,0	-4,0	-15,8
Straw yield	SB	3,1	4,6	32,5	48,6	-27,2	-17,1	-11,9
	SB50	24,3	11,9	-2,7	5,6	20,5	2,5	-15,7
	WW	-16,5	-14,0	92,7	83,1	-13,2	-43,7	17,9
	WW50	-21,6	-24,2	-19,2	-6,3	-23,0	-4,8	-19,5
Grain yield	SB	-5,9	6,7	26,3	95,4	-37,8	-26,0	-5,2
	SB50	56,1	27,7	1,8	18,9	32,4	8,6	-6,7
	WW	-28,6	-5,7	65,2	65,4	-2,9	-38,7	23,4
	WW50	-35,5	-16,9	-7,0	8,9	-19,0	-3,1	-12,1
Number of plants	SB	2,8	-14,0	-1,9	6,5	0,0	-9,3	0,0
	SB50	12,0	1,9	-10,2	0,0	3,7	-17,6	8,3
	WW	-9,9	4,7	3,1	-4,7	-18,8	-4,2	-9,9
	WW50	13,1	0,6	7,1	4,8	-8,9	11,3	-3,0
Number of grains	SB	63,0	45,5	28,6	103,9	2,4	-0,5	4,6
	SB50	43,1	17,2	-2,3	12,1	24,5	-4,2	-12,6
	WW	-12,8	-4,4	41,2	47,3	-11,1	-11,5	3,1
	WW50	-5,5	-1,8	2,2	6,9	-11,3	1,1	-4,4
Maximum plant height	SB	3,7	1,3	9,7	6,5	-7,9	-13,4	-3,5
	SB50	2,7	1,0	2,0	2,8	-2,8	-2,8	-2,6
	WW	3,1	-0,2	24,4	25,2	-4,7	-8,4	-4,2
	WW50	-4,9	-6,0	6,3	0,0	-4,0	-3,9	-0,1
TKG	SB	1,5	-6,1	-6,9	2,5	-13,7	-9,9	-5,8
	SB50	3,5	-1,7	-7,3	-4,1	-6,9	-3,1	-4,1
	WW	-5,1	-3,5	1,2	1,2	-1,7	-11,6	2,9
	WW50	-10,1	-7,8	-2,2	-5,6	-3,9	-4,5	-4,5
Protein (%)	SB	15,9	0,3	32,0	28,1	-12,3	-11,7	-7,7
	SB50	4,2	-1,4	6,2	9,8	-7,9	-7,2	-0,7
	WW	3,7	6,8	23,7	32,2	6,8	5,1	0,0
	WW50	9,8	13,1	6,6	14,8	4,9	3,3	3,3
Starch (%)	SB	-0,6	0,9	-1,4	-1,5	1,7	2,0	2,2
	SB50	0,3	1,1	0,8	0,1	1,3	1,8	1,4
	WW	-0,4	-0,9	-1,6	-2,2	-0,4	-1,1	-0,4
	WW50	-1,3	-1,6	-1,1	-1,3	-0,7	-1,3	-0,7

3.3. Deduction of optimum melioration distance and material

The development of optimum melioration distance is a two-tier process. On the one hand, it is influenced by the development of machinery (which is one of the main milestones of the BonaRes Soil[3] project) that can implement subsoiling as shown in Figure 2.3 as a single-phase project. This machinery also has to fulfill the traffic regulations; thus, machine width is limited to 3 m. On the other hand, the evaluation of yields in the distance to the melioration demonstrates the point where no beneficial effects of treatment are present.
The results of subsoiling on regularly tilled land in this study show that yields and yield parameters vary at a distance of 50 cm to the melioration, but none of these effects is significant. Applying subsoiling and subsoiling combined with the introduction of organic material at fallow land (Jakobs et al. (2017), see Appendix A) a continuous decreasing effect with increasing distance to the subsoiling is present. The results of this trial show that observations in two ranges to the melioration (50 cm distance and 100 cm distance) allow separation into two significantly different groups. The yields in 100 cm distance are significantly lower than at part of melioration. At 50 cm distance results are neither significantly different from the melioration nor 100 cm distance.
These results allowed the conclusion that a melioration distance of 100 cm promotes continuous positive results for a whole crop area, respectively to the effects of pre-trial on fallow land. The machinery of 3 m working width with distances of 1 m (one melioration strip each meter) was developed by Andreas Christ, ILT University of Bonn, as master thesis (Konstruktion und Bewertung eines mehrreihigen Versuchsträgers zur reihigen Applikation organischer Materialien, unpublished) and application for a patent is running.
Concerning the different incorporation materials, results of pre-trial (see Annex A) have shown that inhomogeneous and damp materials are not suitable for incorporation as their pourability is not secured (cattle manure). Most significant effects in short-term and on a two-year-period emerge under dense C:N ratios (biocompost) and materials with moderate to large C:N ratios (green waste compost, sawdust, and chopped straw) decrease yields. However, long-term effects of these materials may come into account.
Results of year 2 show that the yield of WW and SMCS is increased compared C, even though this is not statistically secured. This demonstrates that the implementation of chopped straw has only adverse effects on the short-term. Since the incorporation of biocompost has a strong fertilizer effect on the subsoil and significantly increases yields, a combination with chopped straw seems suitable. Mixing

biocompost and straw can lead to results which are positive on the short-term and last on the longer term.

4. CONCLUSION

Subsoiling and subsoiling combined with the introduction of organic materials, produce either positive or negative effects towards an untreated control. Effects vary among materials and machinery.

The usage of machinery which is designed for deep field tillage (spader machine) accompanied with weighty machinery which led to problems of specific working within a furrow. Construction and design of a specialized incorporation tool based on a tine allowing easy practicability of subsoiling procedure. The investigation of machinery is up to now finished and enables subsoiling in 1-meter distances with a total working width of 3 m. Future plant observations have to evaluate if closer or wider subsoiling distances would be more beneficial as these assumptions of distance are based on results of the pre-trial at fallow land.

By this, the evaluation procedure of yield development should be continued for another few years. Certainly, SD's of most treatments were very high, and observation of 1-meter, respectively 2-meters per plot is not enough. Harvesting of crops using a parcel thresher should be included to gain yield information from a higher sample size.

Concerning the different materials, materials with dense C:N ratios (biocompost) are highly valuable for yield development. Materials with wide C:N ratios (chopped straw) come into account over time and mixing of both materials might results in an improved mixed substrate for subsoiling. However, the effects of materials with moderate (green waste compost) C:N ratios are not beneficial within a two-year-period but become it on the longer term. Materials with wide C:N ratios being highly lignified (sawdust) are not suitable. Single subsoiling improved soil conditions and may be an effective solution at field sites with strongly restricted fertilizer application guidelines.

In total subsoiling and its combination with organic materials can be highly valuable to yield development of cereal crops and improve soil conditions if optimum machinery and materials are used. However, these statements are based on results from an experimental site which is regularly tilled and of good soil conditions. To give final recommendations experimental sites with soil physical problems (e.g., root-restricting soil layers), other soil compositions (e.g., very sandy soils) and strong weather impacts (e.g., regular absence of rainfall and hot weather conditions) must be implemented to state beneficial effects of this tillage procedure at times of climate change.

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Short-term effects of in-row subsoiling and simultaneous admixing of organic material on growth of spring barley (*H. vulgare*)

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Abstract

Previous studies have shown that deep tillage, so-called subsoiling, is beneficial for yield development, and that tillage of deeper soil layers can promote water and nutrient availability during dry periods. The application of composts to the topsoil has been widely studied and evaluated, and it has been shown to improve soil stability and plant N uptake. These effects can differ over time depending on the compost type. Since dry periods have become more frequent, sustainable soil tillage and fertilizer practices must be developed. A combination of deep soil tillage and compost application might be a way to ensure proper plant supply during dry periods. Therefore, a field experiment on spring barley growth was carried out to evaluate the short-term effects of in-row subsoiling with simultaneous admixing of compost. Two types of composts and one organic fertilizer (Bio: decomposed organic waste, Green: decomposed green cuttings and CM: cattle manure) were admixed into the subsoil, and a control treatment received single deep loosening (DL) to a depth of 0.6 m. Yield development, yield parameters and grain quality were analysed and showed that the DL and Bio treatments resulted in the highest yields, and a significantly increased ear density and number of kernels. The TKW (100-kernel weight) of the CM treatment was significantly lower than the other treatments. In all treatments, a clear trend of decreasing yields with increasing distance to the melioration was observed. Thus a subsoil tillage every meter can increase overall yield development and offers a new perspective for sustainable crop production.

Keywords: Subsoil, deep loosening, biocompost, green compost, cattle manure, spring barley

Introduction

Several climate models indicate a general trend towards warmer and drier summer conditions in Europe, which is challenging agriculture in the 21st century. Warmer and drier summer conditions imply changes in temperature and precipitation that can be associated with higher risks of heatwaves, droughts and heavy precipitation events (Seneviratne *et al*., 2006). These changes may have a great impact on soil performance thus affecting agricultural productivity, because, as soils dry, water uptake by plants is reduced and growth is restricted (Davies, 1991). Moreover, the soil structural conditions affect the spatial distribution of roots and the plants ability to take up water (Pardo *et al*., 2000). When drought intensifies, the distribution of water uptake by plants changes from the topsoil to the subsoil (Bréda *et al*., 1995). The studies of Kirkegaard *et al*. (2007), indicate that deeper soil layers remain unaffected by temporary dehydration in contrast to the topsoil. Therefore, it can be assumed that dry periods may have a minor impact on plant development if plants are able to easily access the subsoil with their roots, thus utilizing nutrients, water and carbon from these soil layers. The method of integrating the subsoil into soil cultivation can be beneficial because changes in soil structure will affect plant growth, mostly by modifying the root physical environment and the water and nutrient cycles (Angers & Caron, 1998). Batey (2009) found that the subsoil provides a significant proportion of the water required by crops to meet transpiration demands. In dry and warm summers, when soil moisture deficit is high, a restricted ability of roots to reach subsoil water causes moisture stress (Batey, 2009) and may result in reduced yields. However, this can be prevented by relatively small amounts of easily accessible subsoil water, which is highly

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valuable to the yield (Kirkegaard *et al*., 2007). Nevertheless, the structure and density of subsoils always have to be considered when describing water extraction from and root growth into these soil layers (Wang & Smith, 2004). An effective method to enable root development into the subsoil is subsoiling. Subsoiling can increase the infiltration rate of soils, reduce bulk density and thus improve grain yield (Ishaq *et al*., 2001). The term 'subsoiling' is used to describe various methods of deep soil tillage. Blackwell *et al*. (1990), concluded that slotting can be carried out on a wide range of soils and needs to be combined with gypsum as single slotting is not persistent. In contrast, Ellington (1986), pointed out that gypsum depressed wheat growth while single deep slotting increased it. The effect of subsoiling on maize growth was examined by Gajri *et al*. (1994). They demonstrated that soil strength decreased due to deep soil tillage, and plants responded with deeper and denser rooting. These findings were confirmed by a recent study from Cai *et al*. (2014) who found that maize plants, grown under subsoil tillage up to 50 cm, had increased dry yield and grain yield compared to plants grown using conventional tillage. Cai *et al*. (2014), concluded that roots were more likely to grow downwards with deeper subsoil tillage in soil. Hartmann *et al*. (2008) focused on different subsoil loosening strategies and showed a biomass improvement of 78% in maize after deep soil slotting compared to the control treatment. They concluded that plants have an improved access to soil water and therefore sufficient water supply at important physiological stages. Mullins *et al*. (1994) examined the physical changes of in-row subsoiling on cotton plants. They demonstrated that in-row subsoiling resulted in a significant reduction in penetration resistance and cotton plants responded with higher root densities. They predicted that the increased root density could be beneficial during drought stress periods. Ross (1986) also found that effects of subsoiling were the greatest under droughty conditions, and Marks & Soane 1987, showed that the effects strongly depend on the soil type, crop and season.

Besides the loosening of deep soil layers enabling root growth, the increase in soil fertility is a key factor for sustainable crop production. Many studies have demonstrated that long-term amendments of organic wastes and animal manures are beneficial for crop production (e.g. Debosz *et al*., 2002; Erhart *et al*., 2005; Evanylo *et al*., 2008; Annabi *et al*., 2011). Diacono and Montemurro (2010) asserted that the development of a sustainable agriculture, which implies sustainable management practices, is the challenge for the future. They suggested that the application of organic materials, for example, organic wastes and animal manures is favourable because they enhance soil organic N content and store it for mineralization in the following cropping seasons.

Soil fertility and soil aggregate stability can also be enhanced by the application of organic wastes (Abiven *et al*., 2009; Diacono & Montemurro, 2010).

However, Previous work has mainly focussed on either the effects of subsoiling or the effects, especially long term, of compost and manure application. The effect of deep-placed fertilizer on various crops (e.g. ploughed under, Larson *et al*., 1960; subsoil fertilization, Ross, 1986; deep mixing of fertilizer and subsoil, Marks & Soane, 1987) was to significantly increase yields compared to the control treatments. Generally, this effect is associated with deeper rooting of crops, more efficient water extraction and improved nutrient supply. However, these studies examined the effect of mineral fertilizers in deeper soil layers while Gill *et al*. (2008) researched the effect of deep-placed organic material. Their results show a doubling of biomass production in wheat and an increase in grain yield of 1.7 times compared to the untreated control. Based on this, a combined deep loosening of soils and admixing of organic material might be highly beneficial for yield development. The materials selected in present study have different temporal effects on soil stability, as well as different C/N ratios and total N contents. Abiven *et al*. (2009) concluded that easily decomposable products (biocompost, green waste) have an intense and transient effect on soil stability, while recalcitrant products (cattle manure) have a lower but longer-term effect.

This study examines the effect of deep soil loosening with admixing of organic material into the subsoil (30–60) focussing on short-term effects (one growing season). Based on literature analysis we hypothesize that single deep loosening and admixing of organic material increases yield development. To emphasize the single effects of this tillage option, a fallow area was chosen, as farmland soils are regularly tilled and well structured. This area has no history in soil tillage, and differences in plant development can only be reduced to the single effects of deep loosening and admixing of organic material.

Materials and methods

Experimental design

The experiment was conducted at the 'Meßdorfer Feld' experimental research station (50°43′N, 7°03′E), University of Bonn, Germany. The soil is a Luvisol derived from loess (FAO, 2015). Mean annual temperature is 10.3 °C with a mean annual precipitation of 669 mm. Weather data are presented in Figure S2. The field site was left fallow with uncontrolled growth in recent years. In total, the experiment included four different treatments replicated three times (Table 3). Each plot had a size of 3.0 × 2.0 m with a subsoil tillage stripe of 2.0 × 0.3 × 0.4 m in the centre.

Field site preparation included the removal of uncontrolled growth, followed by primary and secondary soil tillage (Figure 1). The removal of uncontrolled grow entailed the mechanical removal of weeds to ensure a uniform soil

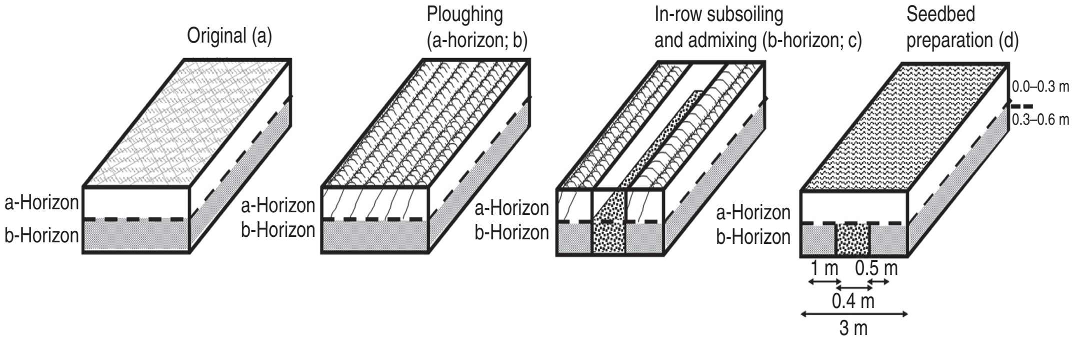

Figure 1 Sketch of field site preparation. Preparation included the removal of uncontrolled growth (a), followed by ploughing up to 0.3 m (b). The slots were prepared using a compact excavator, and material was manually intermixed (c). The topsoil was laid back and reconsolidated. Disc harrowing was applied for seedbed preparation (d).

surface (Figure 1a). Primary soil tillage involved mouldboard ploughing to a depth of 30 cm (Figure 1b). After this, slots were prepared using a compact excavator (Type: Kubota K008-3). One slot was prepared and centred within a width of 3 m. The slot had a width of 0.4 m based on the dimensions of the excavator shovel. The a-horizon (0–0.3 m) of the soil was laid aside, and the b-horizon (from 0.3 m) was dredged up to 0.6 m using the shovel. Organic material was placed within the slot on top of the b-horizon and manually intermixed with it (Figure 1c) at a volume fraction of 11%, a control treatment received only single subsoil loosening.

Afterwards, the a-horizon was returned and the soil was recompacted by driving over with the compact excavator. Secondary soil tillage included rotary harrow with seedbed preparation (Figure 1d). In total, three types of organic material (two different composts and cattle manure) were admixed to the b-horizon. They were chosen based on their accessibility and economic options for farmers. The composts (i) biocompost from decomposed organic household wastes and (ii) green compost from decomposed green cuttings from bushes and trees correspond to the German standard assurance system for composts (RAL-Gütesicherung). The cattle manure was purchased from the 'Frankenforst' experimental farm, University of Bonn. Samples of all materials were oven-dried at 105 °C to determine the dry matter content (see Table 1). The composts were sieved afterwards for particle size fractionation (Kromer & Schmittmann, 1999; Table 2). However, sieving of cattle manure was not feasible after drying.

Plant observations

To evaluate the effect of subsoil amendment on plant development, continuous plant observations were conducted during the vegetation period. The observations were carried out following the guidelines of the German 'Bundessortenamt' (Bundessortenamt, 2000). Within one plot, the observations were made in the middle of the slot (part of subsoil amendment), and at two distances from the slot (0.5 and 1 m, see Figure 1d) to determine the effect of

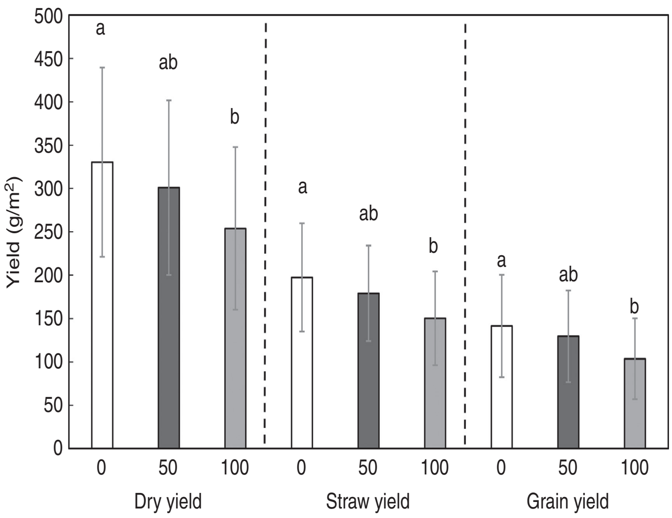

Figure 2 Yield on all treatments. Letters indicate significant differences between the yields ($P < 0.05$). Yield shown are average values of all treatments at the distance from the mid-point of residue incorporation. x-axis: 0: mid point of resisude incorporation; 50: 50 cm distance to mid point of residue incroporation and 100: 100 cm distance to mid point of residue incorporation.

the amendment. To avoid any border effects, each plot included a border of one seeding row. The number of ears and plant height was measured at the time of grain development. Plants were harvested at the time of threshing ripeness. One metre per observation row was harvested. Dry yield (total biomass), straw yield and grain yield after threshing were determined. The total number of kernels per square metre, 1000-kernel weight (TKW) and kernels per ear were calculated. Grain quality parameters were examined using NIR technology. To determine the effects of subsoiling on grain size, grains were sieved in a sieving tower with sieving holes of <2.8, 2.8–2.5, 2.5–2.3 and >2.3 mm.

Table 1 Characterization of organic materials

Subsoil tillage material	Dry matter content (%)	SD	Total N (kg/t)	C/N ratio
Biocompost[A]	56.01[a]	0.96	12.8[a]	13[a]
Green compost[A]	50.60[b]	3.03	9.2[a]	22[a]
Cattle manure[B]	19.75[c]	2.25	5.5[b]	24[b]

Lowercase letters: significant differences at $P < 0.1$ between organic materials. [A]Total N content based on the analysis of the composting plant. [B]Total N content based on literature values (KTBL, 2015).
SD: standard deviation

Penetrometer measurements

Penetrometer measurements were undertaken on an adjoining field in preparation for the experiment (see Figure S1). Measurements were undertaken on an undisturbed control and within the centre of deep loosening slot. An ASAE standard (American Society of Agricultural and Biological Engineers, 2006) penetrometer was used (Sun *et al*., 2003). Data represent average penetration resistances of $n = 5$ measurements.

Data analysis

Analysis of variance was performed using SPSS version 20 for Windows. A one-way ANOVA followed by Tukeys's significant difference test (*post hoc* test) was used to test the effects of treatments and distance to the subsoil tillage.

Results

Effect of subsoil amendment on plant development

To determine the effect of subsoil tillage on plant development, average yields at different distances from the subsoil tillage were analysed (Figure 2). A correlation analysis was performed to determine plant-specific parameters that

Table 2 Sieving analysis of composts

	Sieving size						
Compost	<3 mm	3–6 mm	6–10 mm	10–15 mm	15–20 mm	20–25 mm	>25 mm
Biocompost	71.2	11.2	7.4	6.6	1.7	1.6	0.4
Green waste	58.4	14.2	11.6	8.2	3.5	2.9	1.2

Table 3 Treatment overview for barley plants grown under subsoil amendment with admixed organic material

Treatment	Distance to centre of incorporation	Subsoil tillage
DL0	Centre	Deep loosening up to 60 cm
DL50	50 cm to DL0	–
DL100	100 cm to DL0, effective control treatment	–
Bio0	Centre	Deep loosening + admixing of biocompost
Bio50	50 cm to Bio0	–
Bio100	100 cm to Bio0	–
Green0	Centre	Deep loosening + admixing of green compost
Green50	50 cm to Green0	–
Green100	100 cm to Green0	–
CM0	Centre	Deep loosening + admixing of cattle manure
CM50	50 cm to CM0	–
CM100	100 cm to CM0	–

influence yield development at different distances from the mid-point of residue incorporation (Table 4). Dry yield straw yield and grain yield were significantly higher ($P < 0.05$) in areas of subsoil tillage compared to those at 1 m distance (Figure 2). However, yields were not significantly different 0.5 m from the subsoil tillage. The correlation analysis showed a moderate positive (mid-point) to strong (0.5 and 1 m distance) correlation between straw yield and grain yield at the mid-point of incorporation. In contrast, correlation between dry yield and grain yield shows a very strong positive correlation for all distances. The number of kernels also has a very strong positive correlation with the grain yield and dry yield, while correlation to straw yield differs from moderate to strong. The correlation of TKW to grain yield provides weak negative correlations which are significant at $P > 0.05$. For correlation of TKW versus dry yield and TKW versus kernel number, weak R-values can be seen. However, for TKW versus dry yield, the correlation is significantly negative at 1 m distance from the mid-point of incorporation, while for TKW versus kernel number, the correlation is significantly negative at the mid-point of subsoil tillage. Additional growth parameters cannot be clearly related to yield development. Even though significant correlations were detected at some showed distances, the R-values support only weak-to-moderate correlations.

Effect of admixing material on yield

Deep loosening (DL) of the soil and deep loosening with admixing of biocompost (Bio) provided significantly higher dry yields in the amended part (DL0 and Bio0) than in 100 cm (DL100 and Bio100) distances from it. The yield of the DL0 was almost equal to Bio50, and Bio100 was just slightly lower than DL50.

Regarding the straw yield (Figure 4), significant differences ($P > 0.1$) were detected between Bio0 and Bio100, and CM0 and CM100. The DL treatments and Green treatments showed no significant differences in straw yield. For the DL0 and DL50 treatments, a nearly equal straw yield was found, while for DL100 it was lower. Figure 5 shows the grain yield on the different treatments and distances to the subsoil tillage. DL0 had a significantly ($P > 0.1$) higher grain yield compared to DL50 and DL100. Bio0 had the overall highest grain yield, and grain yield of Bio100 was significantly lower. For CM, the grain yield of CM50 was higher than CM0. Green provided no significant differences in grain yield, even though a trend of decreasing grain yields from Green0 to Green100 is noticeable. A statistical comparison of the different materials in distance to the mid-point of residue incorporation was not significant at $P > 0.1$ (Figures 3 and 5).

Effect of admixing material on grain quality parameters

The effect of admixing material on grain quality parameters was evaluated by a sieving analysis and NIR analysis. The sieving analysis allowed a separation into four groups (Figure 6). A trend towards decreasing proportions of grains >2.8 mm with increasing distance to the mid-point of subsoil tillage was found for Bio and Green treatments. In contrast, the DL and CM treatments had higher proportions at 100 cm distance than at 50 cm distance to the subsoil tillage. All treatments had approximately 34% in the fraction 2.8 mm. The fraction <2.2 mm was the lowest mass proportions.

The grain quality parameters, protein and starch content, are presented in Figure 7. The protein content of the different treatments varied between 13% and 17%, while the vast majority was around 15%. Overall, the protein contents of DL had the lowest variation, while the variation for Green was the highest (Figure 7). There were no significant differences in protein content within or between treatments.

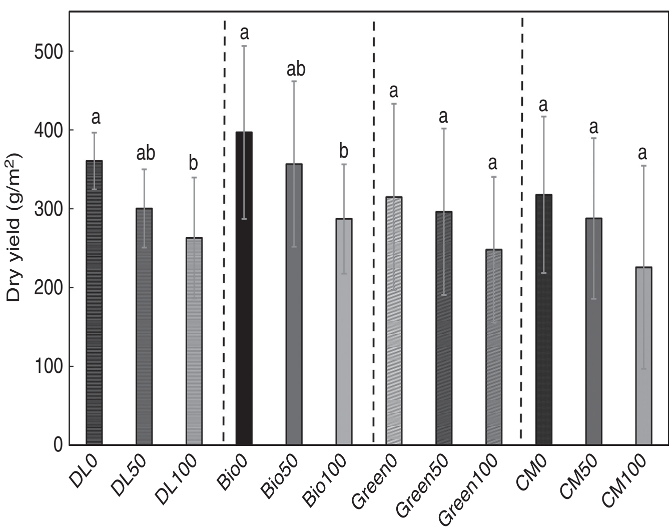

Figure 3 Dry yield. Letters indicate significant differences within the treatments ($P < 0.1$).

Table 4 Pearson's correlation analysis for yield and grain quality parameters of barley

	Grain yield			Straw yield			Dry yield			Kernel number			TKW			Ear number			Protein			Starch		
	0	50	100	0	50	100	0	50	100	0	50	100	0	50	100	0	50	100	0	50	100	0	50	100
Grain yield																								
0	1																							
50		1																						
100			1																					
Straw yield																								
0	0.61**			1																				
50		0.73**			1																			
100			0.73**			1																		
Dry yield																								
0	0.89**			0.90**			1																	
50		0.92**			0.93**			1																
100			0.92**			0.94**			1															
Kernel number																								
0	0.97**			0.63**			0.89**			1														
50		0.90**			0.82**			0.92**			1													
100			0.95**			0.72**			0.89**			1												
TKW																								
0	−0.51**			−0.06			−0.31			−0.33*			1											
50		−0.42**			−0.00			−0.22			−0.02			1										
100			−0.50**			−0.28			−0.41**			−0.24			1									
Ear number																								
0	0.37**			0.44**			0.45**			0.39*			−0.12			1								
50		0.26			0.05			0.17			0.14			−0.26			1							
100			0.48**			0.38*			0.46**			0.43**			−0.36*			1						
Protein																								
0	−0.03			0.19			0.09			0.01			0.23			0.01			1					
50		−0.44**			−0.38*			−0.44**			−0.32			0.31			−0.58**			1				
100			−0.28			−0.28			−0.31			−0.24			0.17			−0.21			1			
Starch																								
0	0.06			−0.07			−0.01			0.00			−0.30			−0.04			−0.39*			1		
50		0.46**			0.23			0.37*			0.34*			−0.31			0.46**			−0.63**			1	
100			−0.26			−0.16			−0.22			−0.29			−0.03			−0.07			−0.46**			1

*$P < 0.05$; **$P < 0.01$; parameters grain yield, straw yield, dry yield, kernel number, ear number is related to per m^2; TKW 1000-kernel weight.

The analysis of starch content resulted in significant differences across the treatments at a distance of 0.5 m to mid-point of subsoil tillage. Furthermore, Green treatments resulted in significantly different starch contents. There were no significant differences within the other treatments.

Discussion

Effect of subsoil tillage on yield development

Our results showed the highest dry yields, straw yields and grain yields in areas of subsoil tillage (Figure 2). These yields were significantly higher than those at a 1 m distance. The results of Cai *et al.* (2014), demonstrate that subsoiling improves the soil physical conditions and reduces soil mechanical resistance to root penetration, allowing root penetration into deeper soil layers. These deeper soil layers store minerals nutrients and water, which are of major importance for plant development during important physiological stages (Hartmann *et al.*, 2008). Based on the explanations of Hartmann *et al.* (2008), and Cai *et al.* (2014), it can be assumed that subsoil tillage promoted root growth into the subsoil. Thus, plants were able to utilize water, minerals and nutrients from deeper soil layers. The correlation analysis resulted in very strong correlations between grain yield versus kernel number and straw yield versus number of grains. For grain yield, the correlations slightly decrease with increasing distance to the subsoil tillage, while for straw yield, the opposite occurs. Passioura (1976) and Gill *et al.* (2008), emphasize that plants which are able to access water from the subsoil late in the growing season can translocate products of photosynthesis directly into grain development. The statistically higher grain yields in areas of subsoil correlation can be explained by this.

Effect of different treatments on yield

According to the explanations of Abiven *et al.* (2009), the effect of the admixed materials can be described follows. Concerning soil stability, all materials have a strong effect but on a different timescale. Composts reach their maximum effect on soil stability within a few months, while cattle manure reaches its maximum. Abiven *et al.*, (2009) argue these temporal differences reflect the presence of prehumic substances in biocompost and green compost. For cattle manure, the presence of humic substances is crucial for soil stability. In summary, the short-term effects of organic matter on soil stability can be associated with the turnover of microbial products and cells, while the long-term effects can be explained by humified compounds (Wordell-Dietrich *et al.*, 2016). Even though Abiven *et al.* (2009) classified biocompost and green compost as having a strong and intermediate effect on soil stability, the analysis of dry matter content and sieving (Tables 1 and 2) showed structural differences between the materials.

Biocompost had a higher dry matter content than green compost and more than 70% of the particles were <3 mm, while for green compost it was only 58%. Furthermore, the total N content of biocompost was higher, and the C/N ratio as having smaller than green compost. Overall, Bio provided the highest dry yields. Significant differences within the treatments occured for DL and Bio. For DL, this was due to the direct effect of the subsoiling. The overall dry yield and grain yield were higher at DL0 than DL100, (Figures 3 and 5). This can be explained by the thesis of Kirkegaard *et al.* (2007), that subsoil water used in the postanthesis period is highly beneficial for grain yield. The strong short-term effect of Bio on yield development can be explained by the results of Diacono and Montemurro (2010) and Erhart *et al.* (2005). They argue that the introduction of

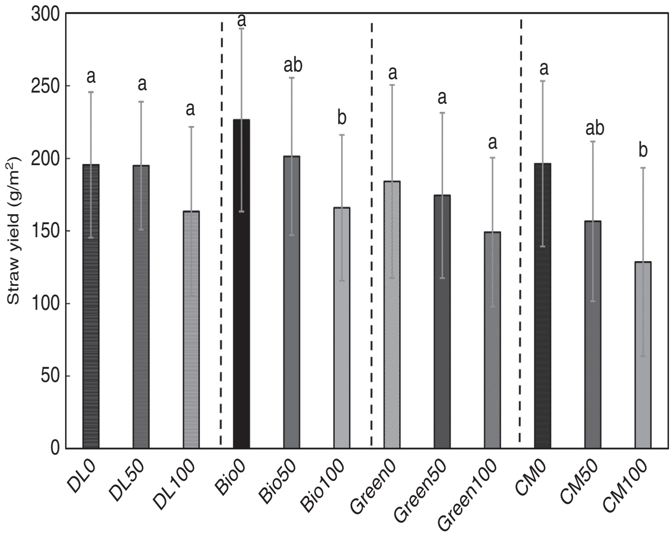

Figure 4 Straw yield. Letters indicate significant differences within the treatments ($P < 0.1$).

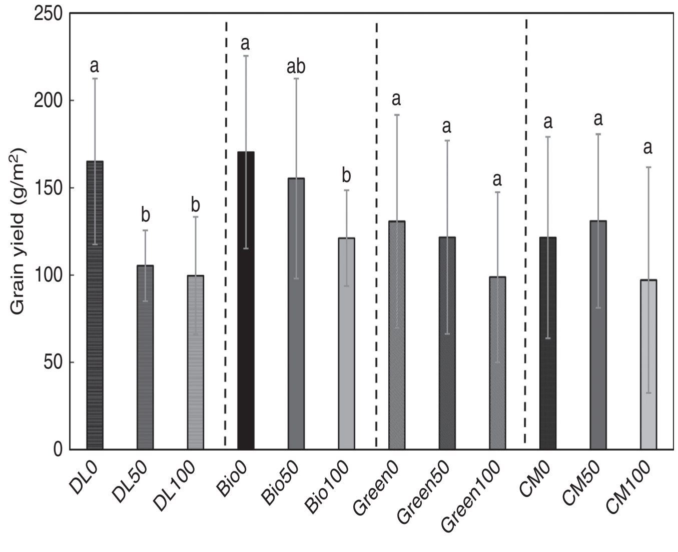

Figure 5 Grain yield. Letters indicate significant differences within the treatments ($P < 0.1$).

microorganisms during admixing of compost stimulates plant growth and ensures proper N supply during early growth stages and after pollination. The lack of yield differences on the Green and CM treatments can be traced back to the fact that a fallow area was chosen to investigate the effect of deep loosening. The choice of this field site also resulted in high standard deviations within the replications.

Effect of subsoil tillage on yield parameters

According to the classification of Abiven *et al.* (2009), similar effects on yield of green waste and biocompost could be expected. However, the short-term yield effect of biocompost on growth of spring barley was stronger than the effect of green compost. The number of kernels per ear was highest in Bio50. Yet, as Bio0 provided 34% more kernels than Bio100 and 33% more ears, we can directly contribute the higher grain yield to the increased ear density (Table 5). The ear density as well as the kernel number is significantly higher ($P > 0.1$) at Bio0. These results are consistent with Gill *et al.* (2008) who found a similar relationship under deep-placed organic amendment. For Green, there was a trend towards yield increase under admixing (Green0), but the yields did not reflect this. Plants of Green50 were smaller, but number of kernels per ear and TKW were the highest. The number of ears in Green0 were 11% higher than for Green100, while the number of kernels was 35% higher. These results contrast to those of

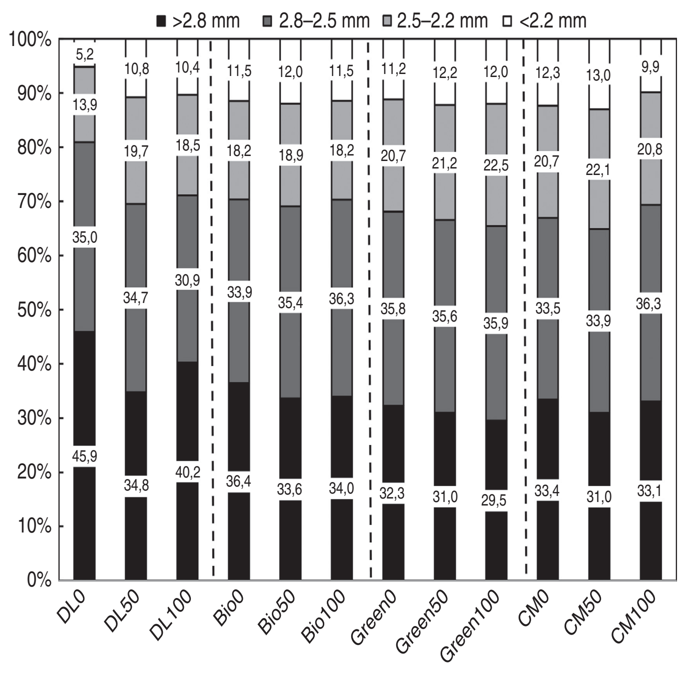

Figure 6 Distribution of kernel size.

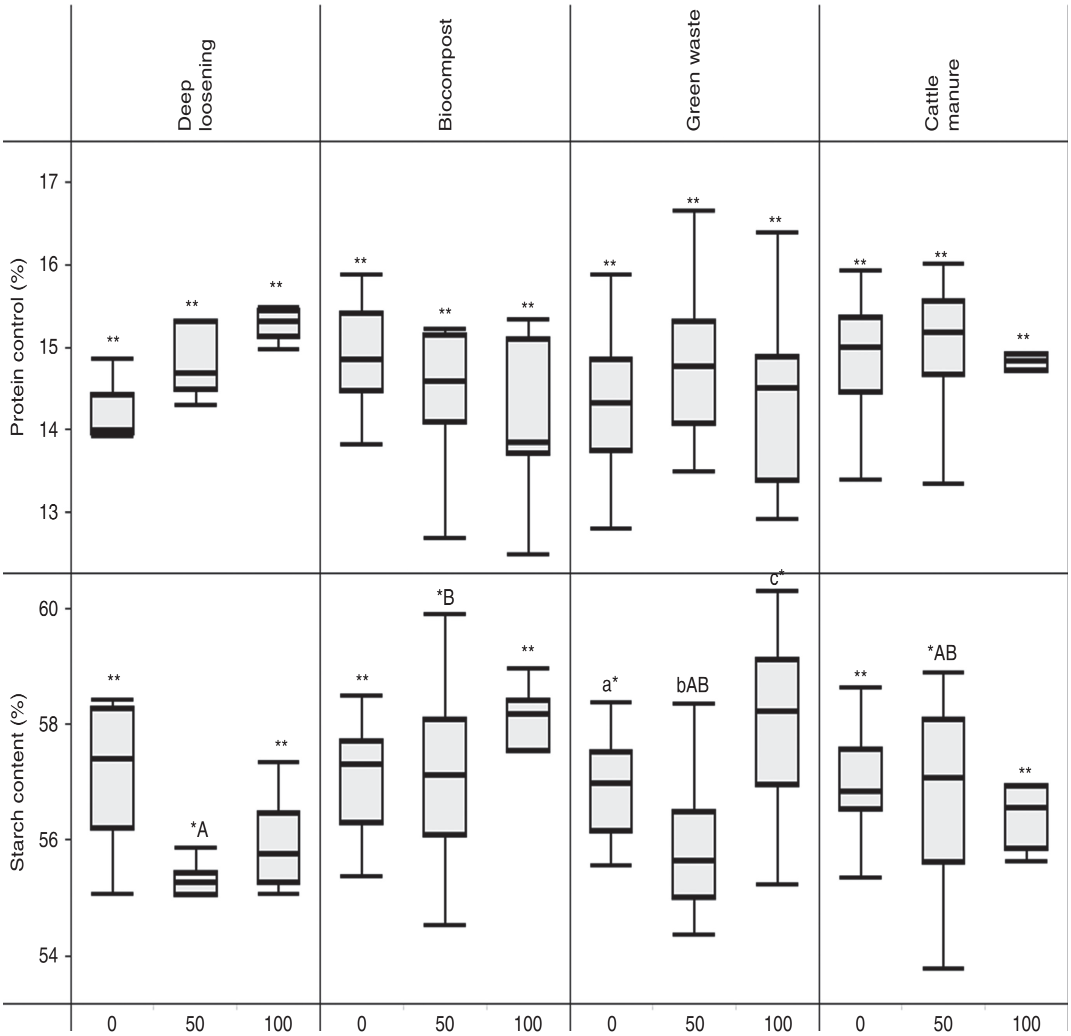

Figure 7 Box plots of protein and starch content analysis. Black lines within the box plots represent the median value. Lowercase letters: significant differences at $P < 0.1$ within the treatment. Uppercase letters: significant difference sat $P < 0.1$ within the subsoil tillage distances (0: subsoil tillage; 50: 50 cm distance to subsoil tillage; 100: 100 cm distance to subsoil tillage) *ns: not significant at $P < 0.1$ (treatment or distance) **ns: not significant at $P < 0.1$ (treatment and distance).

Bio and the increase in yield of Green0 could not be linked to an increased ear density. The relatively large C/N ratio of green waste might have led to a competition of microbial community and plants for soil N, thus immobilizing it (Amlinger *et al*., 2003). The well-studied positive effects of green waste compost application (Debosz *et al*., 2002; Ros *et al*., 2006; Evanylo *et al*., 2008; Peltre *et al*., 2015) might be manifested over longer periods. The application of cattle manure to soils is known to increase soil chemical, physical and biological properties (Lupwayi *et al*., 2014). Plant height was highest under CM0, while the number of ears and the kernel number did not increase. The studies of Whalen *et al*. (2000), showed that cattle manure increases soil pH and thus plant-available nutrients in the short-term (weeks). While in the longer-term, a decrease can be observed due to immobilization or stabilization. These findings promote the development of significantly higher straw yield under CM0, but grain yield did not increase. The short-term increase in N seemed to be beneficial for plant development during stem elongation but not during anthesis and postanthesis. Regarding differences of the treatments, it can be figured out that the ear number of Bio0 is significantly higher and the one of CM0 significantly lower. TKW of CM0 is significantly lower than for the other treatments. All other yield parameters did not result in significant differences.

Development of grain yield parameters

A general relationship between grain size, protein content and starch content exists. Smaller kernels have lower starch and higher protein contents. Consequently, bigger kernels

Table 5 Yield parameters of barley plants grown under subsoil tillage with admixed organic material

Treatment	Ear number (m^2)	Kernel number ($m^2 \times 1000$)	TKW[a]	Plant height (cm)
DL0	306*[AB]	4.3**	26.0*[A]	52**
DL50	272**	3.2**	31.3*[A]	48**
DL100	309**	3.0**	30.8*[A]	48**
Bio0	367[abB]	4.9[ab]*	29.4*[B]	54**
Bio50	330[bc]*	4.6[bc]*	30.9*[A]	51**
Bio100	276[c]*	3.6[c]*	30.7*[A]	50**
Green0	291*[AB]	3.9**	30.9*[B]	50**
Green50	273**	3.7**	31.7*[A]	48**
Green100	262**	2.9**	30.9*[A]	48**
CM0	236*[A]	3.6**	31.5*[B]	51**
CM50	273**	4.1**	31.7*[A]	47**
CM100	249**	3.0**	31.9*[A]	47**

[a]1000-kernel weight. Lowercase letters: significant differences at $P < 0.1$ within the treatment. Uppercase letters: significant differences at $P < 0.1$ within the subsoil tillage distances (0: subsoil tillage; 50: 50 cm distance to subsoil tillage; 100: 100 cm distance to subsoil tillage). *ns: not significant at $P < 0.1$ (treatment or distance); **ns: not significant at $P < 0.1$ (treatment and distance).

have higher starch content and lower protein content. Thus, a negative relationship between protein and starch content exists (Henry & Kettlewell, 1996; Wrigley, 2010). The general range of protein content for barley ranges from 8 to 15% and for starch is between 51 and 72%. The specific contents are mainly influenced by environmental factors and fertilizer practice (Simmonds, 1995; Henry & Kettlewell, 1996). This relationship can be observed in the results from the DL treatment. DL0 has the highest proportion of kernels >2.8 mm (Figure 6). The results of NIR analysis show lowest protein contents and highest starch contents (Figure 7). The results for protein content correlate with the decreasing yields with increasing distance to the subsoil tillage. In contrast, starch content did not steadily decrease between DL0 and DL100. The Bio treatments had slightly more kernels >2.8 mm, but overall, the kernels were about the same sizes. Bio0 had the highest protein and the lowest starch contents. This is in contrast to the theory that higher yields always imply a reduction in protein content and an increase in starch content. Nevertheless, all the values were in the normal range for barley. The Bio treatments seemed to support a good supply of water and nitrogen which might have been the basis for the increased protein content.

Green produced significantly different starch contents.

Green50 has the lowest starch but the highest protein contents, while Green0 has the lowest protein but not the highest starch content. This supports the theory that the C/N ratio of green waste compost might have led to an immobilization of N, and extra N derived from compost input was not available at important stages of grain development. CM produced the highest grain yields under CM50 which is reflected by the kernel size distribution, with a trend towards smaller kernels under CM50 reports (Figures 5 and 6). However, there were only small difference in the mean values of protein and starch content. The effect of CM admixing was mainly detectable on the development of straw yield but not on grain yield. The results of NIRs analysis reflect this. For protein content, no significant differences were noticed across the treatments. Starch content of DL50 and Bio50 treatments were significantly different from each other.

Conclusions

This paper emphasized the short-term effects of deep loosening of the subsoil in combination with admixing of organic material. The different organic materials were shown to promote short-term improvements in yield even though the literature suggested mainly long-term effects for some of the materials. Single deep loosening and admixing of biocompost into the subsoil produced the highest yields. Thus, we can conclude that loosening of the subsoil leads to a better plant supply. Admixing of biocompost, which introduces active biomass into the subsoil, further influences plant development in terms of significantly increased ear densities and kernel numbers, while starch and protein content did not change significantly. The observations showed that subsoil loosening with simultaneous admixing of organic material was still beneficial at a distance of 0.5 m from the amendment site.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Penetration resistance of soil, data represents average value of n = 5 .

Figure S2. Monthly average temperatures and total rainfall during the experiment (2016).

B. Publication 2: Main-trial 'Campus Klein Altendorf'

agronomy

MDPI

Article

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.

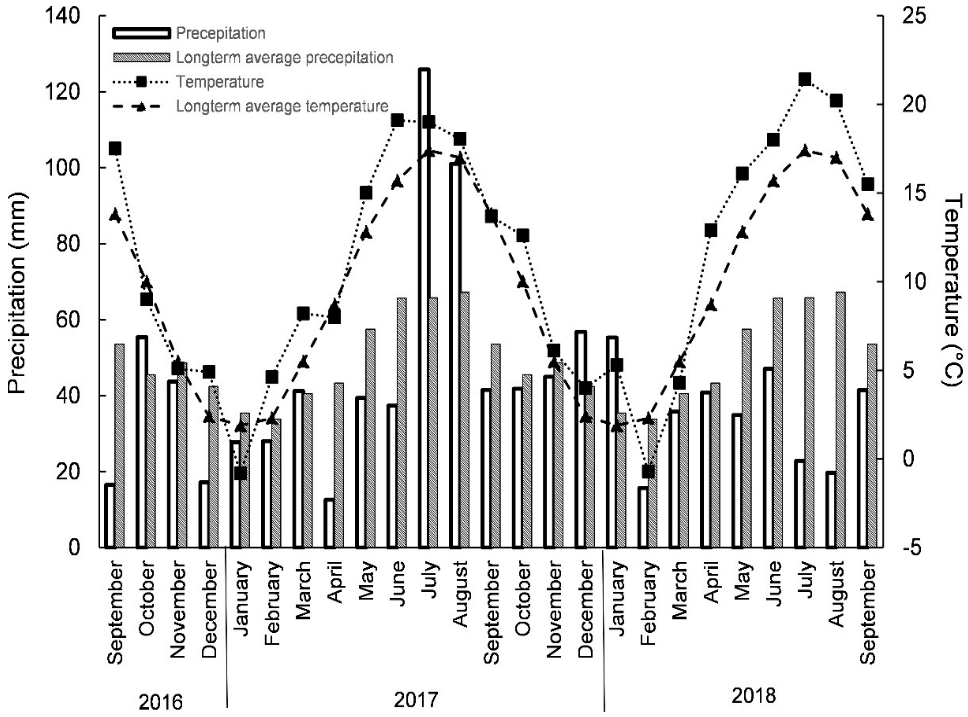

Figure 1. Overview of weather data during the vegetation period (2016–2018).

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 Spader machine	DL 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 Spader machine	DLB 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 (%)							C:N	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						
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 (%)
	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
Spring barley	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
	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
Winter wheat	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

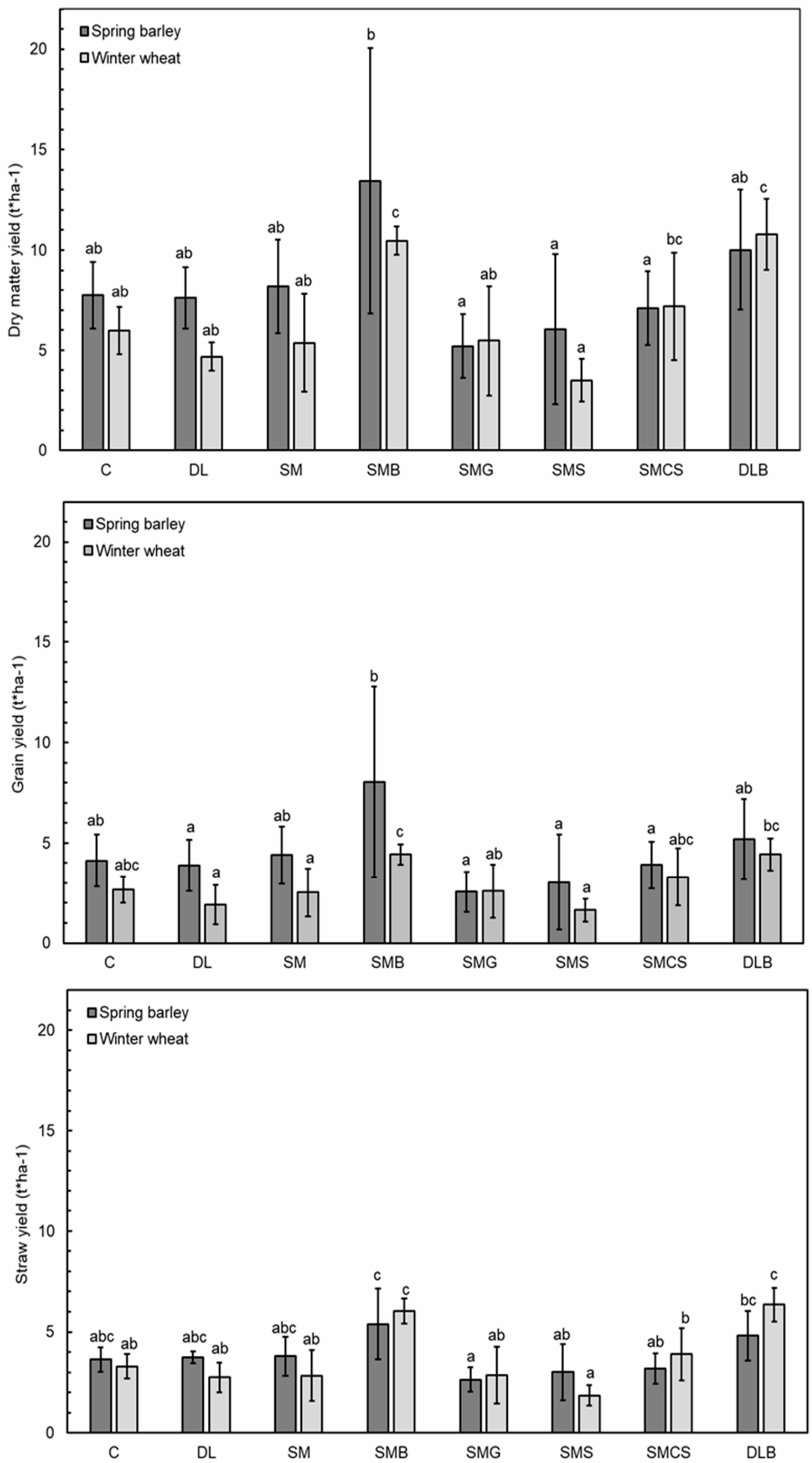

Figure 2. Dry yield, grain yield and straw yield of spring barley (2017) and winter wheat (2018). Different letters indicate significant differences between the treatments in each year ($p < 0.05$, Tukey's test), error bars represent ± SD ($n = 6$). C: control, DL: deep loosening with tine, SM: spader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

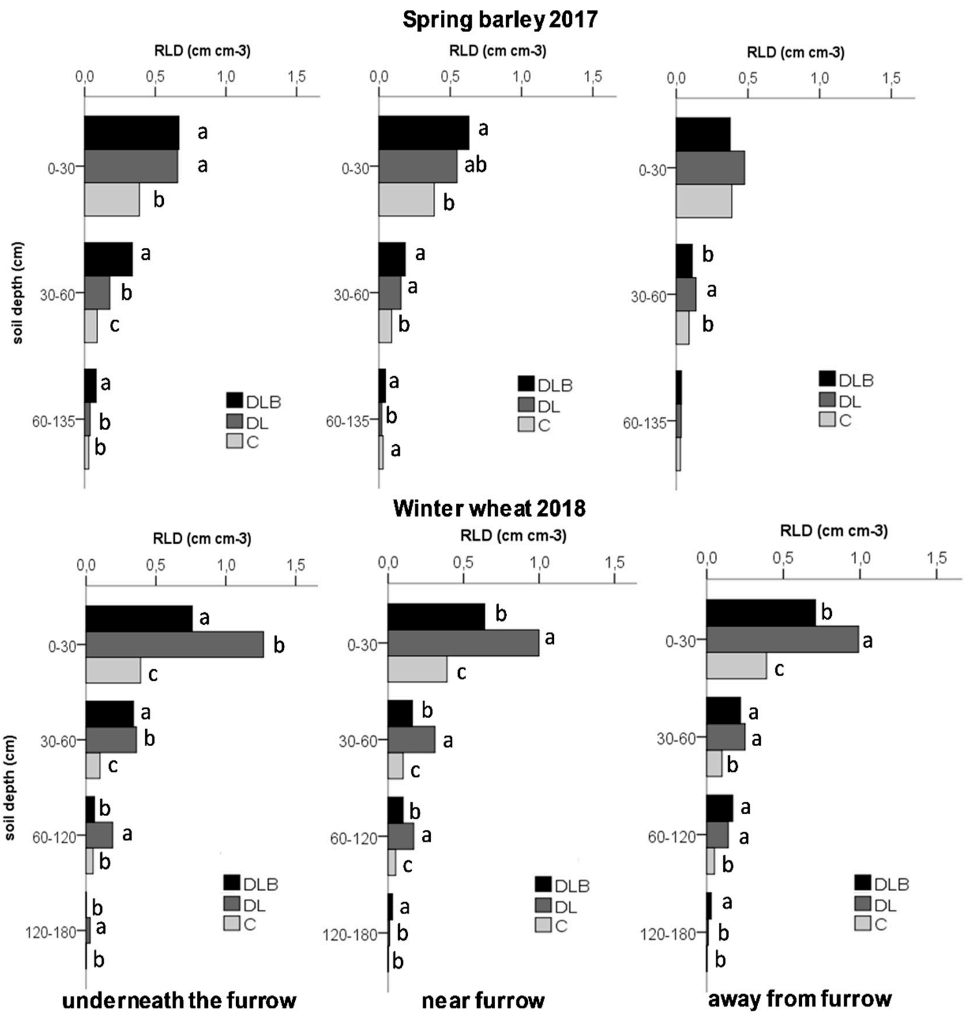

Figure 3. Mean root-length density of three soil depth classes (2017) and four soil depth classes (2018). From left to right: directly underneath the furrow, near the furrow (up to 20 cm distance) and away from the furrow (2017: 20–85 cm distance, 2018: 20–35 cm distance). Different letters indicate 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.

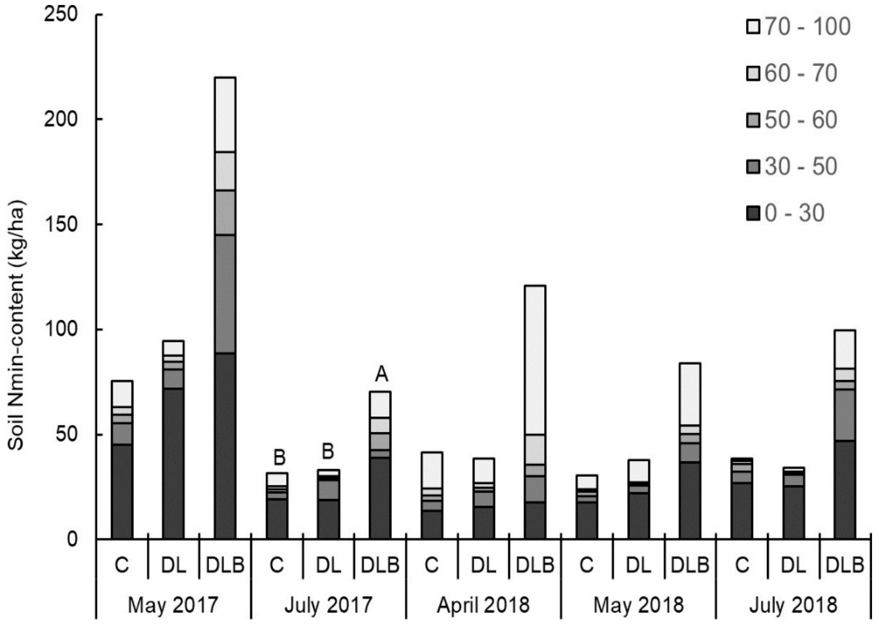

Figure 4. Soil mineral nitrogen at five sampling dates in five soil depth classes, respectively. Different letters indicate significant differences of within one sampling date (Tukey's test, $p < 0.05$). In May 2017 (only two field replicates sampled) and July 2018 (samples from three field replicates 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.

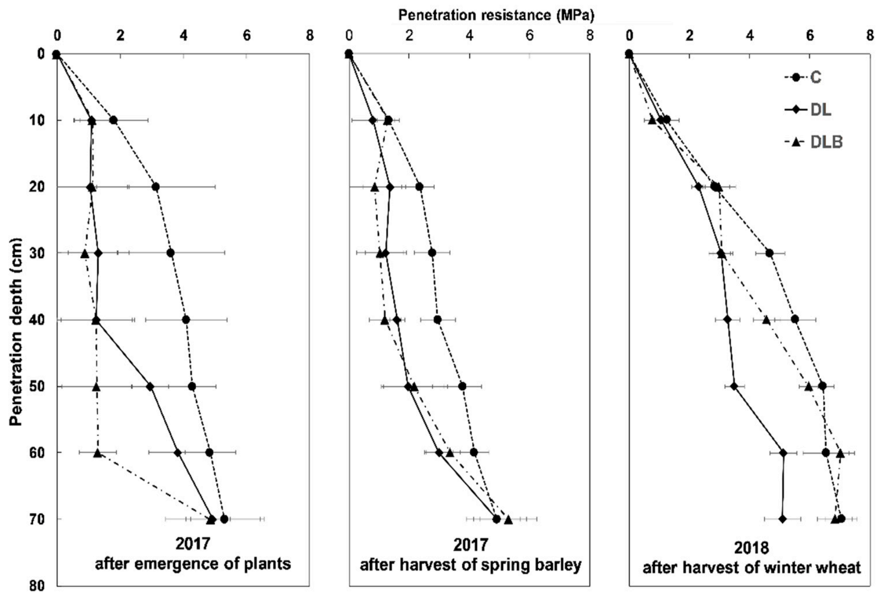

Figure 5. Measurements of penetration resistance. Measurements represent average values of $n = 9$ measurements. Error bars represent ± SD ($n = 9$). C: control, DL: deep loosening with tine, DLB: deep loosening with tine and bio compost.

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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