Research Article

Coverage plants and their effects on the physical attributes of red-yellow latosol cultivated with corn

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Through the interpretation of soil attributes it is possible to characterize the changes resulting from the adoption of different managements. The use of sustainable and conservationist production systems, such as the use of cover crops, has contributed to the improvement of the physical, chemical and biological attributes of the soil. This study aimed to analyze the effects of cover plants of the *brachiaria* (*Urochloa ruziziensis*), forage turnip (*Raphanus sativus*), crotalaria (*Crotalaria juncea*), millet (*Pennisetum glaucum*) versus mechanized operation with scarifier without soil cover on the attributes soil physicists with a history of five primary periodic soil preparation systems, used since 2014: P1-plowing harrow; P2-disc plow; P3-rotary hoe; P4-no-till; P4-scarifier. In the layers from 0.10 m to 0.20 m and from 0.20 m to 0.30 m, where soil compaction was found, the cover plants reduced on average 37.2% and 47.2% of the RMSP, respectively. In general, forage turnip was the species that stood out the most in improving soil density.

Key words: Soil physics, cover crops, soil preparation, porosity

INTRODUCTION

Soil attributes can characterize the changes resulting from the adoption of different managements. The most used parameters in soil physical assessment are soil density and porosity (Carvalho, et al. 2014), particle density (Baptista, et al. 2017) and soil mechanical resistance to penetration (RMSP) (Tavares, et al. 2014).

The negative impacts on the physical quality of the soil as a result of agricultural mechanization makes tropical soils compact and, therefore, an unfavorable environment for the development of crops, in addition to the degradation of the environment, especially when there is excessive use of machinery in soil preparation. Although there is no consensus regarding the effects of compaction on the increase in aerial biomass of crops (Fenner, 2008), it is associated with many environmental and agronomic problems (Keller, 2012).

Agricultural mechanization generates greater operational capacity in the field and reduces the demand for labor, which can result in lower production costs. However, the excessive use of machines in the field causes losses in the porosity and permeability of the profile, reducing the infiltration and storage of water and hindering the growth and absorption of nutrients by the cultures. Supplement with information from the paragraph above and make the last sentence a hook for the next paragraph.

For the verification of soil compaction, it is necessary to have the characterization of its texture, in order to consider the critical values of density in the range of 1.45 g cm^{-3} for soils with more than 55% clay, 1.55 g cm^{-3} for soils with 55% to 20% clay and 1.65 g cm^{-3} for soils with less than 20% clay (Reinert, et al. 2001). Regarding the soil's mechanical resistance to penetration, the critical values vary between 6 MPa and 7 MPa for sandy soils and 2.5 MPa for clayey soils (Sene, et al. 1985). The macroporosity has a lower limit of 0.10 cm^3 cm^{-3} so that the roots can have satisfactory oxygenation for their growth (Reinert, et al. 2001).

The adoption of sustainable and conservationist production systems, such as the use of cover crops, has contributed to the improvement of physical, chemical and biological attributes of the soil, mainly due to the soil cover, which contribute to the reduction of compaction and erosion, minimizing the losses of water, soil and nutrients, in addition to promoting the accumulation of organic material on the soil surface and reduction of Green House Gas (GHG) emissions (Favarato, et al. 2015; Oliveira, et al. 2015; Colombo, et al. 2017). Cover

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crops provide phytomass on the soil surface and their plant residues can reduce the impact of rain and increase water infiltration (Guedes Filho, et al. 2013; Ambrosano, et al. 2014; Bettiol, 2014). In addition, growing cover crops in the off-season has a positive impact on increasing crop productivity, in addition to maintaining straw and increasing agricultural productivity (Dias, et al. 2015).

The use of cover crops, due to the penetration of the root system, allows the soil to be decompacted without the need to turn it over (Severiano, et al. 2010; Santos, et al. 2014). Aggregating crops with an aggressive root system can minimize the negative effects of soil degradation through improvements in its structure (Cunha, et al. 2011). The roots of cover crops play a key role in improving and structuring the soil. The construction of the soil profile is important, but its effects on agricultural productivity are still poorly recognized (EMBRAPA, 2017). In a literature review on the cost-effectiveness of compaction mitigation technologies, concluded that mechanized operations have an expensive economic cost for farmers (Tim Chamen, et al. 2014).

Knowledge of edaphic conditions and soil quality can help in evaluating the quality of the recovery process and proper soil management. Most studies consider only plant development however, the physical characteristics of the soil must be treated with care because they can be the main limitations in areas where fertility is already corrected and can be monitored by several parameters (Long, et al. 2011). Conservation practices are important for sustainable agriculture, in order to eliminate or reduce soil disturbance and use cover crops that stimulate the activity of the microbiota of the soil and increases the stock of organic carbon (Silva, 2020). Cover plants have the function of biological soil decompaction, breaking the layer that is more uniformly compacted, different from what happens with the use of subsoilers (Camargo, et al. 1997; Aita, et al. 2003). In addition, the aggressive root system of cover crops extracts nutrients and after their accumulation there is decomposition and gradual release in the soil (Fiorin, 1999).

From this, this study aims to analyze the effects of cover crops of brachiaria species (*Urochloa ruziziensis*), radish (*Raphanus sativus*), sunn hemp (*Crotalaria juncea*), and millet (*Pennisetum glaucum*) versus mechanized operation with a chisel on the physical attributes of the soil with a history of different types of soil preparation.

MATERIALS AND METHODS

History of the area and characterization of the experimental area

The work was developed in the experimental area of the Federal University of Vicosa, campus of Rio Paranaiba, with an altitude of 1128 m, located in the geographical position (19°12'43" S and 46°07'56" W). The area belongs to the São Francisco River basin, Alto Paranaiba region, municipality of Rio Paranaiba (MG).

The municipality has a humid temperate climate, being classified by the Köppen scale as Cwb. This climate is characterized by having two very well defined seasons, with a moderately hot and rainy summer and a dry and cold winter.

The average annual temperature is 20.4°C and the average annual rainfall of 1570 mm.

The experimental area has a history containing the different types of preparation since the year 2014 in which it was previously formed with pasture (*brachiaria*). Each year, after preparing the soil, crops were grown in the area: soybeans in 2014, corn for grain production in 2015 and corn for silage production in 2016 and 2017. In 2018, beans were cultivated, with conventional primary tillage with heavy harrow throughout the area. During the year 2019, until the installation of the experiment in the subplots (October 2019), the area was left fallow with cover of weeds and *brachiaria*.

For the installation of the subplots, the control of weeds and *brachiaria*, after the fallow, was done through a mowing and an application of glyphosate (4 L/ha).

Installation of subplots

A completely randomized design (DIC) was used in a split-plot design with four replications. The plots contained the five main treatments with previously adopted periodic primary soil tillage systems (preparation history since 2014) using: P1-harrow; P2-disc plow; P3-rotary hoe; P4-no-tillage; P4-scarifier. The subplots, installed in October 2019, included four cover crops brachiaria (*Urochloa ruziziensis*), radish (*Raphanus sativus*), sunn hemp (*Crotalaria juncea*), millet (*Pennisetum glaucum*) and a treatment with mechanized operation (control), characterized by mechanical scarifier without ground cover. The plots had dimensions of 10 m in length per 10 m wide and were divided into 2 m wide and 10 m long subplots. Within the subplots, the evaluated layers of 0.0 m up to the layer of 0.40 m for density and porosity and even 0.60 m for mechanical resistance of the soil to penetration, with evaluation of 0.10 m to 0.10 m (RMSP).

After controlling weeds and *brachiaria* with mowing and application of glyphosate, the sowing of the four cover species was carried out manually at the beginning of the rainy season of 2019 after opening the planting furrow, with a no-tillage seeder and chemical fertilization base. The spacing between rows was 0.50 m and the planting density was 20 seeds/m for radish and *brachiaria*, 30 seeds/m for sunn hemp and 60 seeds/m for millet. The base fertilization was carried out in the furrows at a dose of 215 kg/ha of the formula 08-28-16. At 90 days after planting, the cover crops were mowed with a mower mounted on the three points of the tractor for the evaluation of the physical attributes of the soil hello and later sand re carry out the planting of the corn crop.

Evaluation of the physical attributes of the soil

Density: Undisturbed soil sampling was carried out in each experimental unit before fallow and after cover crops was grown. Sampling was performed with an Uhland auger, with a 100 cm³ volumetric ring. In this study, the density was determined in 0.10 m layers along the profile up to the 0.40 m layer by the volumetric ring method (Donagema, 2011).

After collecting the samples, the volumetric rings were identified, sealed with porous fabric and fixed with rubber and plastic lids, placed in Styrofoam boxes and taken to the laboratory for analysis. Density was determined after porosity evaluations on the same undisturbed samples taken in the

experiment. The samples after saturation and suction on a tension table for the determination of macroporosity, microporosity and total porosity were placed in a forced ventilation oven at a temperature of 105°C until constant mass was obtained. After drying, the samples were weighed on a 0.01 g precision balance to obtain the dry mass of the soil and the density was calculated (Equation 1), with values expressed in g.cm^{-3}, discounting the ring mass, volumetric, porous fabric and rubber that fixed it.

Equation 1: $Ds = \dfrac{a}{b}$

Ds=Soil density (g.cm^{-3})

a=Mass of the dry sample at 105°C (g)

b=Volume of the volumetric ring (cm³)

Porosity: For porosity evaluation, the same undisturbed samples collected for density determination were used. Total porosity was determined by calculating the ratio between the density of the oven-dried soil and the particle density (Equation 2) determined by the volumetric flask method (Donagema, 2011). Particle density consists of determining the volume of alcohol needed to fill the capacity of a 50 mL volumetric flask containing 20 g of soil. In the calculation of the density of particles one has that:

Equation 2: $PT = \left(Dp - \dfrac{a}{50-b} \right)$

Dp=Particle density (g.cm^{-3})

a=Mass of the dry sample at 105°C (g)

b=Volume of alcohol spent (cm³)

After determining the density of particles and density of the dry soil, the total porosity is calculated in Equation 3.

Equation 3: $PT = \left(1 - \dfrac{Ds}{Dp} \right) 100$

PT=Total porosity percentage (cm³.cm-³)

Ds=Soil density (g.cm^{-3})

Dp= Particle density (g.cm^{-3})

The microporosity is defined by the volume of water that is removed in the micropores of the undisturbed samples (Equation 4) that are submitted to a suction of 6 kPa in the tension table (Donagema, 2011). The determination of the water mass of the micropores is obtained by weighing the mass of the sample after an equilibrium time of 24 h and is discounted from the dry soil mass. This gives the formula for calculating microporosity:

Equation 4: $Mi = \dfrac{(a-b)}{c}$

Mi= Microporosity (cm³.cm^{-3})

a=Mass of the sample-cylinder-fabric-rubber assembly after equilibrium at 6 kPa (g)

b=Dry soil mass at 105°C (g)

c=Volume of the volumetric ring (cm³)

Macroporosity, in turn, is given by the difference between total porosity and microporosity in Equation 5.

Equation 5: $Ma = (PT - Mi)$

Ma=Macroporosity (cm³.cm^{-3})

PT=Total porosity (cm³.cm^{-3})

Mi=Microporosity (cm³.cm^{-3})

Mechanical resistance of soil to penetration: To determine the RMSP before and after the cultivation of cover crops, an impact penetrometer model IAA/Planalsucar-Stolf, type 2 conical tips, with a diameter of 12.83 mm and a solid angle of 30°, standard plunger of 4 kg and height for vertical displacement of the plunger of 0.40 m (Asae, 1999). In the determination made before the cultivation of cover crops, three profiles were evaluated per experimental unit, in layers of 0.10 m to a depth of 0.60 m, to determine the RMSP and the average value in each layer was used to represent each parcel. All RMSP evaluations took place on the same day and on the side where the undisturbed soil samples were obtained to evaluate soil density and moisture.

The results obtained with the impact penetrometer, provided in "cm impact-1", were transformed into kgf cm-2, according to equation 1 (Stolf, 1991) and subsequently multiplied by the factor 0.098 to transform the mechanical strength of the soil to penetration in MPa (Equation 6).

Equation 6: $IC = \left(\dfrac{Mg+mg}{A} \right) + \left[\left(\dfrac{M}{M+m} \right) x \left(\dfrac{Mg \times h}{A+P} \right) \right] (1)$

CI=Cone index (kgf.cm-2)

Mg=Mass of piston weight (kgf)

mg=Mass of the penetrometer without the plunger (kgf)

A=Area of the base of the cone (cm²)

M=Mass of piston (kg)

m=Mass of the penetrometer without the plunger (kg)

h=Plunger drop height (cm)

P=Unit penetration caused by an impact (cm)

At the end of the establishment of the coverage plans, the verification of the RMSP was carried out again with the same methodology previously along the profile in layers of 0.10 m to a depth of 0.60 m. The evaluation was carried out with the same impact penetrometer used for the characterization prior to the installation of the experiment. Four profiles were evaluated for each subplot containing the cover crops on the different soil preparations, totaling 400 sampling points. All points were sampled on the same day and during the rainy season in which the soil moisture was completely homogeneous along the profile, without the possibility of any variation in the RMSP due to this, leading to erroneous interpretations of this physical attribute of the soil ground.

Statistical analysis

The data were submitted to the Levene, Jarque-Bera (Jarque, et al. 1980) and Generalized ESD (Rosner, 1983) tests to evaluate the conditions of homogeneity of variances, normality of residuals and presence of outliers, respectively. Data analysis of variance was performed, and the means were compared by the Student Newman-Keuls (SNK) test at 5% probability when there were significant differences found by the F-test. The statistical tests were performed using the SPEED Stat software (Carvalho, et al. 2017).

RESULTS AND DISCUSSION

Before the cultivation of cover crops, it was verified that the density was obtained from 1.02 g cm^{-3} to 1.05 g cm^{-3} in the layer from 0.10 m to 0.20 m and from 1.21 g cm^{-3} to 1.25 g cm^{-3} in the 0.20 m to 0.30 m layer. The RMSP values in the 0.20 m to 0.30 m layer are above the critical value of 2.5 MPa, being in the range of 2.46 MPa to 3.37 MPa (Davies, et al. 1991; Tardieu, 1994). Also for tillage with rotary hoe and no-tillage, compaction was observed in the layer from 0.10 m to 0.20 m, obtaining 2.63 MPa and 2.92 MPa, respectively (Table 1).

Such results are related to the penetration capacity of soil preparation equipment, where the rotary hoe penetrates only up to 0.10 m of depth and the other equipment can penetrate below this depth, forming a compacted layer at a depth of 0.20 m. In the no-tillage system, the verification of compaction in the layer from 0.10 m to 0.20 m is due to the influence of the passes of the tractor wheels over time without soil preparation.

The soil's mechanical resistance to penetration proved to be more sensitive than the soil density in the evaluation of a possible compaction. Note that the upper layer showed low DS and RMSP values, possibly due to the action of organic matter. Still, in general, these values were similar to those found in the layer below 0.40 m, which can be explained by the smaller effect of organs active organs of agricultural equipment used at greater depths. These results were also observed by (Gamero, et al. 1990). This conclusion can be taken from the homogeneity of humidity in which there was no significant difference between the evaluated layers, not interfering with the penetration of the penetrometer rod throughout the profile up to the last layer. It was observed that the cover crops decompacted the soil, considerably reducing all RMSP values (Table 2).

In the 0.10 m to 0.20 m layer, where values of 2.92 MPa for PD and 2.63 MPa for ER were previously observed, but after the cultivation of cover crops, values between 1.66 MPa to 1.91 MPa for these treatments, verifying an average reduction of 37.2%. In the 0.20 m to 0.30 m layer, previous RMSP values were between 3.37 MPa and 2.86 MPa. However, after the cultivation of cover crops, the SPMR was in the range of 1.66 MPa to 1.91 MPa for PD and 2.25 and 1.91 MPa for ER. This means an average reduction of 47.2% in PD and 27.3% in RE. There was no significant difference between treatments in the layers from 0.40 m to 0.50 m and 0.50 m to 0.60 m. There is no exact consensus on the critical level of RMSP (Betioli Júnior, et al. 2012) due to the dependence on moisture for its assessment, sampling time, collection day period (Peixoto, et al. 2019), soil type, management practices and type of penetrometer used (Alesso, et al. 2017). However, most results in the literature indicate root growth impediment from 2.5 MPa onwards. In the layer from 0.00 m to 0.10 m, although there was no statistical difference between the cover crops within each soil preparation, in the preparation with GA, the forage radish reduced 45.45% in density from 1.10 g cm^{-3} to 1, 05 g cm^{-3} (Table 3).

Table 1. Soil density (Ds), Soil Mechanical Resistance to Penetration (RMSP) and Soil moisture (U%), determined before the installation of cover crops, in different systems of primary soil preparation. Density, RMSP and moisture data after mechanized operations of AD (disc plough), GA (harrow to harrow values), ES (scarifier), ER (rotary hoe) and no PD (no-till).

Depth (m)	preparation systems					
	GA	ES	AD	PD	ER	CV (%)
	Ds (g cm-3)					
0.00-0.10	1.10 bA	1.09 cA	1.05 cA	1.08 bA	1.02 bA	4.17
0.10-0.20	1.23 aA	1.25 aA	1.24 aA	1.22 aA	1.21 aA	4.11
0.20-0.30	1.22 aA	1.22 abA	1.25 aA	1.22 aA	1.21 aA	3.51
0.30-0.40	1.20 aA	1.22 abA	1.22 aA	1.20 aA	1.17 aA	2.69
0.40-0.50	1.15 abA	1.18 abA	1.18 abA	1.17 abA	1.14 aA	2.86
0.50-0.60	1.16 abA	1.17 bcA	1.12 bcA	1.16 abA	1.15 aA	3.38
M	**RMSP (MPa)**					
0.00-0.10	0.83 cA	1.06 bA	0.72 cA	1.28 cA	0.83 bA	20.42
0.10-0.20	2.07 aba	2.24 abA	2.24 abA	2.92 abA	2.63 aA	19.63
0.20-0.30	2.47 aB	2.46 aB	2.63 aAB	3.37 aY	2.86 aAB	14.4
0.30-0.40	2.41 aA	2.41 aA	2.01 bA	2.92 abA	2.69 aA	19.07
0.40-0.50	1.96 abA	1.84 abA	1.96 bA	2.13 bcA	2.13 aA	14.95
0.50-0.60	1.73 bA	1.73 abA	1.73 bA	2.07 bcA	2.01 aA	18.92
M	**U%**					
0.00-0.10	32.82 aA	31.95 aA	31.72 aA	29.83 aA	30.91 aA	12.64
0.10-0.20	31.11 aA	30.88 aA	31.69 aA	31.24 aA	30.96 aA	7.51
0.20-0.30	31.48 aA	30.69 aA	31.33 aA	31.53 aA	30.76 aA	7.73
0.30-0.40	31.42 aA	31.68 aA	31.77 aA	31.98 aA	31.84 aA	7.44
0.40-0.50	33.62 aA	32.60 aA	33.22 aA	33.23 aA	33.02 aA	5.46
0.50-0.60	34.02 aA	33.75 aA	34.65 aA	33.48 aA	33.80 aA	4.95

Note: Uppercase letters in the row and lowercase letters in the column do not differ from each other by SNK to 5%.

Table 2. Soil mechanical resistance to Mpa penetration after planting the plants.

Portion	GA	ES	AD	PD	ER	*mm	CV%
Subplot	0.00 m to 0.10 m						25.14%
millet	1.07 Aa	1.41 Aab	1.58 Aa	1.32 Aa	1.32 Aa		
Brachiaria	1.32 Aa	1.32 Aab	1.49 Aa	1.41 Aa	1.49 Aa		4.95
Crotalaria	1.49 Aa	1.24 Ab	1.49 Aa	1.41 Aa	1.41 Aa		
fodder turnip	1.15 Aa	1.66 Aab	1.49 Aa	1.41 Aa	1.41 Aa		
scarifier	1.49 Aa	1.75 Aa	1.41 Aa	1.58 Aa	1.26 Aa		
mm							
	0.10 m to 0.20 m						12.42%
Brachiaria	1.66 Aa	1.75 Aab	1.75 Ab	1.83 Aa	1.83 Aa		
fodder turnip	1.91 ABa	1.99 Aa	1.66 Bb	1.75 ABa	1.83 ABa		
Crotalaria	1.83 Aa	1.49 Bb	1.83 Aab	1.83 Aa	1.66 Ba		
millet	1.66 Ba	1.66 Bb	2.04 Aa	1.91 ABa	1.66 Ba		
scarifier	1.66 Aa	1.75 Aab	1.66 Ab	1.75 Aa	1.83 Aa		
mm							
	0.20 m to 0.30 m						17.86%
Brachiaria	2.00	1.75	2.08	1.91	2.00	1.95 a	
fodder turnip	1.91	2.00	1.83	1.75	2.25	1.95 a	
Crotalaria	1.75	2.00	2.08	1.75	2.00	1.91 a	
millet	2.00	2.08	2.08	1.66	1.91	1.95 a	
scarifier	1.91	2.00	1.91	1.66	2.20	1.94 a	
mm	1.92 A	1.96 A	2.00 A	1.75 A	2.07 A		
	0.30 m to 0.40 m						19.67%
Brachiaria	1.66 Aa	1.66 Aa	1.58 Aa	1.58 Aab	2.00 aa		
fodder turnip	1.75 Aa	1.75 Aa	1.58 Aa	1.49 Aab	1.75 Aa		
Crotalaria	1.49 Aa	1.75 Aa	1.83 Aa	1.41 Ab	1.83 Aa		
millet	1.75 Aa	1.49 Aa	1.66 Aa	1.66 Aab	1.58 Aa		
scarifier	1.58 Aa	1.91 Aa	1.58 Aa	1.91 Aa	1.66 Aa		
mm							
	0.40 m to 0.50 m						24.88%
Brachiaria	1.58	1.49	1.15	1.24	1.49	1.39 a	
fodder turnip	1.15	1.49	1.24	1.24	1.41	1.31 a	
Crotalaria	1.24	1.32	1.24	1.07	1.58	1.29 a	
millet	1.49	1.41	1.49	1.41	1.32	1.42 a	
scarifier	1.32	1.24	1.32	1.24	1.26	1.28 a	
mm	1.36 A	1.39 A	1.29 A	1.24 A	1.41 A		
	0.50 m to 0.60 m						9.97%
Brachiaria	0.99	0.99	0.99	0.99	1.07	1.00 a	
fodder turnip	0.99	0.99	0.99	1.07	1.07	1.00 a	
Crotalaria	0.99	0.99	0.99	1.28	1.07	1.02 a	
millet	0.99	0.99	0.99	0.99	1.07	1.00 a	
scarifier	0.99	0.99	0.99	0.99	0.99	0.99 a	
mm	0.99 A	0.99 A	0.99 A	1.00 A	1.05 A		

Note : *mm=marginal means when there is no interaction between treatments. AD (disc plough), GA (harrow to harrow values), ES (scarifier), ER (rotary hoe) and no PD (no-tillage). Means followed by the same letter, uppercase in the line and lowercase in the column, do not differ from each other by the SNK test at 5%.

Table 3. Density (Ds), microporosity (micro), macroporosity (macro) and total porosity (PT) of the soil at a depth of 0.00 m to 0.10 m, determined after the installation of cover crops, in different primary tillage systems ground.

Portion	GA	AD	ER	PD	ES	*mm	CV%
Subplot	Ds(g/cm³)						5.72%
Brachiaria	1.05 Aa	1.07 Aa	1.07 Aa	1.07 Aa	1.01 Aa		
fodder turnip	1.02 Ba	1.10 Aa	1.05 ABa	1.07 ABa	1.07 ABa		
Crotalaria	1.10 Aa	1.05 Aa	1.08 Aa	1.08 Aa	1.04 Aa		
millet	1.09 Aa	1.04 Aa	1.06 Aa	1.06 Aa	1.08 Aa		
scarifier	1.08 Aa	1.08 Aa	1.05 Aa	1.05 Aa	1.06 Aa		
mm							
	micro (cm³/cm³)						18.08%
Brachiaria	0.46	0.50	0.48	0.51	0.46	0.48 a	
fodder turnip	0.46	0.47	0.46	0.46	0.45	0.46 a	
Crotalaria	0.48	0.43	0.45	0.44	0.42	0.44 a	
millet	0.48	0.46	0.45	0.47	0.47	0.46 a	
scarifier	0.48	0.47	0.46	0.47	0.47	0.47 a	
mm	0.47 A	0.46 A	0.46 A	0.47 A	0.45 A		
	macro (cm³/cm³)						4.76%
Brachiaria	0.16 Aa	0.11 Aa	0.12 Aa	0.09 Aa	0.21 Aa		
fodder turnip	0.20 Aa	0.10 Aa	0.17 Aa	0.14 Aa	0.15 Aa		
Crotalaria	0.10 Aa	0.19 ABa	0.15 ABa	0.11 ABa	0.22 ABa		
millet	0.10 Aa	0.18 Aa	0.19 Aa	0.15 Aa	0.12 Aa		
scarifier	0.12 Aa	0.13 Aa	0.20 Aa	0.15 Aa	0.14 Aa		
mm							
	EN (cm³/cm³)						2.65%
Brachiaria	0.62 Aa	0.61 Aa	0.60 Aa	0.60 Aa	0.67 Aa		
fodder turnip	0.66 Aa	0.57 Ba	0.63 ABa	0.60 ABa	0.60 ABa		
Crotalaria	0.57 Aa	0.62 Aa	0.60 Aa	0.55 Aa	0.64 Aa		
millet	0.57 Aa	0.64 Aa	0.64 Aa	0.62 Aa	0.59 Aa		
scarifier	0.60 Aa	0.60 Aa	0.66 Aa	0.62 Aa	0.61 Aa		
mm							

Note: *mm=marginal means when there is no interaction between treatments.
AD (disc plough), GA (harrow to harrow values), ES (scarifier), ER (rotary hoe) and no PD (no-tillage). Means followed by the same letter, uppercase in the row and lowercase in the column, do not differ from each other by the SNK test at 5% error probability.

In the most superficial layer of the soil, there was no interaction between treatments for microporosity, although such values are within the ideal considering the critical values, as pointed out (Michelon, et al. 2009). Regarding the total porosity, there was no difference between the cover crops; however the treatment with GA and forage radish had the highest PT, reaching 0.66 cm³/cm³. The ground cover retains its structure and the removal of this cover results in an increase in density (Jat, et al. 2017). Studying wheat cultivation in a dystrophic Red Latosol with 50% clay found a productivity reduction of 18% where the density was 1.62 g cm^{-3} (Silva, 2003). For these experimental conditions and for the same type of soil, the highest density was 1.10 g cm^{-3}.

According to (Fonseca, et al. 2007), the density is not influenced by soil moisture and the critical value is 1.40 g cm^{-3}, where values above this limit the development of the plant's root system. (Reinert, et al. 2001) pointed out that for a soil with 55% to 20% the critical value is 1.55 g cm^{-3}. In addition, a high density also negatively influences soil infiltration and the transport of water and gases (Fonseca, et al. 2007). As for macroporosity, considering that values lower than the critical value of 0.10 dm dm-1 (Reinert, et al. 2001; Vomocil, et al. 1966) implies the lack of oxygenation of the roots, the results are within the ideal. For the experiment in question, the

macroporosity was in the range of 0.10 cm³/cm³ to 0.22 cm³/cm³, being ideal for the oxygenation of the plants. Cover crops also reduced soil density in the 0.10 m to 0.20 m layer (Table 4).

In the layer of 0.10 m to 0.20 m, values between 1.05 g cm^{-3} and 1.18 g cm^{-3} were observed with the conduction of the cover plants and between 1.21 g cm^{-3} and 1.25 g cm^{-3} before installation of the experiment with these plants. This indicates an average reduction of 9.75%. There was no difference in soil microporosity for all treatments. The macroporosity was higher with the plow harrow and lower with the scarifier (Souza, et al. 2005).

In the layer from 0.20 m to 0.30 m there was interaction between treatments in all attributes evaluated (Table 5).

The harrow obtained the best density values in two types of soil cover. In the cover with millet the density was 1 g cm^{-3} and in the forage radish it was 1.05 g cm^{-3}. For this preparation, millet reduced 18% and forage radish 14% in relation to the condition prior to their cultivation. The positive influence of grasses on soil structuring has been demonstrated in many studies (Rashid, et al. 2016; Naresh, et al. 2017). Millet has vigorous and abundant roots, providing a good effect in this aspect (Passot, et al. 2016). The lowest microporosity was found in the PD and scarifier without ground cover.

Compaction is usually more easily observed in the layer between 0.20 m and 0.30 m, due to the action of organs active parts of the equipment being regulated to act up to a depth of 0.20 m during conventional preparation, over several years of cultivation, resulting in the so-called "harrow foot", "plow foot", or "sill". The increase in microporosity concomitantly with the reduction in macroporosity is characteristic of probable compaction (Fonseca, et al. 2007). As there was no evidence of this behavior, there was no compression. In addition, observing the values prior to the installation of the experiment, the cover crops promoted a decrease in soil density, showing to be a good alternative for the improvement of this attribute. In the layer from 0.30 m to 0.40 m there were also significant reductions in soil density with the use of cover crops, mainly in the preparations with harrow and scarifier (Table 6).

Table 4. Density (Ds), microporosity (micro), macroporosity (macro) and total porosity (PT) of the soil at a depth of 0.10 m to 0.20 m, determined after the installation of cover crops, in different primary tillage systems ground.

Portion	GA	AD	ER	PD	ES	*mm	CV%
Subplot	Ds (g/cm³)						3.87%
Brachiaria	1.05 Aa	1.06 Ab	1.08 Aa	1.12 Aa	1.10 Ab		
fodder turnip	1.07 Ba	1.12 Aa	1.13 Aa	1.12 Aa	1.18 Aa		
Crotalaria	1.10 Aa	1.16 Aa	1.14 Aa	1.12 Aa	1.13 Aab		
millet	1.07 Ba	1.11 ABab	1.14 Aa	1.12 Aa	1.13 Aab		
scarifier	1.07 Aa	1.13 Aa	1.13 Aa	1.12 Aa	1.12 Ab		
mm							
	micro (cm³/cm³)						4.13%
Brachiaria	0.41	0.45	0.44	0.47	0.40	0.43 a	
fodder turnip	0.37	0.46	0.45	0.44	0.45	0.43 a	
Crotalaria	0.40	0.43	0.46	0.46	0.46	0.44 a	
millet	0.44	0.41	0.48	0.43	0.45	0.44 a	
scarifier	0.43	0.44	0.48	0.50	0.46	0.48 a	
mm	0.41 A	0.44 A	0.46 A	0.48 A	0.44 A		
	macro (cm³/cm³)						2.82%
Brachiaria	0.13 Aa	0.06 Aa	0.08 Aa	0.09 Aa	0.06 Ba		
fodder turnip	0.19 Aa	0.13 Ba	0.09 Ba	0.11 Ba	0.12 Ba		
Crotalaria	0.18 Aa	0.11 Ba	0.10 Ba	0.13 ABa	0.11 Ba		
millet	0.17 Aa	0.11 ABa	0.11 ABa	0.09 Ba	0.17 Aa		
scarifier	0.07 Ab	0.10 Aa	0.10 Aa	0.07 Aa	0.18 Aa		
mm							
	EN (cm³/cm³)						1.91%
Brachiaria	0.54 Aa	0.51 Aa	0.52 Aa	0.56 Aa	0.46 Aa		
fodder turnip	0.56 Aa	0.59 Bb	0.54 Ba	0.55 Ba	0.57 Bb		
Crotalaria	0.58 Aa	0.54 Ab	0.56 Aa	0.59 Aa	0.57 Aab		
millet	0.61 Aa	0.52 ABab	0.59 Ba	0.52 Ba	0.62 Bab		
scarifier	0.50 Aa	0.54 Ab	0.58 Aa	0.57 Aa	0.64 Aa		
mm							

Note: *mm=marginal means when there is no interaction between treatments.
AD (disc plough), GA (harrow to harrow values), ES (scarifier), ER (rotary hoe) and no PD (no-tillage). Means followed by the same letter, uppercase in the row and lowercase in the column, do not differ from each other by the SNK test at 5% error probability.

Table 5. Density (Ds), microporosity (micro), macroporosity (macro) and total porosity (PT) of the soil at a depth of 0.20 m to 0.30 m, determined after the installation of cover crops, in different primary tillage systems ground.

Portion	GA	AD	ER	PD	ES	*mm	CV%
Subplot	Ds (g/cm³)						4.06%
Brachiaria	1.04 Ba	1.07 Bb	1.14 Aa	1.12 Aa	1.13 Aab		
fodder turnip	1.05 Ca	1.13 ABa	1.13 ABa	1.08 Ba	1.15 Aab		
Crotalaria	1.04 Ba	1.11 Aab	1.10 Aa	1.11 Aa	1.11 Aab		
millet	1.00 Ca	1.09 Babe	1.13 ABa	1.09 Ba	1.17 Aa		
scarifier	1.05 Ba	1.14 Aa	1.13 Aa	1.10 Aa	1.11 Ab		
mm							
	micro (cm³/cm³)						5.87%
Brachiaria	0.42 Aa	0.40 Aa	0.42 Aa	0.48 Aa	0.43 Aa		
fodder turnip	0.41 Aa	0.41 Aa	0.42 Aa	0.42 Aa	0.45 Aa		
Crotalaria	0.40 Aa	0.40 Aa	0.43 Aa	0.47 Aa	0.48 Aa		
millet	0.46 Aa	0.42 Aa	0.44 Aa	0.45 Aa	0.42 Aa		
scarifier	0.42 Aa	0.41 Aa	0.44 Aa	0.32 Bb	0.41 Aa		
mm							
	macro (cm³/cm³)						5.56%
Brachiaria	0.19 Aa	0.24 Aa	0.19 Aa	0.08 Bb	0.06 Ba		
fodder turnip	0.24 Aa	0.24 Aa	0.18 Aa	0.15 Aa	0.13 Bab		
Crotalaria	0.23 Aa	0.24 Aa	0.14 Ba	0.11 Bab	0.08 Ba		
millet	0.16 Aa	0.24 Aa	0.08 Ba	0.07 Bab	0.14 Bab		
scarifier	0.21 Aa	0.24 Aa	0.13 Ba	0.23 Aa	0.18 Aa		
mm							
	EN (cm³/cm³)						1.98%
Brachiaria	0.61 Aa	0.64 Aa	0.61 Ba	0.56 Ba	0.49 Bab		
fodder turnip	0.65 Aa	0.65 Aa	0.60 BC	0.57 Ba	0.58 Aab		
Crotalaria	0.63 Aa	0.64 Aa	0.57 Ba	0.58 Ba	0.56 Bab		
millet	0.62 Aa	0.66 Aa	0.57 Ba	0.52 Ba	0.56 Bb		
scarifier	0.63 Aa	0.65 Aa	0.57 Ba	0.55 Ba	0.56 Ba		
mm							

Note: *mm= marginal means when there is no interaction between treatments.
AD (disc plough), GA (harrow to harrow values), ES (scarifier), ER (rotary hoe) and no PD (no-tillage). Means followed by the same letter, uppercase in the row and lowercase in the column, do not differ from each other by the SNK test at 5% error probability.

Table 6. Density (Ds), microporosity (micro), macroporosity (macro) and total porosity (PT) of the soil at a depth of 0.30 m to 0.40 m, determined after the installation of cover crops, in different primary tillage.

Portion	GA	AD	ER	PD	ES	*mm	CV%
Subplot	Ds (g/cm³)						5.08%
Brachiaria	1.05 Aa	1.06 Ab	1.08 Aa	1.12 Aa	1.10 Ab		
fodder turnip	1.07 Ba	1.12 Aa	1.13 Aa	1.12 Aa	1.18 Aa		
Crotalaria	1.10 Aa	1.16 Aa	1.14 Aa	1.12 Aa	1.13 Aab		
millet	1.07 Ba	1.11 ABab	1.14 Aa	1.12 Aa	1.13 Aab		
scarifier	1.07 Aa	1.13 Aa	1.13 Aa	1.12 Aa	1.12 Ab		
mm							
	micro (cm³/cm³)						18.21%
Brachiaria	0.41	0.42	0.42	0.43	0.41	0.42 a	
fodder turnip	0.45	0.44	0.43	0.43	0.41	0.43 a	
Crotalaria	0.40	0.44	0.42	0.43	0.41	0.42 a	
millet	0.46	0.43	0.44	0.42	0.43	0.44 a	
scarifier	0.42	0.48	0.44	0.43	0.43	0.44 a	
mm	0.43 A	0.44 A	0.43 A	0.43 A	0.42 A		
	macro (cm³/cm³)						3.86%
Brachiaria	0.23 Aab	0.22 Aa	0.18 Aa	0.17 Aa	0.18 Aa		

					mm
fodder turnip	0.18 Ab	0.11 Bb	0.10 Bb	0.16 Aa	0.14 Aa
Crotalaria	0.28 Aa	0.12 Bb	0.15 Ba	0.16 Aa	0.10 Ba
millet	0.23 Aab	0.10 Bb	0.15 Ba	0.13 Ba	0.16 ABa
scarifier	0.23 Aab	0.10 Bb	0.15 Bb	0.13 Ba	0.16 ABa
mm					
EN (cm³/cm³)					2.41%
Brachiaria	0.64 Aa	0.64 ab	0.60 Aa	0.60 Aa	0.59 Aab
fodder turnip	0.63 Aa	0.55 Bb	0.53 Ba	0.59 ABa	0.55 Bab
Crotalaria	0.68 Aa	0.56 Bb	0.57 Ba	0.59 Ba	0.51 Cb
millet	0.69 Aa	0.53 BCb	0.59 Ba	0.55 Ba	0.59 Bab
scarifier	0.65 Aa	0.58 Bab	0.59 Ba	0.56 Ba	0.59 Bab
mm					

Note: *mm= marginal means when there is no interaction between treatments.
AD (disc plough), GA (harrow to harrow values), ES (scarifier), ER (rotary hoe) and no PD (no-tillage). Means followed by the same letter, uppercase in the row and lowercase in the column, do not differ from each other by the SNK test at 5% error probability.

The authors of (Gal, et al. 2007; D'Haene, et al. 2008) found that the effects of soil management and its cover are limited to a depth of 20 cm. However, the results of this work showed a reduction of 3.3% of the forage radish in the preparation with a scarifier and 12.5% of the *brachiaria* in the preparation with a harrow in the layer below the depth of 0.20 m. Mechanical interventions, such as subsoiling or scarification, are not always efficient to mitigate soil compaction, as they usually have a temporary effect, which requires frequent repetitions (Tim Chamen, et al. 2014). However, cover crops are a good alternative for decompacting the soil, obtaining good results in the physical attributes of the soil (Severiano, et al. 2010; Jimenez, et al. 2008). Cover crops have advantages over mechanized management systems as they promote the breakdown of soil structures while cover crops favor the production of root exudates, that are agents of aggregation of soil particles and also improves porosity at the expense of root growth (Rosa, 2013).

CONCLUSION

In general, the cover crops *brachiaria*, forage radish, crotalaria and millet provided improvements in the physical attributes of the soil in relation to the conditions prior to its implementation. There was a decrease in RMSP in all treatments after growing cover crops within the different soil preparations. In general, the forage radish was the species that most stood out in the positive results of improvement for the physical attributes of the soil.

REFERENCES

1. Aita C, Giacomoni SJ (2003). Decomposition and nitrogen release from cultural residues of single and intercropped ground cover plants. Rev Brazil Science Solo. 27(4): 601-612.

2. Alesso CA, Masola MJ, Carrizo ME, Imhoff SC (2017). Estimating sample size of soil cone index profiles by bootstrapping. Rev Brazil Science Solo. 41.

3. Ambrosano EJ, Rossi F, Guirado N, Schammass EA, Muraoka T, Trivelin PCO, Ambrosano GMB (2014). Green manuring in organic agriculture. IN: Lima Filho, Oscar F de; Ambrosano, Edmilson J; Rossi, Fabricio; Carlos, João A.D (edn). Green manure and cover crops in Brazil. Fundamentals and Practice. Brasília, DF: Embrapa. p: 507.

4. ASAE. American Society of Agricultural Engineers (1999). Soil cone penetrometer. In: ASAE Standards 1999: standards practices engineering data. (46th edn). pp: 834-835.

5. Baptista PHD, Almeida DE LPG, Tavares UE, Nascimento VN, Sarmento RM (2017). Spatial variability of soil physical attributes under mechanized harvesting of buffel grass in agreste region of Pernambuco. Eng in Agr. 25(4): 307-317.

6. Betioli Junior E, Moreira WH, Tormena CA, Ferreira CJB, Silva Alvaro P, Giarola NFB (2012). Optimal water range and degree of compaction of a Red Latosol after 30 years under no-tillage. Rev Brazil Science Solo. 36(3): 971-982.

7. Bettiol ACT (2014). Effects of cover crops on soil chemical attributes. Faculty of Agricultural and Veterinary Sciences, Universidade Estadual Paulista, Jaboticabal. Dissertation (Master's).

8. Camargo OA, Alleoni LRF (1997). Soil compaction and plant development. Piracicaba: Esalq. p: 132.

9. Carvalho AMX, Mendes FQ (2017). Speed Stat: a minimalist and intuitive spreadsheet program for classical experimental statistics. Proceedings of the 62nd Annual Meeting of the Brazilian Region of the International Society of Biometrics.

10. Carvalho MA, Ruiz HA, Costa LM, Passos RR, Araujo CAS (2014). Granulometric composition, density and porosity of aggregates in Red Latosol under two soil covers. Rev Bras Eng Agríc Ambient. 18(10): 1010-1016.

11. Colombo GA, Lopes MBS, Dotto MC, Campestrini R, DE Oliveira Lima S (2017). Physical attributes of a dystrophic red-yellow latosol under different management systems in the cerrado of Tocantins. Digital Field. 12(1).

12. Cunha EQ, Stone LF, Moreira JAA, Ferreira EPB; Didonet AD, Leandro WM (2011). Soil tillage systems and cover crops in the organic production of beans and corn: I- physical attributes of the soil. Rev Bras Cienc Solo. 35(2): 589-602.

13. Dhaene K, Vermang J, Cornelis WM, Leroy BLM, Schiettecatte W, Deneve S, Gabriels D, et al (2008). Reduced tillage effects on physical properties of silt loam soils growing root crops. Soil Tillage Res. 99(2): 279-290.

14. Davies WJ, Zhang J (1991). Root signals and the regulation of growth and development of plants in drying soil. Annu Rev Plant Physiol Plant Mol Biol. 42:55-76.

15. Dias MJ, Alves SF, Fialho ER, Gomes DO (2015). Probability of occurrence of chemical attributes in an oxisol under no-tillage. Caatinga Magazine. 28(4).

16. Donagema GK, Fields DVB, Calderano SB, Teixeira WG; Viana JHM (2011). Soil analysis methods manual. (2nd edn). Rio de Janeiro: Embrapa Solos. p: 230.

17. EMBRAPA (2017). Hedge Plants: What is it?

18. Favarato LF, Souza JL, Galvão, JCC, De Souza CM; Guarçoni RC (2015). Soil chemical attributes on different cover crops in the organic no-tillage system. Braz J of Sust Agr. 5(2).

19. Fenner PT (2008). Soil compaction. In: Machado CC (edn). Forest Harvest. (2nd edn). Viçosa: UFV. pp: 388-409.

20. Fiorin JE (1999). Soil fertility recovery plants. In: Course on basic aspects of soil fertility and microbiology under no-tillage. Passo Fundo: Aldeia Norte. p: 39-55.

21. Fonseca GC, Carneiro MAC; Costa AR, Oliveira GC, Balbino LC (2007). Physical, chemical and biological attributes of cerrado dystrophic red latosol under two crop rotations. Trop Agriculture J. 37(1): 22-30.

22. Gal A, Vyn TJ, Micheli E, Kladivko EJ, Mcfee WW (2007). Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths. Soil Tillage Res. 96(1-2): 42-51.

23. Gamero CA, Benez SH (1990). Evaluation of soil condition after tillage operation. In: Silveira GM IV Study cycle on agricultural mechanization. Jundiaí: Fundacao Cargill. p.12-21.

24. Guedes Filho O, Silva AP, Giarola NFB, Tormena CA (2013). Structural properties of the soil seedbed submitted to mechanical and biological chiseling under no-tilage. Geoderma. 204-205: 94-101.

25. Jarque CM, Bera AK (1980). Efficient tests for normality, homoscedasticity and serial independence of regression residuals. Economics Letters. 6(3): 255-259.

26. Jat HS, Datta A, Sharma PC, Kumar V, Yadav AK, Choudhary M, Choudhary V, et al. (2017). Assessing soil properties and nutrient availability under conservation agriculture practices in a reclaimed sodic soil in cereal-based systems of North-West India. Arch Acker Pflanzenbau Bodenkd. 64(4).

27. Jimenez RL, Goncalves WG, Araújo Filho JV, Assis RL, Pires FR, Silva GP (2008). Growth of cover crops under different levels of compaction in a Red Latosol. Rev Bras Engineer Agricultural Environment. 12(2): 116-121.

28. Keller T (2012). 41st Brazilian Congress of Agricultural Engineering and 10th Latin American and Caribbean Congress of Agricultural Engineering. London.

29. Longo RM, Ribeiro AI, Melo WJ (2011). Recovery of degraded soils in cassiterite mineral exploration: microbial biomass and dehydrogenase activity. Bragantia. 70(1):132-138.

30. Michelon Cleudson J, Carlesso Reimar, Petry Mirta T, Melo Giane L, Renato B Spohr, Juliano G de Andrade (2009). Physical quality of irrigated soils in some regions of Central Brazil. Rev Bras Engineer Agricultural Environment. 13(1): 39-45.

31. Oliveira DMS, Lima RP, Verburg EEJ (2015). Soil physical quality under different swine manure management and application systems. Rev Bras Engineer Agri Env. 19(3): 280-285.

32. Passot S, Gnacko F, Moukouanga D, Lucas M, Guyomarch S, Ortega BM, Atkinson JA, et al. (2016). Characterization of pearl millet root architecture and anatomy reveals three types of lateral roots. Front Plant Sci. 7:829.

33. Peixoto DS, Silva BM, Oliveira GC, Moreira SG, Silva F, Curi N (2019). A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. Soil Tillage Res. 194:104307.

34. Rashid MI, MujaWar LH, Shahzad T, Almeelbi T, Ismail IMI, Oves M (2016). Bacteria and fungi can contribute to nutrients bioavailability and aggregate formation in degraded soils. Microb Res. 183(3):26-41.

35. Reinert DJ, Reichert JM, Silva VR (2001). Physical properties of soils in an irrigated no-tillage system. In: Carlesso R, Petry MT, Rosa GM, Ceretta CA (edn). Sprinkler irrigation in Rio Grande do Sul. Santa Maria: UFSM. p: 165.

36. Rosa HA (2013). Structuring potential of cover species in a clayey Latosol and its effects on crambe grain and oil yield. Dissertation (Master's in Energy in Agriculture) State University of Western Paraná, Cascavel. p: 28.

37. Rosner B (1983). Percentage points for a generalized ESD many-outlier procedure. Technometrics, 25(2): 165-172.

38. Santos FS, Luiz Antonio Zanão Junior, Deonir Secco, Patrícia Pereira Dias, Fabíola Tomassoni, Natália Pereira (2014). The use of cover crops in the recovery of compacted soils. Acta Iguazu. 3(3): 82-91.

39. Sene M, Vepraskas MJ, Naderman GC, Denton, HP (1985). Relationships of soil texture and structure to corn yield response to subsoiling. Soil Sci Society of America J. 49: 422-427.

40. Severiano EC, Oliveira GC, Dias Junior MS, Costa KAP, Castro MB, Magalhães EN (2010). Uncompaction potential of an Argisol promoted by Tifton 85 grass. Rev Bras Engineer Agricultural Environment. 14(1): 39-45.

41. Silva, VG DA (2020). Fluxes of nitrous oxide, mineral N and carbon fractions in soil cultivated with corn in succession to cover crops. Brasília: Faculty of Agronomy and Veterinary Medicine, University of Brasília. Doctoral thesis. p: 123.

42. Silva VR (2003). Physical and water properties of soils under different compaction states. Santa Maria: UFSM. Doctoral Thesis. p: 171.

43. Souza ED, Carneiro MAC, Paulino HB (2005). Physical attributes of a quartzarenic neosol and a red latosol under different management systems. Agropec Bras. 40(11): 1135-1139.

44. Stolf R (1991). Theory and experimental test of formulas for transforming impact penetrometer data into soil strength. Brazilian J Soil Science. 15(2): 229-35.

45. Tardieu F (1994). Growth and functioning of roots and of root systems subjected to soil compaction: Towards a system with multiple signaling? Soil and Tillage Res. 30(2-4): 217-243.

46. Tavares UE, Montenegro AAA, Rolim MM, Silva JSS, Vincent TFS, Andrade CWL (2014). Spatial variability of penetration resistance and soil moisture in Fluvic Neosol. Water Resources and Irrigation Manag. 3(2): 79-89.

47. Tim Chamen WC, Moxey AP, Towers W, Balana B, Hallett PD (2014). Mitigating arable soil compaction: A review and analysis of available cost and benefit data. Soil Tillage Res. 146: 10-25.

48. Vomocil JA, Flocker WJ (1961). Effect of soil compaction on storage and movement of soil, air and water. Trans ASABE. 4: 242-246.