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Research Article

Tillage System Comparison in Organic Farming: Effects on N Mineralization, Soil Microbial Biomass, and Yield

Meike Grosse[1,*], Thorsten Haase[2] and Jürgen Heß[3]

[1]Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany
[2]Landesbetrieb Landwirtschaft Hessen, Kassel, Germany
[3]University of Kassel, Witzenhausen, Germany

*Corresponding author: E-Mail: meike.grosse@zalf.de; Tel.: +49 33432 824086; Fax: +49 33432 824082

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Abstract: The nitrogen supply can be a yield-limiting factor in organic farming, especially when reduced tillage is applied. An organic field experiment was conducted from 2007 to 2013 to analyse the potential of the nitrogen supply through the efficient use of green manure crops in different tillage systems. Three farming systems were compared: a stubble cleaner system (SC) and a plough system (PL), both in a cereal-based crop rotation, and another plough system in a crop rotation that included alfalfa grass ley (PLALF). In the fifth year of the experiment, the experimental design was extended into a split plot design, and seven green manure treatments (*Lolium perenne*, *Phacelia tanacetifolia*, *Sinapis alba*, a mixture of *Sinapis alba* and *Trifolium resupinatum*, *Trifolium resupinatum*, *Vicia sativa*, and bare fallow as the control) were integrated into each of the three systems. The effects of the three systems and the green manure treatments on N mineralization, the soil microbial biomass and the yield of the main crops of oats and field beans in the sixth and seventh years of the experiment were analysed. The results showed that the choice of green manure species was of minor importance in the PLALF system. This system generally successfully supplied N to the oats with oat yields from 3.6 to 5.1 t per ha. *Vicia sativa* was the most promising green manure crop in the SC and PL systems, with the N_{min} values and oat yields (4.0 and 4.6 t per ha) being similar to those in the PLALF system. In the subsequent year, the PLALF system again was more successful in most of the N_{min} assessments than the PL and SC systems, which often had rather similar results. In addition, a main crop of field beans was able to compensate for the differences in the N_{min} content, and the yields were similar in all three systems (3.1 to 3.7 t per ha). The microbial biomass in the top soil was significantly increased in the reduced tillage system compared to the plough systems. In conclusion, reduced tillage in organic farming can promote soil microorganisms and be competitive if the nitrogen supply is improved through the efficient use of green manure or an adequate leguminous main crop.

Keywords: Alfalfa grass; green manure; N mineralization; reduced tillage; *Vicia sativa*.

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1. Introduction

Methods with reduced tillage, such as shallow ploughing, are recognized as environmentally friendly alternatives to conventional ploughing. Shallow ploughing (approx. 12–20 cm) offers numerous advantages for the structure of the soil and soil life. These advantages include the enrichment of organic material, soil organisms and nutrients on the soil surface [1]. Continuous biopores can develop in the subsoil [1]. Additionally, energy consumption and working time are minimized with shallow ploughing compared to deep ploughing [1,2].

However, if conventional ploughing is avoided in organic farming, the nitrogen supply for the crops may be reduced due to potentially low or delayed mineralization [2,3]. Furthermore, weed pressure may increase with reduced tillage [2]. Therefore, it is difficult to set the plough aside, as it is seen as a reliable instrument for the stimulation of mineralization and for weed control. Because no easily soluble fertilizers and no synthetic pesticides may be used in organic farming, reduced tillage can cause yield losses in these systems [2,4].

To use reduced tillage in organic farming, the whole system needs to be adapted [2]. In addition to the tillage method, the crop rotation has to be adjusted. The change in crop rotation offers farmers the possibility to respond to the challenges of reduced tillage. The integration of green manure crops into crop rotation is essential. Green manure crops have the potential to bring additional Nitrogen into the soil and to control weeds through competition [2,5–7]. Therefore, a smart use of green manure crops in organic reduced tillage systems can decrease or even prevent completely yield losses [8].

To compare a cropping system with continuous shallow ploughing to two systems with conventional ploughing and two different crop rotations, in 2007, a multi-year field experiment was established at the experimental farm of the University of Kassel. For the shallow ploughing system, an advanced stubble plough, the stubble cleaner produced by the company Zobel/Rot am See, was chosen. As its mouldboards are smaller than those of conventional ploughs, the soil is not only turned but also more thoroughly mixed [9]. Because of its shallow operating mechanism, the organic matter remains on the surface of the soil, which promotes tilth. In 2011, *i.e.*, in the fifth year of the experiment, green manure crops were integrated into all systems.

The effects of the three systems and the green manure treatments on N mineralization, the soil microbial biomass and the yield of the main crops of oats and field beans are the subjects of this paper. On the basis of the test results from the sixth and seventh years of the trial, the systems were compared to test the following hypotheses:

• Leguminous green manure crops are able to compensate for the reduced N mineralization in the reduced tillage system, while high N using species will suffer more from reduced tillage.

• The content of the microbial biomass in the top soil increases after six years of exclusive cultivation with the stubble cleaner in comparison to the plough systems.

• Leguminous green manure crops promote the yield of the non-leguminous main crop in the reduced tillage system, while in the plough systems the effect is less pronounced. In the following year, a leguminous main crop is able to compensate for the differences in N_{min} content of the different tillage systems.

2. Material and Methods

2.1. Site Description

The trial was conducted on the experimental farm of the University of Kassel, the state-owned Frankenhausen farm (51.412 N, 9.439 E; 231 m above sea level), on the "Untere Kiebitzbreite" field. The soil type is Haplic Luvisol. The soil texture in the plough horizon ranges from strong clayey silt (Ut4) to very silty clay (Tu4) [10]. The pH value in the plough horizon is 6.6, and the C_{org} content is 1.16%.

2.2. Weather Conditions

The temperature profile during the trial period from 2011 to 2013 was similar to the 30-year average (Figure 1). The greatest deviation was a significantly cooler March 2013.

Precipitation was lower than average in many months. May 2013 stood out due to its above-average total rainfall (data from 2011 to 2013 from the weather stations at Frankenhausen, Kassel Calden airport and Kassel Harleshausen; long-term average data from the German Meteorological Service (DWD), Kassel weather station).

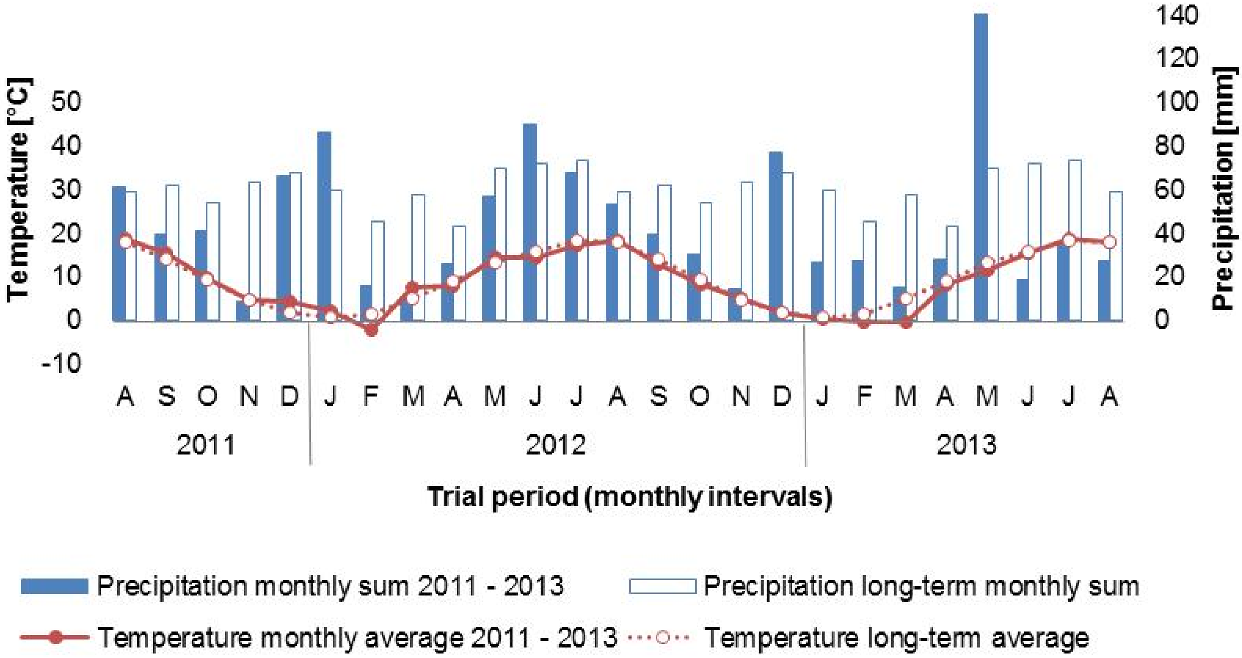

Figure 1. Weather pattern during the trial period from 2011–2013 and the long-term average.

2.3. Trial Setup

A multi-year trial was carried out in 2007 as a randomized block design with four field replications. Originally the experiment was set up to test if the stubble cleaner is as effective for the control of *Cirsium arvense* as pre crop alfalfa. Therefore, one crop rotation with alfalfa grass was established in combination with conventional tillage and a cereal based crop rotation in combination with conventional tillage and in combination with reduced tillage. The conventional tillage in autumn consisted of a double stubble breaking with the cultivator followed by ploughing to a depth of 25 cm, and reduced tillage was carried out exclusively with the stubble cleaner to a maximum depth of 10 cm [11].

Alfalfa grass was sown in 2008 as a second crop rotation. The mixture consisted of 80% alfalfa and 20% grass (based on the seed weight). The cultivation of alfalfa grass lasted three years. The alfalfa grass was mowed two to three times per year, and the harvested biomass was removed. Tillage in this crop rotation took place after 2010 in the same way as the conventional tillage in the cereal-based crop rotation (Figure 2). The details on tilling and sowing are given in Table 1.

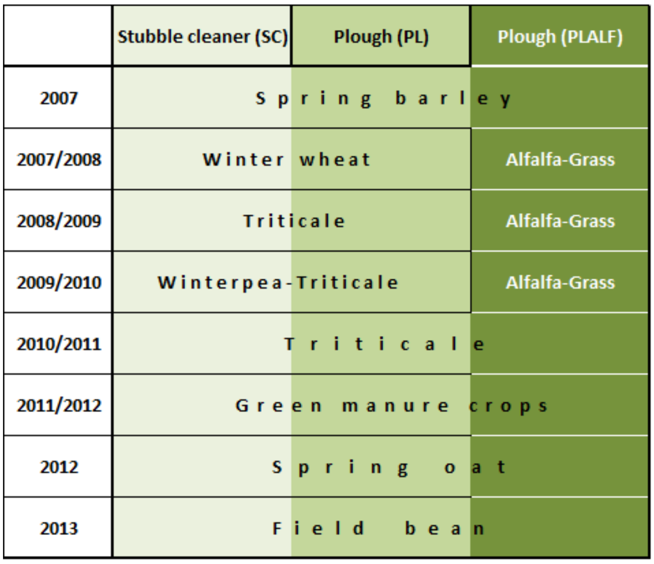

Figure 2. Scheme of the crop rotation and tillage systems of the long-term trial (2007 to 2013) on the experimental farm 'Domaene Frankenhausen'.

Table 1. Details of the tillage methods, dates and depths.

Date	Plough systems	Depth / Row spacing	Stubble cleaner system	Depth / row spacing
August 24, 2011	Plough Rotary harrow	Depth 25 cm	Stubble cleaner	Depth 8-10 cm
August 30/31, 2011	Sowing green manure, rolling	Row spacing 18.75 cm	Sowing green manure, rolling	Row spacing 18.75 cm
October 17, 2011	Flame weeding fallow plots		Flame weeding fallow plots	
April 16, 2012	Mulching the green manure (rotary mower) Cultivator	Depth 7-10 cm	Mulching the green manure (rotary mower) Stubble cleaner	Depth 7-10 cm
April 17, 2012	Rotary harrow Sowing (oats)	Row spacing 12 cm	Rotary harrow Sowing (oats)	Row spacing 12 cm
August 13, 2012	Harvesting (oats)		Harvesting (oats)	
October 01, 2012	Plough	Depth 25 cm	Stubble cleaner	Depth 8 cm
October 29, 2012	-		Stubble cleaner	Depth 10 cm
April 18, 2013	Spring tine cultivator	Depth 8 cm	Spring tine cultivator	Depth 8 cm
April 22, 2013	Rotary harrow Sowing (field beans)	Row spacing 15 / 45 cm	Rotary harrow Sowing (field beans)	Row spacing 15 / 45 cm
June 11, 2013	Hoeing		Hoeing	
August 26, 2013	Harvesting (field beans)		Harvesting (field beans)	

In autumn 2011, the single factor trial was extended by the factor of green manure in a split plot design. The fourfold replication was maintained. The following legume and non-legume green manure species were cultivated in pure stands and in a mixture of two species (Table 2):

Table 2. Overview of green manure species that were tested in the trial.

Green manure species	Cultivar	Seeding density	Abbreviation
Lolium perenne	Lemmos	40 kg ha^{-1}	LP
Phacelia tanacetifolia	Boratus	12 kg ha^{-1}	PT
Sinapis alba	Asta	20 kg ha^{-1}	SA
Sinapis alba and *Trifolium resupinatum* (mixture)	Asta; Marco Polo	10 kg ha^{-1} each	SATR
Trifolium resupinatum	Marco Polo	20 kg ha^{-1}	TR
Vicia sativa	Ereica	40 kg ha^{-1}	VS
Bare fallow (= control)			BR

In the trial year 2011/12, all the treatments were sampled or assessed (= 84 plots). In the trial year 2012/13, only selected plots were sampled or assessed in order to check whether the various green manure species still had an effect in the second year of cultivation after growing green manure. The following treatments were selected for this purpose: Bare fallow, *S. alba* and *V. sativa* (= 36 plots).

In the trial year 2011/12, growing the green manure crops was followed by sowing the main crop oats (*Avena sativa, Cv.* Scorpion, 400 germinable grains per m^2). In the trial year 2012/13, field beans were sown (*Vicia faba, Cv.* Bioro, 40 germinable grains per m^2).

No fertilization was carried out during the trial period. No weed control was carried out in 2011/12. The area was hoed once in 2012/13.

2.4. Data Collection

The above-ground biomass yield of green manure was determined on November 17, 2011. For this purpose, a square area with a side length of 1.5 m per plot was cut off directly above the ground by hand and then weighed, and the dry matter was determined by drying a subsample of the harvested material at 60°C for 48 hours (until constant weight). In addition to the determination of yield, the samples were used to analyse the total nitrogen content (N_t) and carbon content (C_t) of the above-ground biomass.

Oat was also harvested by hand on August 13, 2012. For this purpose, half a square metre of land was harvested twice per plot. The beans were also harvested by hand on August 26, 2013. For this purpose, five metres of two rows of crops per plot were cut off just above the ground.

To analyse the nitrogen available to plants in the soil, samples up to a depth of 90 cm in 30 cm intervals were taken on three (2011/12) or four (2012/13) dates spread over the trial year. If sampling to a depth of 90 cm was not possible due to the soil conditions, the soil was sampled to a depth of 60 cm. A mixed sample was taken from three cores per plot. The samples were immediately cooled and carried to a freezer as soon as possible. The samples were examined according to DIN ISO 14255 and DIN EN ISO 11732 in the Landesbetrieb Hessisches Landeslabor, Kassel. The entire sample material was tested for NO_3-N, and the samples from the top soil were also tested for NH_4-N. For the top soil N_{min} content was calculated by summating the NO_3-N and NH_4-N values, whereas N_{min} for the subsoil consists only of the NO_3-N values, as NH_4-N is negligible below the top soil on this site.

In spring 2013, the soil was tested for the content of the microbial biomass in addition to the N_{min} sampling. The samples were taken according to the layers of the tillage depths, i.e., 0–10 cm (corresponding to the working depth of the stubble cleaner), 10–25 cm (corresponding to the plough depth) and 25–50 cm (an uncultivated layer). A mixed sample was taken from seven cores per large plot according to the crop rotation—tillage system treatments. The analysis was performed using the chloroform fumigation extraction method [12]. Bulk density was also examined in these layers. For its determination calibrated soil rings of 100 cm^3 volume were inserted vertically in the middle of each layer. They were dried at 105°C until weight constancy. The dry weight was determined and after subtracting the weight of each ring and the lids the soil weight of the ring volume was obtained and bulk density could be calculated.

2.5. Data Analysis

The mean values and standard errors were calculated to describe the distribution of N_{min}, the C and N contents, and the green manure and main crop yields. Each data set was assessed for normally distributed residuals (Kolmogorov-Smirnov test). The large plot, small plot and block as fixed factors were examined for significant effects and interactions using a univariate analysis of variance. If the analysis of variance showed significant effects or interactions, a post hoc test (Tukey-B) was then carried out for the factor combination of green manure x tillage or for the individual factors (alpha $\leq$ 0.05). Significant differences between treatments are indicated by different letters in the figures except in the figures for N_{min}-content. For these figures letters are shown in tables in the attachment for better legibility.

The statistical analyses were performed with SPSS-21 [13].

3. Results

3.1. Green Manure—Yield and C/N Ratio

The analysis of variance of green manure crop and tillage/crop rotation system for green manure above ground biomass yield, green manure above ground biomass N content and green manure C/N ratio showed a significant influence of the green manure crops, the tillage/crop rotation systems and a significant interaction at the 0.001 probability level each (Table 3).

The stubble cleaner system (SC) led to the lowest green manure yield for each green manure species, with the exception of *V. sativa*, which had a similar yield in each system. *L. perenne*, *P. tanacetifolia*, *S. alba* and the mixture of *S. alba* and *T. resupinatum* each had the lowest yield, approximately 0.5 t dry matter per hectare, in the stubble cleaner system. *T. resupinatum* could not be sampled due to its poor field emergence. The highest yield, approximately 1.5 t DM per hectare, was achieved by *S. alba* in the plough-alfalfa grass (PLALF) system and by *V. sativa* in all three systems (Figure 3).

The green manure in the PLALF system had the highest N content, and green manure in the SC system had the lowest, with the exception of *V. sativa*, which had the highest N content of all green manure crops in all three tillage systems. The N content of *V. sativa* ranged from 47.3 kg N ha^{-1} in the PLALF system to up to 57.5 kg N ha^{-1} in the PL system. In the SC system, the N content of V. sativa was 52.8 kg N ha^{-1}. In this system, the difference between *V. sativa* and the other green manure species was particularly great (Figure 4).

Table 3. Summary of analysis of variance of green manure crop (GRM) and tillage/crop rotation system (TCS) for GRM above ground biomass yield, GRM above ground biomass N content and GRM C/N ratio.

Source of variation	GRM yield	GRM N content	GRM C/N ratio
Green manure (GRM)	***	***	***
Tillage/crop rotation system (TCS)	***	***	***
GRM x TCS	***	***	***

*** Significant at the 0.001 probability level

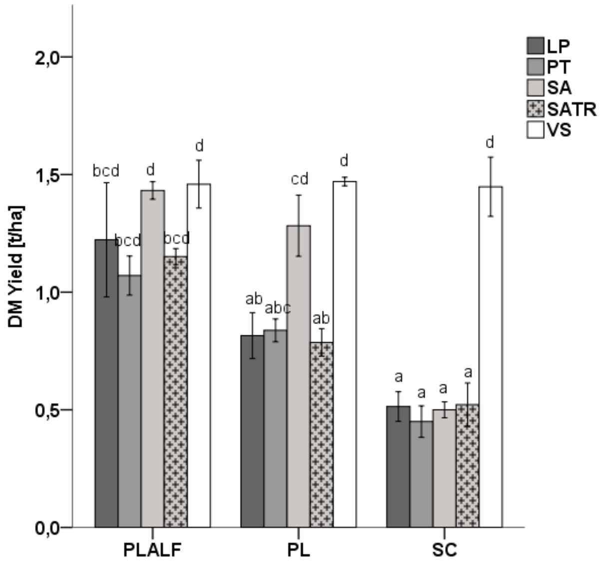

Figure 3. Biomass yield of green manure crops sown in different tillage/crop rotation systems, harvested on November 17, 2011. Error bars represent the standard errors. PLALF = plough in crop rotation with alfalfa grass ley, PL = plough in cereal-based crop rotation, and SC = stubble cleaner in cereal-based crop rotation. LP = *L. perenne*, PT = *P. tanacetifolia*, SA = *S. alba*, SATR = mixture of *S. alba* and *T. resupinatum*, and VS = *V. sativa*.

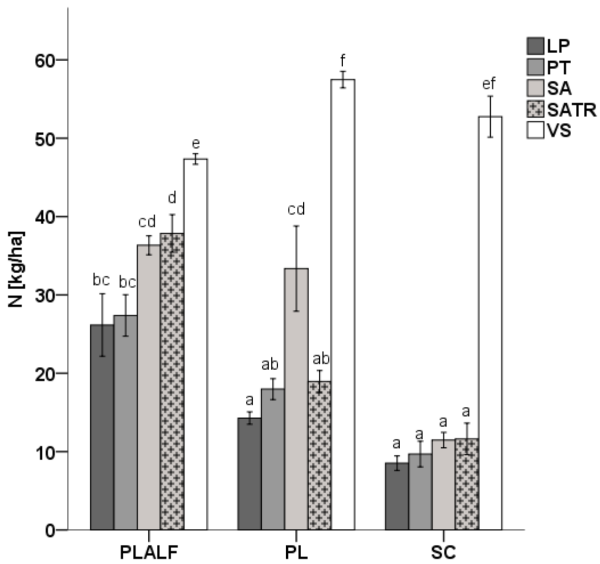

Figure 4. N content of green manure crops on November 17, 2011. For abbreviations, see Figure 3. Error bars represent the standard errors.

Of the green manure species studied, *L. perenne* had the highest C/N ratio, ranging from 16.1 in the PLALF system to 21.3 in the SC system. *S. alba* had a slightly lower C/N ratio (15.3 – 16.7) than *L. perenne*. The mixture of *S. alba* and *T. resupinatum* had a C/N ratio between 12.8 and 17.1. *P. tanacetifolia* had a C/N ratio between 12.8 and 15.9. *V. sativa* had the lowest C/N ratio (9.4-10.6). For each green manure treatment except for *V. sativa*, the C/N ratio was lowest in the PLALF system and highest in the SC system. For the C/N ratio of *V. sativa*, there were no detectable differences between the systems (Table 4).

Table 4. C/N ratio (means and standard errors) of green manure crops depending on tillage system. Different letters indicate significant differences between the three systems.

Green manure	PLALF-system		PL-system		SC-system	
L. perenne	16.1	±0.35^{d}	19.8	±1.34^{ef}	21.3	±0.75^{f}
P. tanacetifolia	12.8	±0.53^{bc}	15.9	±0.42^{cd}	15.9	±0.59^{cd}
S. alba	15.3	±0.63^{cd}	16.1	±0.91^{d}	16.7	±0.27^{d}
Mixture of *S. alba* and *T. resupinatum*	12.8	±0.56^{bc}	16.1	±0.60^{d}	17.1	±0.54^{de}
V. sativa	10.6	±0.38^{ab}	9.4	±0.20^{d}	10.1	±0.23^{ab}

3.2. Trial Year 2011/2012—N Dynamics

The analysis of variance of N_{min} from the 15.03.2012 showed a significant influence of the green manure crops, the tillage/crop rotation system and a significant interaction for all three soil layers at the 0.001 probability level each (Table 5). On the 15.05.2012 there was a significant influence of the tillage/crop rotation system for all three soil layers at the 0.001 probabililty level each and a significant influence of the green manure crops and a significant interaction for the top soil at the 0.01 probability level each (Table 5). On the 05.09.2012 there was a significant influence of the tillage/crop rotation system for the two sampled soil layers at the 0.001 probabililty level each and there was a significant interaction at the 0.05 probability level for the top soil and at the 0.01 probability level for the layer 30–60 cm (Table 5).

Table 5. Summary of analysis of variance of green manure crop (GRM) and tillage/crop rotation system (TCS) for N_{min} in three soil layers (05.09.2012 two soil layers) on three assessment dates.

Source of variation	15.03.2012			15.05.2012			05.09.2012	
	0-30 cm	30-60 cm	60-90 cm	0-30 cm	30-60 cm	60-90 cm	0-30 cm	30-60 cm
Green manure (GRM)	***	***	***	**	n.s.	n.s.	n.s.	n.s.
Tillage/crop rotation system (TCS)	***	***	***	***	***	***	***	***
GRM x TCS	***	***	***	**	n.s.	n.s.	*	**

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

n.s. not significant

On March 15, 2012, *V. sativa* achieved the significantly highest N_{min} values in all tillage systems. In the PLALF system, the difference between *V. sativa* and the other green manure treatments was smaller than that in the PL and SC systems. *L. perenne* led to the lowest N_{min} values in the PLALF and PL systems (Figure 5a and Table A1).

On May 15, 2012, the PLALF system had the significantly highest N_{min} content in each layer. With regard to green manure, *L. perenne* and bare fallow led to the significantly lowest value, but *V. sativa* led to the significantly highest N_{min} content in the 0–30 cm layer in each tillage system. *T. resupinatum* led to similarly high N_{min} values in the PL system as *V. sativa* but not in the SC system (Figure 5b and Table A2).

On September 05, 2012, the N_{min} content in the PLALF system was approximately twice as high as that in the other two tillage systems. The N_{min} content was significantly highest in the SATR treatment of the PLALF system. In the other two tillage systems, the N_{min} content in the SATR treatment was as low as that in the other green manure treatments (Figure 5c and Table A3).

3.3. Main Crop Yield—Oats

The analysis of variance of oats yield showed a significant influence of the green manure crops, the tillage/crop rotation systems and a significant interaction each on the 0.001 probability level, both for grain yield and straw yield.

The SC system had the lowest grain yield, the PLALF system had the highest grain yield, and the PL system had a medium grain yield. Bare fallow, *L. perenne, P. tanacetifolia*, the mixture and *T. resupinatum* led to the lowest grain yields in the SC and PL systems, whereas in the PLALF system, all green manure treatments and the bare fallow treatment led to the highest yields. In the SC system, *S. alba* also led to the lowest oat yields. The only green manure that led to the highest grain yields in the SC system was *V. sativa* (Figure 6).

The SC and PL systems had significantly lower straw yields than did the PLALF system. *S. alba* resulted in a significantly lower straw yield in the SC system than in the PLALF system. *V. sativa* led to the highest straw yields in each system (Figure 7).

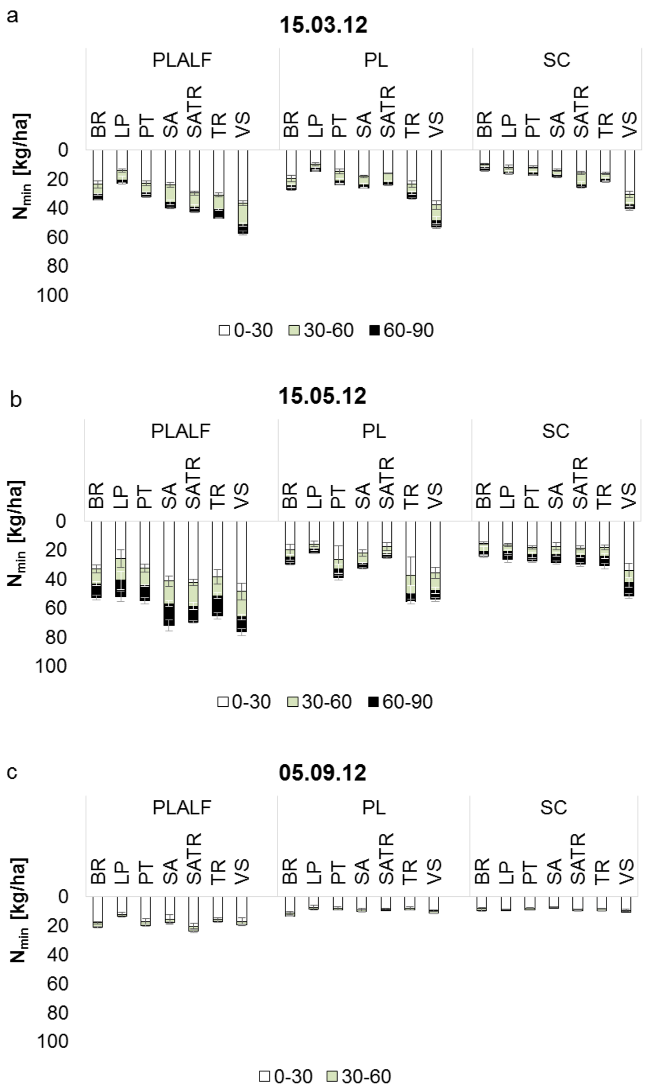

Figure 5. N_{min} content at three (15.03.12 and 15.05.12) or two (05.09.12) soil depths in the six green manure treatments plus in bare fallow sown in different tillage/crop rotation systems. For abbreviations, see Figure 3. Error bars represent the standard errors.

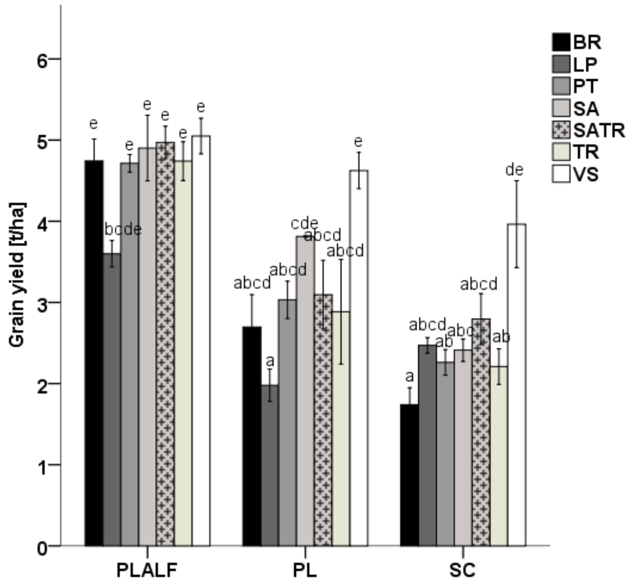

Figure 6. Grain yield of the main crop of oats at an 86% dry matter content. For abbreviations, see Figure 3. Error bars represent the standard errors.

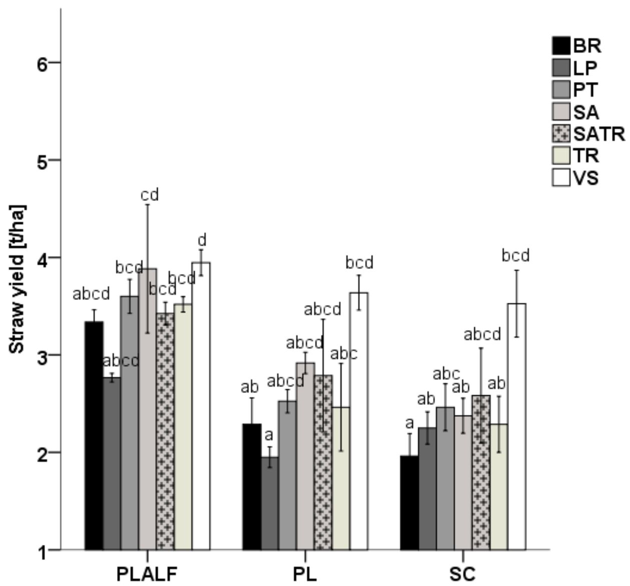

Figure 7. Straw yield of the main crop of oats at an 86% dry matter content. For abbreviations, see Figure 3. Error bars represent the standard errors.

3.4. Trial Year 2012/2013—N Dynamics

The analysis of variance of N_{min} from all the sampling dates in 2013 showed a significant influence of the tillage/crop rotation system for all three layers, with the exception of the top layer on September 08, 2013. The green manure crops had no significant effect on N_{min} in the second year after green manure crop cultivation, and there was no significant interaction (Table 6).

On April 08, 2013, and May 23, 2013, the N_{min} content in the PLALF system was significantly higher in all three layers than in the other two systems (Figure 8; Table A4). On June 18, 2013, the N_{min} content in the 0–30 cm layer was significantly higher in the PLALF system than in the PL system. The N_{min} content in the 0–30 cm layer in the SC system was between that of the other two systems. In the 30–60 cm and 60–90 cm layers, the PLALF system had the significantly highest N_{min} content (Figure 8 and Table A4).

On September 08, 2013, there were no significant differences in the N_{min} content among the different systems in the 0–30 cm layer. The high N_{min} value for the *V. sativa* treatment in the PL system was due to the unusually high value of one subsample, from which the large standard error also originated. The PLALF system had the significantly highest N_{min} content in the 30–60 cm layer, and the SC system had the significantly lowest N_{min} content. The PL system had a medium N_{min} content. In the 60–90 cm layer, the PLALF system again had the significantly highest N_{min} content compared to that of the other two systems. However, the differences among the treatments amounted to only a few kilograms per hectare (Figure 8 and Table A4).

3.5. Microbial Biomass of the Soil

The analysis of variance of N_{mic} and C_{mic} showed a significant influence of the tillage/crop rotation system for the top layer on the 0.01 probability level. After six years of differentiated tillage, the SC system had significantly more N_{mic} and C_{mic} in the top layer than the PLALF and PL systems. In the two lower layers, the three systems did not differ significantly (Figure 9).

3.6. Main Crop Yield—Field Beans

In terms of the bean and straw yield of the field beans, the analysis of variance showed no significant influence neither of the tillage/crop rotation system nor of the green manure treatments in the second year after their cultivation. The bean yield at 86% DM varied between 3.1 t ha^{-1} with the *V. sativa* treatment in the PL system and 3.7 t ha^{-1} with the bare fallow treatment in the PLALF system (data not shown). The straw yield at 86% DM was between 3.5 t ha^{-1} with the *V. sativa* treatment in the SC system and 4.3 t ha^{-1} with the bare fallow treatment in the PLALF system (data not shown).

Table 6. Summary of analysis of variance of green manure crop (GRM) and tillage/crop rotation system (TCS) for N_{min} in three soil layers on four assessment dates.

	08.04.2013			23.05.2013			18.06.2013			08.09.2013		
	0-30 cm	30-60 cm	60-90 cm	0-30 cm	30-60 cm	60-90 cm	0-30 cm	30-60 cm	60-90 cm	0-30 cm	30-60 cm	60-90 cm
GRM	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
TCS	***	***	***	**	***	***	*	***	***	n.s.	*	***
GRM x TCS	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level

n.s. not significant

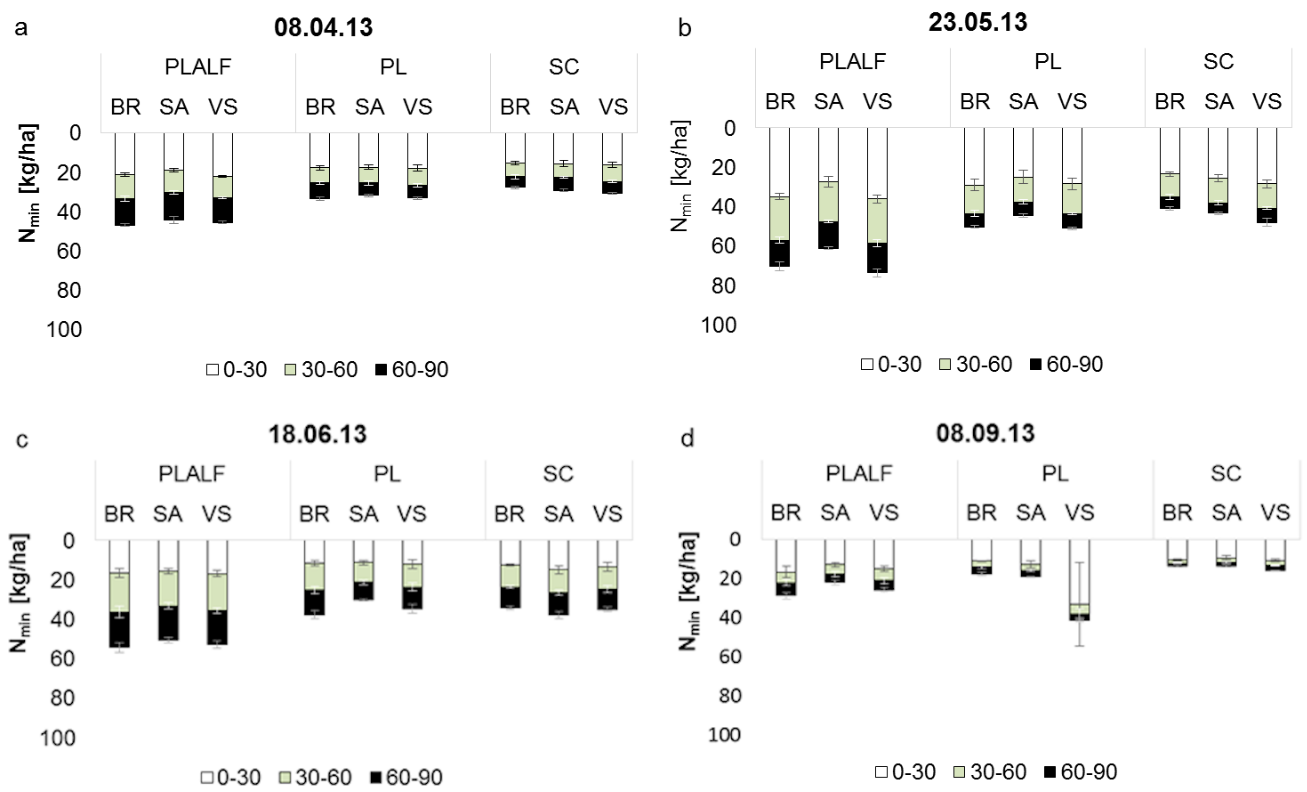

Figure 8. N_{min} content at three soil depths on four assessment dates in 2013 in three green manure treatments in the second year after sowing the green manure crops in different tillage/crop rotation systems. For abbreviations, see Figure 3. Error bars represent the standard errors.

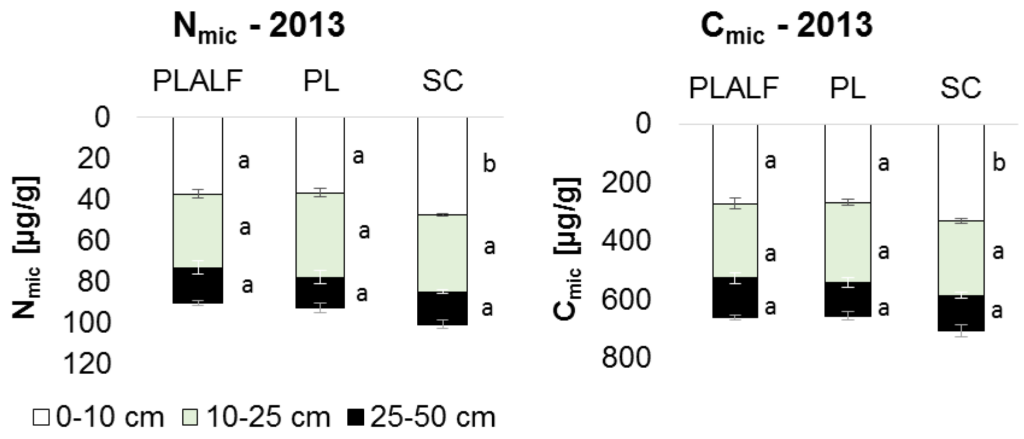

Figure 9. N_{mic} and C_{mic} in spring 2013 at three soil depths of different tillage/crop rotation systems. For abbreviations, see Figure 3. Error bars represent the standard errors.

4. Discussion

4.1. Leguminous green manure crops are able to compensate for the reduced N mineralization in the reduced tillage system, while high N using species will suffer more from reduced tillage

V. sativa proved to be very effective in achieving a high N_{min} content in the SC and PL systems, which both had a reduced N_{min} content compared to the PLALF system. *V. sativa* also led to high N_{min} values in the PLALF system, but the choice of the green manure crop was of minor importance in this system. The greatest differences between the N_{min} values of the *V. sativa*-treatment and the other treatments were found in the SC system. The high N_{min} values of the *V. sativa*-treatment can be attributed to the high N content of *V. sativa*, especially in the PL and SC systems, as well as to its low C/N ratio (Figure 4 and Table 4). Two regressions of N_{min} on March 15, 2012 in the 0–30 cm layer on the N content of green manure crops and the C/N ratio of green manure crops show a slightly greater influence of the N content (R^2 = 0.7555) than the C/N ratio (R^2 = 0.6278) on the N_{min} content of the soil.

T. resupinatum as a second legume species in this trial was not as effective as *V. sativa* due to its low growth. Heavy rainfall two days after the drilling led to silting which probably hampered the germination of this small-seeded legume. *T. resupinatum* seems to be more sensitive to growing conditions than other green manure crops. For *T. resupinatum* strongly fluctuating N contents between 140 kg ha^{-1} and 15 kg ha^{-1} with yields between 3.5 t ha^{-1} and 0.4 t ha^{-1} above ground dry matter biomass are reported in a study by Grosse *et al.* [14].

The C/N ratio of *T. resupinatum* could not be determined due to its low growth. The C/N ratio of *T. resupinatum* is given as 15.8 by Fageria *et al.* [15], i.e., higher than the value of *V. sativa* (9.4 to 10.6) measured in this experiment. Due to the low growth of *T. resupinatum*, very little N was likely bound.

The mixture of *T. resupinatum* and *S. alba* suffered from the low growth of *T. resupinatum*. However, despite half the amount of seeding density for *S. alba* in the mixture compared to *S. alba* in pure stand, the yield and the N content of the mixture was comparable to that in pure stand in the PLALF and the SC system.

L. perenne, as an overwintering species, was the only treatment in the PLALF and PL systems that produced lower N_{min} values before being tilled into the soil than the bare fallow treatment (Figure 5a). Even after being tilled in, *L. perenne* still had the lowest N_{min} values in the PLALF and PL systems (Figure 5b). *L. perenne* had both the lowest N content and the highest C/N ratio of the green manure crops tested (Figure 4 and Table 4) in each system. A high C/N ratio can lead to a temporary immobilization of N, as reported in a study by Baggs *et al.* [16].

The bare fallow was overgrown with weeds in every system despite flame weeding. This result means that N was also retained by the vegetation in these treatments. N mineralisation in all bare fallow treatments was comparable or higher in spring than N mineralisation in the non-legume green manure treatments. This result is in line with results from Baggs *et al.* [16], which showed that N retention through weed cover was as effective as that retained through sown green manure crops. However, it can be assumed that uncontrolled growth will increase the weed pressure in subsequent field crops.

The biomass yield of *S. alba* was significantly higher in the PLALF and PL system than in the SC system. This promotes the hypothesis that high N using crops will suffer more from reduced tillage. However, the N_{min} level of the PL and the SC system was similar at the beginning of 2012, albeit it was somewhat lower in the SC system than in the PL system. This difference, despite beeing small, may result in a difference in yields on the given low N_{min}

level. However, other factors, such as reduced soil loosening at greater depths in the SC system, may also have played a role in the difference in yields.

In the second year after the green manure crops were grown, no effects of the green manure crops on the N content of the soil were detected. In contrast, the influence of crop rotation was measurable throughout the entire trial year. The cereal based crop rotation either with conventional tillage or with reduced tillage had similar N_{min} levels, while the crop rotation which had included alfalfa grass showed a significantly higher N_{min} content on each assessment date.

4.2. The content of the microbial biomass in the top soil increases after six years of exclusive cultivation with the stubble cleaner in comparison to the plough systems

The SC system had significantly more microbial N and C in the top soil (0–10 cm) than did the other two systems, while there were no significant differences in the underlying layers. This result is consistent with that from studies by Berner *et al.* [17], Emmerling [18], Fließbach *et al.* [19] and Kuntz *et al.* [20]. The higher content of microbial biomass in the SC system is a positive result in terms of soil fertility, as the microbial biomass is an important indicator of this [12]. Other studies reported a lower C_{mic} content with reduced tillage than with conventional ploughing, which was attributed to soil compaction and the related adverse conditions for microbial activity [21,22]. It is therefore essential to avoid soil compaction at all costs or to loosen the soil before switching to reduced tillage, since the soil can be less easily loosened with reduced tillage than with deep tillage [2]. Farmers who successfully employ reduced tillage methods are very much aware of this point [23].

4.3. Leguminous green manure crops promote the yield of the non-leguminous main crop in the reduced tillage system, while in the plough systems the effect is less pronounced. In the following year, a leguminous main crop is able to compensate for the differences in N_{min} content of the different tillage systems

The yield of oats in the PLALF system was statistically the same for all green manure treatments. In the PL and SC systems, *V. sativa* led to an oat yield comparable to that of the PLALF system. In the SC system, the difference between the *V. sativa* treatment and the other green manure treatments was more pronounced than that in the PL system. The yield of oats in the PLALF system was statistically the same for all green manure treatments. In the reduced tillage system, it is therefore particularly important to cultivate a green manure crop that grows well within the system, whereas the choice of green manure crop is less important for ploughing systems. When ploughing in a system with a varied crop rotation, including a rotation with a perennial forage, the choice of green manure crop is almost irrelevant. No differences among tillage or crop rotation systems were discernible for the yield of field beans in 2013. The leguminous main crop was thus able to compensate for the existing differences in the N_{min} baseline levels.

The late sowing date (April 22, 2013) could be an explanation for the relatively low field bean yield of less than 4 t ha^{-1}. However, late sowing does not necessarily lead to yield losses, as regional variety trials between 1988 and 2012 have shown [24]. It is possible that spring ploughing would have had a positive effect on the field bean yield rather than tilling with the spring tine cultivator. In a study by Gruber und Claupein [25], the use of cultivators led to large losses in the grain yield of the main crop of field beans. The weather may have had an adverse effect on the grain yield of the field bean. An adequate water supply during the flowering period and the development of the pods is of particular importance for field beans [26]. Drought stress at this time can increase the shedding of flowers and young pods. In this respect, the levels of precipitation in the months of June and July 2013, which were well below average, probably had a negative impact on the field beans.

5. Conclusions

V. sativa proved to be very effective in achieving both a high N_{min} content and yield of oats in the stubble cleaner (SC) and plough (PL) systems. The high N content and the low C/N ratio of *V. sativa* may have been the cause of the success of this green manure treatment. In the crop rotation with alfalfa grass (PLALF), the choice of green manure did not play a major role.

The field bean as a legume was insensitive to the various systems.

In the cereal-based crop rotation, the PL system was only partially superior to the SC system in terms of the stimulation of mineralisation and oat yield. The negative impact of unilateral crop rotation overshadowed the effects of tillage. A diverse crop rotation including forage growing would create better starting conditions for the use of a device for reduced tillage, and even ploughing the alfalfa or clover grass would not necessarily have to be done with a conventional plough. However, there is still a need for further research and testing in this area.

This study confirms that organic farming depends on a combination of different practices for successful arable farming (such as stubble breaking, primary tillage, mechanical weed control, green manure cultivation, crop rotation, and perennial forage growing) and that a reduction in one area (*e.g.*, tillage) requires intensification in another (*e.g.*, the diversification of the crop rotation).

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Appendix

Table A1. Labelling of the significant differences within one soil layer for the N_{min} samples from 15.03.2012.

15.03.2012	PLALF-system							PL-system							SC-system						
	BR	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**	**BR**	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**	**BR**	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**
0-30	efgh	abc	defg	fgh	ghi	hij	ij	cdef	ab	abc	bcdef	abcde	defgh	j	a	abc	abc	abc	abcd	abcdef	ghi
30-60	abcd	abcd	abcd	de	bcde	bcde	e	abc	ab	abcd	abcd	abcd	abcd	cde	a	ab	abc	ab	abcde	abc	abcd
60-90	abc	ab	ab	abc	abc	c	c	ab	a	ab	ab	a	abc	bc	ab	a	a	a	a	a	abc

Table A2. Labelling of the significant differences within one soil layer for the N_{min} samples from 15.05.2012.

15.05.2012	PLALF-system							PL-system							SC-system						
	BR	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**	**BR**	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**	**BR**	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**
0-30	abcd	abcd	abcd	bcd	cd	abcd	d	abc	a	abcd	abc	a	abcd	abcd	a	a	ab	a	ab	ab	abcd
30-60	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
60-90	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Table A3. Labelling of the significant differences within one soil layer for the N_{min} samples from 05.09.2012.

05.09.2012	PLALF-system							PL-system							SC-system						
	BR	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**	**BR**	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**	**BR**	**LP**	**PT**	**SA**	**SATR**	**TR**	**VS**
0-30	cd	abc	cd	bcd	d	bcd	cd	abc	a	a	ab	a	a	ab	a	a	a	a	a	a	ab
30-60	ab	a	ab	ab	b	ab	ab	ab	a	a	a	a	a	ab	a	a	a	a	a	a	a

Table A4. Labelling of the significant differences within one soil layer for the N_{min} samples from 2013.

	08.04.2013		
	PLALF-system	**PL-system**	**SC-system**
0-30	b	a	a
30-60	b	a	a
60-90	b	a	a
	23.05.2013		
0-30	b	b	a
30-60	b	b	a
60-90	b	b	a
	18.06.2013		
0-30	b	b	ab
30-60	b	b	a
60-90	b	b	a
	08.09.2013		
0-30	n.s.	n.s.	n.s.
30-60	b	ab	a
60-90	b	b	a