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The impact of the termination technology of agro-ecological service crops on soil properties in open field vegetable production

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Abstract. The agro-ecological service crops (ASC) are introduced in the agro-ecosystems to provide or enhance ecological services, thus promoting the whole soil-plant system equilibrium. To avoid competition with the subsequent cash crops, the growth of the interposed ASC is terminated in advance of the cash crop planting. The traditional, most widespread technique to terminate the ASC is incorporation as green manure into the soil by tillage (GM). However, since tillage includes energy and labour consuming and soil disturbing operations, the use of no/reduced tillage techniques (as the roller crimping technology-RC) has received increasing interest.
An international research consortium (SOILVEG) including Estonian Crop Research Institute, was established in 2015 with the aim to study among others the impact of ASC termination on soil dry bulk density (BD), water content, soil structure and microbiological activity. Data are collected from Estonian trials in 2016 and 2017 at Jõgeva.
The physical properties of 0–40 cm soil layers were determined. Higher BD in soil layers (0–20 cm) of plots with ASC and RC was determined comparing to the GM and control plots. Bigger water content in same layer of plots with ASC and the RC was determined comparing to the GM plots. The use of the ASC-s helped to arise ratio of agronomically preferred soil particles. Microbial activity was estimated by assessing of enzyme dehydrogenase activity in 0–20 cm soil layer. There were no statistically relevant differences in soil dehydrogenase activity (DHA) between the RC and GM treatments.

Key words: agro-ecological service cops (ASC), roller crimping, soil bulk density, soil gravimetric water content, soil structure, soil dehydrogenase activity.

INTRODUCTION

The roller-crimper technology is receiving increasing interest in no-till organic production systems in recent decade as a mean to control weeds, improve soil quality and, reduce labour and fuel costs (Altieri et al., 2011; Luna et al., 2012, Halde et al., 2014). Many studies have shown that the roller-crimper technology and choice of cover crop species influence the weediness of fields and cash crop yield, also soil and plant chemical properties (Mischler et al., 2010; Mirsky et al., 2011; Nord et al., 2012; Canali et al., 2013; Halde et al., 2014). However, the soil physical and biological condition is poorly investigated.

Soil bulk density (BD) plays an important role in crop yield. BD reflects soil ability to function as structural support, has impact on water movement and soil aeration (Arshad et al., 1996; Cresswell & Hamilton, 2002). BD 1.3–1.5 Mg m^{-3} enhances root growth, whereby BD depends on soil texture and the content of organic matter (Guimarães et al., 2002; Tracy et al., 2012). An ideal BD-s for plant growth by soil texture is following: sandy < 1.60, silty < 1.40 and clayey < 1.10 Mg m^{-3}. However, BD values what are for Estonian condition considered to be restricting to root growth are above1.80 Mg m^{-3} for sandy, 1.65 for silty and 1.47 for clayey soil (Arshad et al., 1996).

The tillage practices influence the biological processes in soil through the changes of soil physical properties and distribution of plant residues (Hassink et al., 1993; Miglierina et al., 2000; Bogužas et al., 2010; Carvalho et al., 2010; Janušauskaite, et al., 2013). Soil enzymatic activity is a sensitive indicator to evaluate the influence of different agricultural practices on the soil processes which are carried out by microorganisms (Watts et al., 2010).

The aim of the current study was to investigate the impact of agro-ecological service crops (ASC) and termination technology on soil dry bulk density, water content, structure and microbiological activity.

MATERIALS AND METHODS

Site and soil description and experimental set up

The experiment was carried out on organic field of Estonian Crop Research Institute (58°44'59.41" N, 26°24'54.02" E) in eastern Estonia in 2015 to 2017. The soil of the experimental field was classified as *Calcaric Cambic Phaeozem (Loamic)* clay soil (WRB, 2015). The soil pH_{KCl} was 7.2 and the organic carbon content 2.7%.

Plot size was 4 x 6 m with three replications and 1.5 m stripes between plots (Fig. 1). The field trial was conducted on season 2015/2016 and then switched 50 m to north, to neighbouring trial area on 2016/2017. The precrop on both trial areas was red clover, which was chopped before tillage.

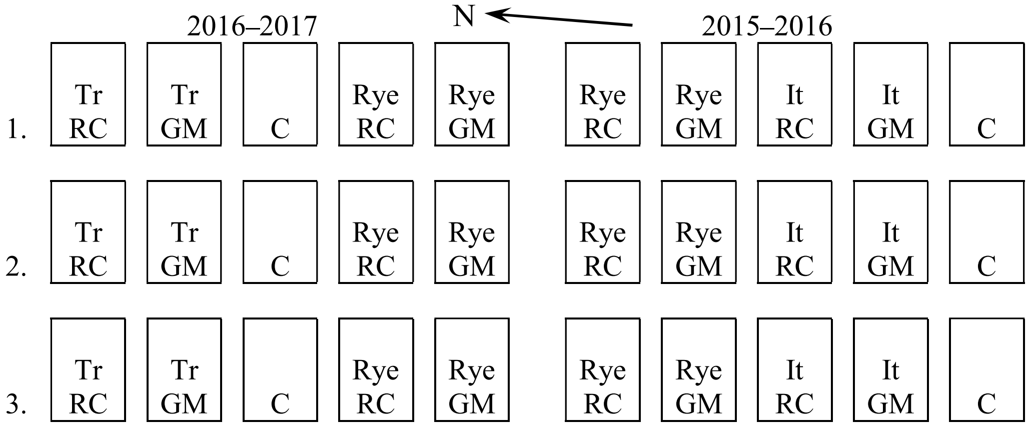

Figure 1. Experimental field design in 2015–2016 and 2016–2017 seasons. Rye – winter rye; It –Italian ryegrass; Tr – winter triticale. C – control, without ASC, RC – the ASC was crimped by roller-crimper, GM – the ASC was chopped by flail mower, incorporated by plough and soil was levelled by tine cultivator; C – control, no ASC, soil was ploughed by plough and levelled by tine cultivator.

Activities on 2015–2016. The first soil tillage on all plots was done after 30 t ha^{-1} solid cattle manure application on the 29th July 2015 with 4-furrow reversible plough (24 cm depth). Cultivating was done with disc cultivator (12–14 cm) on the 9th August and the second time with cultivator with wing tines on the 19th August 2015. The ASC winter rye (*Secale cereale*) `Elvi` 180 kg ha^{-1} and Italian ryegrass (*Lolium multiflorum*) `Talvike` 55 kg ha^{-1} were sown on the 25th August 2015. Control, without ASC (C) was harrowed by rotary harrow (depth 10 cm) on the 4th May 2016. For biomass and C:N ratio measurements the ASC crops were sampled (50 x 50 cm) on the 30th May 2016 and analysed in laboratory of the Estonian University of Life Science department of Soil Science and Agrochemistry. ASC flattening by roller crimper (RC treatment) was done two times on the 6th and four times on the 9th June 2016. Incorporation of the ASC as green manure by chopping and incorporating (GM treatment) with 4-furrow reversible plough (20 cm depth) was made on the 10th June 2016. Control plots and ploughed GM treatment plots were levelled with tine harrow and slat rolls on the 10th June 2016. Cash crop: white cabbage (*Brassica oleracea var. capitata f. alba*) middle-ripening (130 days) cv Jõgeva was planted from 13th to 16th June 2016 by hand. Planting distances were 0.50 m between rows and 0.50 m between plants in the row. Age of the seedlings was 28–30 days. Manual weeding was performed on all treatments on the 25th August. Harvest date was on the 7th October 2016.

Activities on 2016/2017. The first soil tillage on all plots was done after 30 t ha^{-1} solid cattle manure application on the 6th September 2016 with 4-furrow reversible plough (24 cm depth). Cultivating was done with disc cultivator (12–14 cm) on the 7th September. The ASC winter rye (*Secale cereale*) `Elvi/Tulvi` 180 kg ha^{-1} and winter triticale (*Triticosecalium*) `Ruja` 155 kg ha^{-1} were sown on the 8th September 2016. For biomass and C:N ratio measurements the ASC crops were sampled on the 24th May 2017 and analysed. ASC flattening by roller crimper (RC) was done two times on rye and four times (to achieve even termination) on triticale on the 19th June 2017. ASC as green manure (GM) was chopped with flail mower and incorporated with 4-furrow reversible plough (20 cm depth) on the 16th June 2017. Control and GM plots were levelled with tine harrow and slat rolls on the 16th June 2017. Cash crop white cabbage cv Jõgeva was planted on the 19th June 2017 by hand. Planting distances were 0.65 m between rows and 0.50 m between plants in the row. Age of the seedlings was 38 days. All treatments were weeded manually on the 27th July 2017. Harvest date was from the 4th to the 6th October 2017.

Soil bulk density, gravimetric water content and structure

The soil bulk density i.e. BD (Mg m^{-3}), soil gravimetric water content, i.e. GWC (kg kg^{-1}), soil structure K_{str} were assessed in soil layers 0–10, 10–20, 20–30 and 30–40 cm, in October 2016 and 2017. For determination of K_{str} the soil samples of 0–20 cm from three replications were mixed. The BD and GWC were evaluated by Eijkelkamp cylinder (100 cm^3). The soil structure K_{str} (Tamm et al., 2016) was evaluated by USA Standard Testing Sieve and also by method of Swedish University of Agricultural Sciences (Hakansson, 1983; Kritz, 1983) by which the soil has been sieved in laboratory in moist conditions.

The ratio of soil structure K_{str} was calculated as (Tamm et al., 2016):

$$K_{str} = \frac{s_{ps}}{s_{n1}+s_{n2}} \quad (1)$$

where s_{ps} – percentage of soil particles with diameter between 2–4.75 mm (preferred soil structure-*PS*); s_{n1} – percentage of soil particles with diameter < 2 mm (not-preferred soil structure); s_{n2} – percentage of soil particles with diameter > 4.75 mm (also not-preferred soil structure).

The agronomically preferred (0.250–1.0 mm of diameter) and clods (> 9.5 mm of diameter) soil particles at a soil depth 0–20 cm in 2017 were measured in laboratory by air dry soil sieving. After sieving the weight of the soil portions laying on the sieves were weighed and then the relation (%) of the every portion to the total weight was calculated.

Soil dehydrogenase activity

Soil samples (0.2 kg) from each treatment in three replications from the 0–20 cm soil layers with a 16 mm diameter auger were taken on 1.09.2016 and 22.08.2017, during the cabbage growth and almost three month after ASC termination. Samples were sieved (2 mm) and stored at 4 °C until analysis in laboratory. Assessing of soil dehydrogenase activity (DHA) based on Tabatabai (1982). Soil samples (5 g) were incubated at 30 °C for 24 h in the presence of an alternative electron acceptor (triphenyltetrazoliumchloride). The red-tinted product (triphenylformazan) was extracted with acetone and measured in a spectrophotometer at 546 nm.

Data analyses

Observations of soil physical parameters (soil structure, BD, GWC) and dehydrogenase activity based on three sample replicates of related trial plots and soil layers. The data was analyzed by ANOVA. For the soil physical parameters and dehydrogenase activity the Tukey-Kramer Honest Significant Difference (HSD) test was used via the software *JMP 5.0.1.2* (SAS, 2002).

RESULTS AND DISCUSSION

Soil bulk density (BD), gravimetric water content (GWC) and structure(Kstr)

The average soil BD for all trial plots and depths in October of 2016 and 2017 was quite different (Table 1). In both years highest BD was measured in soil layer 30–40 cm. Highest BD occurred in 2016 (20–30 cm layer) in Rye RC plots, where 6 overdrives with the roller crimper was made. Statistical differences between the treatments in depth 0–10, 10–20 and 30–40 cm did not occur during 2016.

The lowest BD occurred in 2017 0–10 cm layer in control plots. In comparison to 2016, in 2017 the BD decreased in 0–10 and 20–30 cm layers of rye RC, rye GM and control plots. In 2016 It RC, It GM and in 2017 Tr RC and Tr GM trial plots the soil BD remained, regardless of the different crops, quite similar in all depths.

During the study the average soil GWC % in 2016 for all treatments and depths was 35.49 % and in 2017 was 31.14 %. In 2016, statistical differences between the treatments did not occur. In 2017 the GWC % in depth 0–10 cm was significantly higher in the RC than in GM and control plots ($P = 0.0013$).

The soil structure and also agronomical preferred soil particles play an important role in water availability and they form like an architecture of the soil (Hunt & Gilkes, 1992). It is essential to crop production (Bronick & Lal, 2005). Our results show (Table 2) in 2017 a better soil structure coefficient (Kstr) in Rye GM (0.58), Tr GM (0.61) and Control (0.53) treatments. Oppositely, a lowest value (0.21) were found in 2016, on control plot. In 2017, the significantly lowest values had RC plots (Rye RC (0.32) and TrRC (0.26)).

Table 1. Mean values of soil bulk density (BD) and gravimetric water content (GWC) in 2016 and 2017

Depth, cm	Treatment	BD, Mg m^{-3}		CWC %, kg kg^{-1}	
		2016	2017	2016	2017
0–10	Rye RC	1.44^{a}	1.10^{bc}	36.00a	38.13^{a}
	Rye GM	1.34^{a}	1.01^{bc}	34.63^{a}	31.67b
	It /Tr RC	1.41^{a}	1.49^{a}	39.64^{a}	34.87^{ab}
	It/Tr GM	1.34^{a}	1.23^{ab}	35.01a	30.70^{b}
	Control	1.36^{a}	0.80c	38.42^{a}	31.10^{b}
	p > F	*ns*	*0.001*	*ns*	*0.0013*
10–20	Rye RC	1.36^{a}	1.46^{a}	34.74^{a}	35.10^{a}
	Rye GM	1.18^{a}	1.38^{ab}	32.87^{a}	33.33^{ab}
	It /Tr RC	1.27^{a}	1.32^{ab}	34.72^{a}	33.30^{ab}
	It/Tr GM	1.23^{a}	1.25^{b}	33.40^{a}	30.87^{a}b
	Control	1.27^{a}	1.25^{b}	36.96^{a}	29.47^{b}
	p > F	*ns*	*0.0018*	*ns*	*0.0015*
20–30	Rye RC	1.60^{a}	1.00^{abc}	34.68^{a}	31.27^{a}
	Rye GM	1.30^{b}	0.89^{c}	34.03^{a}	33.47^{a}
	It /Tr RC	1.33^{b}	1.51^{a}	36.89^{a}	30.33^{a}
	It/Tr GM	1.37^{ab}	1.47^{ab}	36.64^{a}	32.10^{a}
	Control	1.36^{ab}	0.99^{bc}	39.01^{a}	31.97^{a}
	p > F	*0.029*	*0.006*	*ns*	*ns*
30–40	Rye RC	1.66^{a}	1.66^{a}	33.21^{a}	30.17^{a}
	Rye GM	1.52^{a}	1.73^{a}	36.01^{a}	30.20^{a}
	It /Tr RC	1.59^{a}	1.74^{a}	33.52^{a}	23.43^{a}
	It/Tr GM	1.35^{a}	1.63^{a}	35.02^{a}	23.10^{a}
	Control	1.58^{a}	1.67^{a}	34.36^{a}	28.20^{a}
	p > F	*ns*	*ns*	*ns*	*ns*

Note. Different letters behind the mean values indicate significant differences at $p < 0.05$ (Tukey-Kramer HSD test).

Table 2. Mean values of soil structure (Kstr) in 2016 and 2017; agronomically preferred soil particles (0.250–1.0 mm of diameter) and clods (%) (> 9.5 mm of diameter) at a soil depth 0–20 cm in 2017

Treatment	Kstr		0.250–1.0 mm	> 9.5 mm
	2016	2017	2017	2017
Rye RC	0.29^{ab}	0.32^{b}	2.53^{bc}	55.07^{a}
Rye GM	0.38^{a}	0.58^{a}	4.03^{ab}	44.77^{ab}
It/Tr RC	0.35^{ab}	0.26^{b}	1.97^{c}	59.73^{a}
It/Tr GM	0.29^{ab}	0.61^{a}	5.40^{a}	33.53^{b}
Control	0.21^{b}	0.53^{a}	5.13^{a}	34.73^{b}
p > F	*0.05*	*> 0.001*	*0.004*	*0.002*

Note. Different letters behind the mean values indicate significant differences at $p < 0.05$ (Tukey-Kramer HSD test).

Generally, the dependence between agronomical preferred soil particles and cloddy soil is inverse, which is also confirmed by higher clod-like (> 9.5 mm of diameter) and lower 0.250–1.0 mm soil particles proportion in RC treatments. Higher 0.250–1.0 mm and lower > 9.5 mm soil particles proportion were found in GM plots compared to the RC plots.

Wet clay soils are structurally unstable and have high shrink and swell potential (Blanco-Canqui, & Lal, 2008). Although in 2016, were no clear differences of measured soil physical parameters between the treatments, they became evident in 2017 because the weather was very rainy before the RC termination. In 2016 10 days before RC termination was without any precipitation and during whole previous May was only 3.6 mm rain.

Soil dehydrogenase activity (DHA)

In 2016, the comparison of ASC-s showed that soil DHA was highest in the variant with Italian ryegrass (5.41 TPF μg g^{-1} h^{-1}, $P = 0.007$, Table 3) and lowest in control and rye variants (3.97 and 4.47 TPF μg g^{-1} h^{-1}). In 2017, there were no statistically relevant differences between ASC variants. However, it was possible to observe tendency of higher soil DHA in triticale variant (5.46 TPF μg g^{-1} h^{-1}) than in rye and control variants (4.52 and 5.03 TPF μg g^{-1} h^{-1}). During the growth the plants affect the soil microorganism by physiological and morphological mechanisms as nutrient and water use by plants and by differences in root distribution and exudates (Garbeva et al., 2008; Doornbos et al., 2012). The positive effect of the ASC-s on soil microbial communities associated with crop rhizosphere compared to the bare fallow was also observed by Hacquard et al., 2015. After the cover crops management by the different termination technologies, the organic matter breakdown by microorganisms is largely influenced by C:N ratio. The C:N ratio can limit microbial growth when it is above the threshold value of 25–30 (Biddlestone et al., 1994). In 2016 and in 2017, compared to the plant material C:N ratio of rye (2016 – 35.1 and 2017 – 32.5) the Italian ryegrass (31.3) and triticale (24.2) ratios were lower and therefore were suitable for soil microorganisms.

In 2016 and 2017, the soil DHA in all managements was similar and statistical differences between the RC, GM and Control plots did not occur. As well, there were no statistical differences between the management and the ASC interaction. However, there was tendency that in 2016 and 2017, compared to the Control and rye different managements, the soil DHA was slightly higher in treatments with Italian ryegrass and triticale variants where before the cabbage planting the fresh plant material was rolled down. The reason for this may be that in addition to the rye higher C:N ratio, the rolled or incorporated rye left much bigger mulch layer (902–1,065 DM g m^{-2}) on the soil surface than Italian ryegrass and triticale (378–594 DM g m^{-2}). That might reduce the oxygen availability and a lack of oxygen might reduce the soil DHA, especially on the clay soil. While, Jodaugienė et al., 2010 found in their field experiment in medium clay soil, that the mulch layer thickness 5 or 10 cm had no significant effect on soil hydrolytic enzymes. In our experiment the lower soil enzymatic activity in the variants with larger amounts of mulch may have been due to the coincidence of several inappropriate factors. For example in 2016, this could be caused by the high amount of precipitations during the vegetation period (June – 162 mm; July – 78 mm; August–180 mm) compared to average of 1994–2004 (June – 98 mm; July – 77 mm; August –73 mm).

Table 3. Soil dehydrogenase activity (DHA) at a soil depth 0–20 cm in 2016 and 2017

Factor	Variant	2016	2017
		TPF µg g^{-1} h^{-1}	
ASC	Rye	4.47^b	4.52^a
	It 2016/Tr 2017,	5.41^a	5.46^a
	Control	3.97^b	5.03^a
	p > F	*0.007*	*ns.*
Management	RC	4.94^a	5.36^a
	GM	4.93^a	4.62^a
	Control	3.97^a	5.03^a
	p > F	*ns.*	*ns.*
ASC*Management	Rye RC	4.37^a	4.67^a
	Rye GM	4.56^a	4.36^a
	It/Tr RC	5.51^a	6.05^a
	It/Tr GM	5.30^a	4.87^a
	Control	3.97^a	5.03^a
	p > F	*ns.*	*ns.*

Note. Different letters behind the mean values indicate significant differences at $p < 0.05$ (Tukey-Kramer HSD test).

Soil physical properties have significant impact on soil microbial activity, for example Gispert et al. (2013) found soil microbial populations greatest in soils with low bulk density. In present study the soil physical parameters and the soil dehydrogenase activity were not compared because the soils were sampled at a different time.

CONCLUSIONS

The use of the agro-ecological service crops helped to arise ratio of agronomically preferred soil particles. The technology, where the winter rye as ASC was chopped by flail mower, incorporated by plough and after that the soil was levelled by tine cultivator, helped in 2017 to increase the ratio (soil moist sieving) of soil structure. The dependence between agronomically preferred soil particles and cloddy soil was inverse. The sampling period 2016–2017 is quite adequate to make general conclusions about immediate influence of rolling crimping technology method on soil bulk density and gravimetric water content. The tendency of increase of the bulk density with increasing depth was observed on RC rye plots in 2016. However, in 2017 tendency was to the lower bulk densities on GM rye, GM triticale and control plots.

Soil dehydrogenase activity was influenced by the treatment only in 2016, then the dehydrogenase activity was higher in the soils under the ASC Italian ryegrass cultivation than under the winter rye cultivation and in the bare soil. Statistical differences between the roller crimping, chopped/incorporated and plough technology on soil dehydrogenase activity did not occur.

The experiment series could be continued to get more information about the influence of other agro-ecological service crops and termination technology on soil different characteristics.

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REFERENCES

Altieri, M.A., Lana, M.A., Bittencourt, H.V., Kieling, A.S., Comin, J.J. & Lovato, P.E. 2011. Enhancing crop productivity via weed suppression in organic no-till cropping systems in Santa Catarina, Brazil. *Journal of Sustainable Agriculture* **35**, 855–869.

Arshad, M.A., Lowery, B. & Grossman, B. 1996. Physical Tests for Monitoring Soil Quality. In: Doran J.W., Jones A.J., editors. *Methods for assessing soil quality*. Madison, WI, 123–141.

Biddlestone, A.J., Gray, K.R. & Thayanithy, K. 1994. Composting reed beds for aerobic treatment of livestock wastes. In: I.A. Dewi, R.F.E. Axford, I. Fayez, M. Marai and H.M. Oured (Editors), *Pollution in Livestock Production Systems*. CAB International, Wallingford, UK, 345–360.

Blanco-Canqui, H. & Lal, R. 2008. Principles of Soil Conservation. Springer Verlaag, 617 pp.

Bogužas, V., Kairytė, A. & Jodaugienė, D. 2010. Soil physical properties and earthworms as affected by soil tillage systems, straw and green manure management. *Zemdirbyste-Agriculture* **97**(3), 3–14.

Bronick, C.J. & Lal, R. 2005. Soil structure and management: a review. *Geoderma* **24**, 3–22.

Canali, S., Campanelli, G., Ciacci, C., Leteo, F., Testani, E., Montemurro, F. 2013. Conservation tillage strategy based on the roller crimper technology for weed control in Mediterranean vegetable organic cropping systems. *European Journal of Agronomy* **50**, 11–18.

Carvalho, J.L.N., Raucci, G.S., Cerri, C.E.P., Bernoux, M., Feigl, B.J., Wruck, F.J., Cerri, C.C. 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. *Soil and Tillage Research* **110**, 175–186.

Cresswell, H.P., Hamilton, G.J, McKenzie, N., Coughlan, K. & Cresswell, H. 2002. Bulk Density and Pore Space Relations. In: *Soil Physical Measurement and Interpretation For Land Evaluation*. (Eds N.J. McKenzie, H.P. Cresswell H.P., K.J. Coughlan) CSIRO Publishing: Collingwood, Victoria, pp. 35–58.

Doornbos, R.F., van Loon, L.C. & Bakker, P.A.H.M. 2012. Impact of root exudates and plant defense signaling on bacterial communities in the rhizosphere. *Agronomy for Sustainable Developmen* **32**, 227–243.

Garbeva, P., Van Elsas, J.D. & Van Veen, J.A. 2008. Rhizosphere microbial community and its response to plant species and soil history. *Plant and Soil* **302**, 19–32.

Gispert, M., Emran, M., Pardini, G., Doni, S. & Ceccanti, B. 2013. The impact of land management and abandonment on soil enzymatic activity, glomalin content and aggregate stability. *Geoderma* **202–203**, 51–61.

Guimarães, C.M., Stone, L.F. & Moreira, J.A.A. 2002. Soil compaction in a bean crop. II. Effect on root and shoot development. *Revista Brasileira de Engenharia Agrícola e Ambiental* **6**, 213–218.

Hacquard, S., Garrido-Oter, R., González, A., Spaepen, S., Ackermann, G., Lebeis, S, McHardy, A.C, Dangl, J.L., Knight R., Ley R. & Schulze-Lefert, P. 2015. Microbiota and host nutrition across plant and animal kingdoms. *Cell Host Microbe* **17**(5), 603–616.

Hakansson, I. (ed.). 1983. Pnysical conditions in cereal seedbeds. A sampling investigation in Swedish spring-sown fields. Reports from the Division of Soil Management nr. 65. Uppsala, 187 pp.

Halde, C.H., Gulden, R.H. & Entz, M.H. 2014. Selecting Cover Crop Mulches for Organic Rotational No-Till Systems in Manitoba, Canada. *Agronomy Journal* **106**(4), 1193–1204.

Hassink, J., Bowman, L.A., Zwart, K.B., Bloem, J. & Brussard, L. 1993. Relationships between soil texture, physical protection of organic matter, soil biota, and C and N mineralization in grassland soils. *Geoderma* **57**, 105–128.
Hunt, N. & Gilkes, B. 1992. *Farm Monitoring Handbook*. UWA, LMS & DSP, 62 pp.
Janušauskaite, D., Kadžienė, G. & Auškalnienė, O. 2013. The influence of tillage on selected biological parameters. The Effect of Tillage System on Soil Microbiota in Relation to Soil Structure. *Polish Journal of Environmental Studies* **22**(5), 1387–1391.
Jodaugienė, D., Pupalienė, R., Sinkevičienė, A., Marcinkevičienė, A., Žebrauskaitė, K., Baltaduonytė, M. & Čepulienė, R. 2010. The influence of organic mulches on soil biological properties. *Zemdirbyste-Agriculture* **97**(2), 33–40.
Kritz, G. 1983. Physical conditions in cereal seedbeds. Reports from the Division of Soil Management. Swedish University of Agricultural Sciences, S-750 07. Uppsala, pp. 25–36.
Luna, J.M., Mitchell, J.P. & Shrestha, A. 2012. Conservation tillage for organic agriculture: evolution toward hybrid systems in the western USA. *Renewable Agriculture and Food Systems* **27**, 21–30.
Miglierina, A.M., Iglesias, J.O., Landriscini, M.R., Galantini, J.A. & Rosell, R.A. 2000. The effects of crop rotation and fertilization on wheat productivity in the Pampean semiarid region of Argentina. 1. Soil physical and chemical properties. *Soil and Tillage Research* **53**, 129–135.
Mirsky, S.B., Curran, W.S., Mortensen, D.M., Ryan, M.R. & Shumway, D.L. 2011. Timing of covercrop management effects on weed suppression in no-till planted soybean using a roller-crimper. *Weed Science* **59**, 380–389.
Mischler, R.A., Curran, W.S., Duiker, S.W. & Hyde, J.A. 2010. Use of a rolled-rye cover crop for weed suppression in no-till soybeans. *Weed Technology* **24**, 253–261.
Nord, E.A, Ryan, M.R, Curran, W.S, Mortensen, D.A, Steven, B. & Mirsky, S.B. 2012. Effects of management type and timing on weed suppression in soybean no-till planted into rolled-crimped cereal rye. *Weed Science* **60**, 624–633.
Tabatabai, M.A. 1982. Soil enzymes. In: Page, A.L., Miller, R.H. & Keeney, D.R. (Eds.) Methods of Soil Analysis, Part 2 Chemical and Microbiological Properties, second ed., vol. **9**. American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin, 903–947.
Tamm, K., Nugis, E., Edesi, L., Lauringson, E., Talgre, L., Viil, P., Plakk, T., Võsa, T., Vettik, R. & Penu, P. 2016. Impact of cultivation method on the soil properties in cereal production. *Agronomy Research* **14**(1), 280–289.
Tracy, S.R., Black, C.R., Roberts, J.A., McNeill, A., Davidson, R., Tester, M., Samec, M., Korosak, D., Sturrock, C. & Mooney, S.J. 2012. Quantifying the effect of soil compaction on three varieties of wheat (*Triticum aestivum* L.) using xray micro computed tomography (CT). *Plant and Soil* **353**, 195–208.
Watts, D.B., Torbert, H.A., Feng, Y. & Prior, S.A. 2010. Soil microbial community dynamics as influenced by composted dairy manure, soil properties, and landscape position. *Soil Science* **175**, 474–486.
WRB. 2015. World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Reports* No. 106. FAO, Rome.