Soybean off-season management practices: impacts on physical and chemical soil properties and crop yield[1]

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ABSTRACT

Off-season crops diversification and gypsum under minimal tillage can improve soil fertility and reduce soil compaction. The objective of this work was to evaluate changes on soil physical and chemical properties and soybean yield grown over off-season crops in combination with gypsum and chiseling. Treatments consisted of gypsum application (0 and 3,5 t ha^{-1}), two tillage systems (no tillage [NT] and minimal tillage [MT] with chiseling) and four soybean off-season crop successions: maize (M); maize+brachiaria (M+B); millet+crotalaria/wheat (Mi+C/W) and maize+black oats (M+O). Gypsum application reduced resistance to penetration (PR) by 12% in M+B system (1.12 kPa), when compared to the same treatment without gypsum. Gypsum increased surface soil Ca contents, mainly in M/O (from 3.81 to 5.66 cmol$_c$ dm^{-3}). MT decreased PR in M+B, Mi+C/W and M/O, from 1.28 kPa in NT to 0.98 kPa. MT lowered total soil porosity from 66.9 to 63.1%, but reduced Ca contents compared to NT. Cultivation of crotalaria in the off-season reduced Al levels on the soil surface and grasses increased K and P in depth. Despite the improvements in the soil properties, crop rotations, chiseling and gypsum were not able to increase soybean yields in this 18-month experiment, averaging 3904 kg ha^{-1}.

Keywords: chiseling; cover crops; gypsum application; soil fertility; *Glycine max*.

INTRODUCTION

No-tillage (NT) is considered one of the most important soil management systems for the sustainability of Brazilian agriculture (Sá *et al.*, 2017). The absence of soil disturbance in this system benefits soil aggregation, stabilizing organic carbon within aggregates and improving nutrient cycling (Tiecher *et al.*, 2017). However, in soils managed for a long time under NT there is a trend towards higher soil surface compaction (Sales *et al.*, 2016), due to the stability of the aggregates promoted by the action of the roots and the intense machine traffic, resulting in increased soil density and a reduction in macro and microporosity, which may prevent the productive potential of the crops. Also, soils with high clay content and low soil organic matter (SOM) can accentuate the problems of compaction, leading to practices like mechanical chiseling (Secco *et al.*, 2009) under minimal tillage (MT).

The use of chisel plow has been indicated as an alternative to break compacted soil layers in NT acting less aggressively than conventional tillage (Moraes *et al.*, 2016), which promotes intense breakdown and consequently spraying of the soil particles. This practice is generally employed to break through compacted layers, increasing porosity, reducing bulk density and mechanical resistance to root penetration, and increasing the infiltration rate and

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water storage capacity in the soil (Camara & Klein, 2005; Reichert *et al.*, 2009). Although the effects of chisel plow persist for a short period of time (Moraes *et al.*, 2016), their frequent use can reduce soil cover, leading to SOM loss (Raphael *et al.*, 2016). In this way, in the search of a more durable and sustainable option, the use of cover crops has appeared to reduce soil compaction and to promote increases in crop yield (Nicoloso *et al.*, 2008; Blanco-Canqui *et al.*, 2015). Additionally, the management of different crop species with vigorous root system and the addition of adequate amounts of residues, may increase SOM (Locatelli *et al.*, 2020), improve soil physical, chemical and biological quality, promote protection against erosion and maintain the soil moisture (Balota *et al.*, 2014; Frasier *et al.*, 2016). However, in fallow areas during soybean off-season, bare soil can present a reduced soil physical quality and prevent increases in SOM (Rossetti *et al.*, 2012).

Off-season crops can be used as an alternative to promote soil cover and thus, increase the nutrient cycling (Tiecher *et al.*, 2017). The commonly used succession between soybean and maize (second crop) characterized by the low amount of residue produced during a year, can be replaced by introducing cover crops during the off-season period. Therefore, crop rotation in NT has shown positive results in crop yields improvements, as in the case of soybean (Reis *et al.*, 2014) considered the major grain crop cultivated in Brazil NT areas. However, studies related to the use of subtropical cover crops during the soybean off-season and their effects on soil physical and chemical properties are still lacking.

Another management that can be used for improving physical and chemical soil quality, inclusive in deeper layers in NT system, is the application of gypsum ($CaSO_4.2H_2O$), which can dissociate in soil, releasing calcium (Ca) and sulfate (SO_4), or even form chemical complexes with other cations and anions, such as aluminum (Al), allowing this element to remain in less toxic forms in the soil (Caires *et al.*, 1999). This effect can be attributed to several mechanisms, such as the formation of an ionic pair with $AlSO_4^+$ or Al complexation (Van Raij, 2008). The gypsum application can also reduce soil compaction through a flocculating effect, as verified by Borges *et al.* (1997a; 1997b). The Ca and S input also increases cations in soil solution, thus promoting better conditions for root growth within soil profile (Pauletti *et al.*, 2014; Nora *et al.*, 2017). Because of the several positive effects of the gypsum application, Pauletti *et al.* (2014) and Tiecher *et al.* (2018) concluded in their studies that the gypsum can be used to enhance soybean yield.

The hypothesis of this study is that the use of off-season crops combined with the application of gypsum under a no-tillage system can increase soybean yields through the improvement in soil chemical properties, caused by the increase in nutrient availability, and reduction in exchangeable Al levels as a result of gypsum movement in the soil profile. Indirectly, this management can improve soil physical properties creating an environment favorable to root development, without the need for a minimum tillage (chiseling) to accelerate gypsum movement in the profile. Therefore, this study aimed to evaluate the effects of different off-season crops, chiseling and gypsum application during soybean off-season on the physical and chemical properties of the soil, and the outcome on soybean yield.

MATERIAL AND METHODS

The experiment was conducted at Foundation Assis Gurgacz University Center School Farm, located at Cascavel, Paraná State, Brazil, latitude 24° 56’ 15.85” south and longitude 53° 30’ 51.55” west, at an altitude of 698 m. The soil was classified as dystric Ferrasol, and the climate of the region according to Köppen is a subtropical Cfa, with monthly average temperatures between 20.0 °C (February) and 13.8 °C (June), and annual mean precipitation is 1822 mm. The area has been conducted in NT with the succession of soybean (spring/summer) and second crop maize (autumn/winter) since 2001 (Figure 1), with amounts of fertilization and liming unknown.

In August of 2013 (Figure 1) samples were collected to characterize the study area, at 0.0-0.1 m, 0.1-0.2 m and 0.2-0.3 m layers (Table 1). For physical characterization, soil samples were collected in volumetric cylinders to determine soil density, soil porosity (Donagema *et al.*, 2011) and soil penetration resistance (PR). The chemical variables measured were: pH ($CaCl_2$); Organic matter (Walkey-Black); Ca^{2+}, Mg^{2+}, Al^{3+} (KCl 1 mol L^{-1}); K^+ and P (Mehlich-1); following standard methodology (Donagema *et al.*, 2011).

The experimental design was a factorial randomized blocks (2×2×4) with three replicates. The factors were: i) application of two rates of gypsum (G): 0 and 3500 kg ha^{-1}; ii) two tillage systems (TS): no-tillage (NT) and minimal tillage (MT) with use of chiseling; and iii) four soybean off-season crop systems (CS): maize (M), maize+brachiaria (M+B), millet+crotalaria/wheat (Mi+C/W) and maize/oats (M/O), where soybean is cultivated as the main crop in spring/summer, while the other crops are cultivated in the off-season. In the system M+B, maize and brachiaria were intercropped as well as millet and crotalaria in the system Mi+C/T.

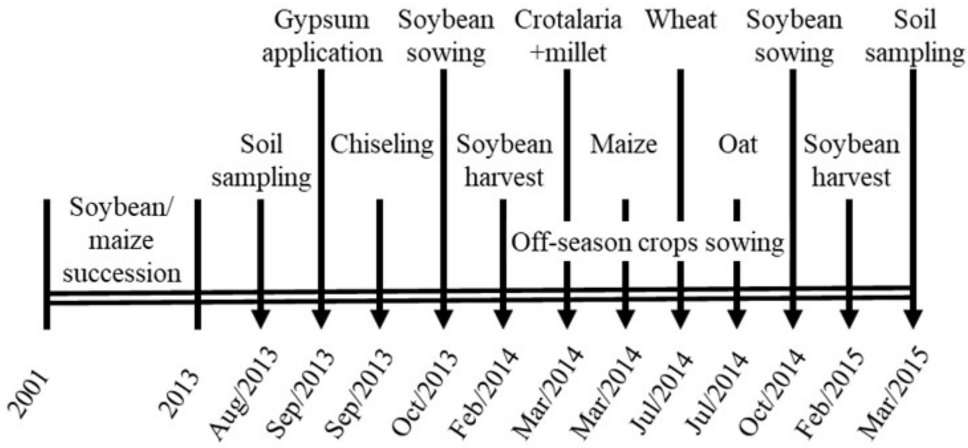

Figure 1: Time-line regarding the application of gypsum, chiseling and sowing of off-season crops, as well as soil sampling times (characterization of the area and study of the effects of treatments), sowing and harvesting of soybean (*Glycine max*) during the period of conduction of the experiment. Cascavel, PR, Brazil.

The gypsum rate was calculated based on the clay content of the soil (Sousa & Lobato, 1996), with manual application at the end of September 2013 (Figure 1). For the mechanical chiseling in MT, a chisel plow with seven iron rods, at a distance of 0.3 m from each other to a depth of 0.3 m, was coupled to the tractor. The rods in the chisel plow were strategically distributed on an iron frame (chassis), each rod having a tip at its base that can be adjusted in terms of angle of attack and inclination to not cause soil inversion. The chiseling was carried out in September 2013 after the application of the gypsum and before soybean sowing (Figure 1). Off-season crops were sown in the period from March to July 2014 (Figure 1) according to the recommended sowing period for each crop in the region. All off-season treatments were fertilized with the same rate, 300 kg ha^{-1} de 0-20-20 and 100 kg ha^{-1} of N about 45 days after plant emergence.

Soybean was sown in October 2014 (Figure 1) to evaluate the effects of the treatments on crop yield. The cultivar used was the NS 4823 RR in a row spacing of 0.45 m and fertilized with 350 kg ha^{-1} of NPK 0-20-20. The control of pests, diseases and weeds was carried out according to the technical recommendation for soybeans. Grain yield was determined in February 2015 (Figure 1) by harvesting the plants in the plot area (4.5 m^2), and the data were corrected to 13% of grain moisture.

Soil samples were taken in March 2015 (Figure 1), 18 months after gypsum and chiseling, and 12 months after off-season crops implantation. Composite samples (n = 8) were taken in the soybean inter-row, at 0.0-0.1, 0.1-0.2 and 0.2-0.3 m layers. Volumetric cylinders were collected to determine soil penetration resistance (PR) in the laboratory using a bench penetrometer. The samples were prepared by removing the soil thick from its extremities and transferred to a specific support for reading on the penetrometer. This model of penetrometer is equipped with a 12.56 mm^2 cone, 60 ° angle and 0.05 m high shank. The stem was introduced into the center of undisturbed soil samples at a constant velocity of 0.00155 m s^{-1}, and PR data expressed in kgf was automatically collected and later transformed into kPa (Figueiredo *et al.*, 2011). Concomitantly, rings were collected to determine soil bulk density (BD) microporsity, macroporosity and total porosity accordingly to Donagema *et al.* (2011). Deformed soil samples were taken with an auger, then air dried and passed through a 2 mm sieve for determination of OM, P, K, Ca, Mg, Al and H+Al contents (Donagema *et al.*, 2011).

The data were tested for homogeneity (Bartlett test) and normality (Shapiro-wilk test). Afterwards, they were submitted to analysis of variance (ANOVA) and F test ($p < 0.05$), when significant, the means were compared by Tukey test ($p < 0.05$). Soil layers were analyzed individually.

RESULTS AND DISCUSSION

Soil physics

There was no triple interaction among factors. Nevertheless, the interaction between gypsum application and off-season crop system influenced soil physical properties in the superficial layer (0.0-0.1 m) (Table 2). The off-season cropped with M+B without gypsum application resulted in the higher PR (1.58 kPa), with a 12% increase in the magnitude of PR, when compared to the same treatment with gypsum application (1.12 kPa). In the absence of gypsum, the off-season cropped with Mi+C/W resulted in lower PR and BD (0.0-0.1 m) than the other crops (Table 2). This can be related to the crop diversity in this system, which results in different root characteristics that contribute to improved aggregate stabilization, reducing BD (Rossetti *et al.*, 2012). According to Alvarenga *et al.* (1995), roots can act directly or indirectly in soil stabilization through the tangle they form, protecting soil aggregates, mainly macroaggregates, and indirectly by their exudation and decomposition, releasing stabilizing organic compounds into the soil and increasing carbon deposition below the soil surface. Therefore, distinct characteristics from each off-season crops, such as thicker roots from crotalaria (Rosolem *et al.*, 2002) and fibrous and deeper roots from millet (Silva & Rosolem, 2001) and brachiaria (Galdos *et al.*, 2020), might have favored the physical attributes when cultivated in a mix, Mi+C and M+B, compared to oats and corn monocultures.

Thus, to maintain soil structure quality with higher porosity and lower BD it is necessary to use plants with diverse and aggressive root systems. Also, at the superficial layer (0.0-0.1 m) gypsum application reduced PR (Table 2), which can be related to enhanced root development due to increase in Ca and reduction on Al contents (Pauletti *et al.*, 2014; Santos *et al.*, 2019). Our data suggest that crop succession associated with gypsum improved the soil physical characteristics as a result of direct combined effect (e.g. increase flocculation and aggregation of soil), and indirectly by the increase of crop root systems improving aggregate stability (Calonego *et al.*, 2017; Blanco-Canqui & Ruis, 2018). Nevertheless, long-term research with off-season crops and gypsum could provide more evident effects in the soil physical attributes.

The interaction between tillage systems and off-season crops showed significant response at 0.0-0.2 m soil layer on PR, BD and total porosity (Table 3). After 18 months, the chiseling, associated with all off-season crops, resulted in 28% lower PR (0.0-0.1 m), than the NT system; the same was observed at 0.0-0.1 m layer with an increase of 30% in M+B, Mi+C/W and M/O after chiseling. This 18-month effect can be attributed to the mechanical effect of chisel shanks on the opening of fissures in soil profile, resulting in large soil blocks, pores and aggregates that reduce BD and PR and increase porosity (Secco *et al.*, 2009; Moraes *et al.*, 2016; Santos *et al.*, 2019). This was clearly observed in M/O system under chiseling (0.1-0.2 m) where the lower PR was supported by increase in macroporosity and total porosity, related to NT.

However, the higher soil BD and PR in NT (Table 3) may not reflect soil compaction. In long-term no-tillage systems, increased soil density can be related to stabilization of aggregates by the thick root mass formed by the combination of different plant species (grasses and legumes) (Silva & Rosolem, 2002; Vezzani & Mielniczuk, 2009; Blanco-Canqui *et al.*, 2010). Under these conditions root growth continues to occur because it is benefited by the presence of macropores from biological activity and pore continuity that allow oxygen diffusion and water plus nutrients flow (Moraes *et al.*, 2016; Blanco-Canqui & Ruis, 2018).

Table 1: Physical and chemical attributes of the soil in the layers 0.0-0.1, 0.1-0.2 and 0.2-0.3 m prior to the implementation of the experiment. Cascavel-PR, Brazil

Soil physics							
Layer	**RP**	**BD**		**Macro**	**Micro**	**TP**	**Clay content**
(m)	**(kPa)**	**(g cm^{-3})**			**(%)**		
0.0-0.1	1.4	1.11		13.26	46.50	59.76	75.90
0.1-0.2	1.9	1.16		10.84	46.81	57.63	80.58
0.2-0.3	1.6	1.13		9.07	49.66	58.72	83.47
Soil chemistry							
Layer	**OM**	**P**	**K**	**Ca**	**Mg**	**Al**	**H + Al**
(m)	**(g dm^{-3})**	**(mg dm^{-3})**			**(cmol$_c$ dm^{-3})**		
0.0-0.1	51.89	7.54	0.42	5.71	2.07	0.05	6.34
0.1-0.2	45.47	3.71	0.36	4.45	1.72	0.04	5.82
0.2-0.3	35.06	2.52	0.27	3.76	1.68	0.05	5.97

RP = soil resistance to penetration; BD = soil bulk density; Macro = macroporosity; Micro = microporosity; TP = total soil porosity; OM = organic matter; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Al = aluminum; H + Al = hydrogen + aluminum.

Table 2: Interaction between gypsum (0 and 3500 kg ha^{-1}) application and off-season crop systems (maize (M), maize+brachiaria (M+B), millet+crotalaria/whea (Mi+C/W) and maize/black oats (M/O)) for soil physical attributes in the layers 0.0-0.1; 0.1-0.2 and 0.2-0.3 m of a distric Ferralsol. Cascavel, PR, Brazil

Crop systems	PR (kPa)		BD (g cm^{-3})		Macro (%)		Micro (%)		TP (%)	
	No gypsum	With gypsum	No gypsum	With gypsum	No gypsum	With gypsum	No gypsum	With gypsum	No gypsum	With gypsum
0.0-0.1 m layer										
M	0.82 Bb	0.90 Aa[1]	0.97 Ba	0.97 Aa	21.68[ns]	20.45 [ns]	43.28 [ns]	44.60 [ns]	65.03 Aa	64.93 Aa
M+B	1.58 Aa	1.12 Ab	1.08 Aa	1.02 Aa	14.30	17.37	47.10	45.88	63.23 ABa	61.40 Aa
Mi+C/W	0.88 Bb	1.03 Aa	0.95 Ba	1.02 Aa	20.00	16.70	44.52	46.52	63.25 ABa	64.52 Aa
M/O	0.77 Bb	1.38 Aa	0.97 ABb	1.07 Aa	21.07	17.67	43.90	43.23	60.92 Bb	64.97 Aa
0.1-0.2 m layer										
M	1.18 Aa	1.27 Aa	1.12 [ns]	1.05 [ns]	15.98 Aa	14.40 Ba	45.10 [ns]	46.05 [ns]	61.07 [ns]	60.43 [ns]
M+B	1.12 Ab	1.73 Aa	1.07	1.10	13.85 Bb	16.45 Aa	46.07	44.95	59.90	61.38
Mi+C/W	1.35 Aa	1.30 Aa	1.05	1.07	15.17 Aa	16.27 Aa	45.77	45.35	60.93	61.63
M/O	1.32 Aa	1.40 Aa	1.08	1.05	16.47 Aa	15.13 ABa	44.93	45.33	61.43	60.47
0.2-0.3 m layer										
M	1.52 [ns]	1.48 [ns]	1.13 [ns]	1.12 [ns]	9.90 [ns]	7.77 [ns]	49.43 [ns]	51.03 [ns]	59.35 [ns]	58.80 [ns]
M+B	1.65	1.47	1.12	1.08	9.83	12.57	49.15	48.08	58.97	60.63
Mi+C/W	1.88	1.90	1.12	1.13	9.55	9.42	49.85	49.78	59.42	59.20
M/O	1.55	1.48	1.10	1.05	10.65	12.20	49.18	49.78	59.82	62.02

[1]Capital letter compare offs-season crop systems within each soil tillage system; lowercase letters compare tillage systems within each off-season crop systems by Tukey test at 5%. ns = not significant. PR = soil resistance to penetration; BD = soil bulk density; Macro = macroporosity; Micro = microporosity; TP = total soil porosity; CV = coefficient of variation.

Soil chemistry

The gypsum application in M, M+B and M/O systems, after 18 months, increased Ca content at 0.0-0.1 m layer and promoted decrease in Mg, P and K at 0.1-0.3 m soil layer under M and M+B (Table 4). The significant reduction on Mg contents at 0.1-0.2 m and K at 0.1-0.2 m and 0.2-0.3 m soil layers with application of gypsum can be explained by the replacing of Mg^{+2} or K^{+} by Ca^{+2} in the soil negative charges (Besen *et al.*, 2021). Thus, causing leaching of these elements in the form of $MgSO_4$ and K_2SO_4, which facilitates their movement down in soil profile. This result may be expected as gypsum application induces Mg deficiency in plants due to leaching (Pauletti *et al.*, 2014). On the other hand, the significant increase on P content in M/O (0.1-0.2 m) (Table 4) can be attributed to the $CaHPO_4$ precipitation resulting from the Ca^{2+} ion, from the dissociation of gypsum, binding to phosphate ion from the soil solution (Zoca & Penn, 2017). This information is also supported by the significant improvements in Ca^{+2} in the superficial layers.

Irrespective to crop rotations, Al levels at 0.0-0.1 m soil layer were reduced in Mi+C/W (Table 4). This reduction is related to the decomposition of straw and by the high Al complexation by organic binders derived from leguminous plants (Xiao *et al.*, 2014). Also, the decomposition of legume-based straw is known to increase soil pH and thus to reduce exchangeable Al in soil (Yuan *et al.*, 2011; Xiao *et al.*, 2014), however we do not observe significant changes in soil pH in our study (data not shown). But, the effects of Al neutralization are characterized by rapidity and short time duration, due to decomposition of organic compounds and decrease in soil pH (Xiao *et al.*, 2014), not being an effective practice to replace liming. These affirmations, associated to the short time of implantation of rotation with legumes in the study, can be responsible for the non-effects in neutralization of this element in deeper layers.

The interaction between gypsum application and off-season crop system showed that in M/O (0.0-0.1 m) and M (0.2-0.3 m) the use of gypsum significantly reduced Al content in 55% and 46%, respectively, in relation to non-application (Table 4). The sulphate anion (SO_4^{2-}) is the main responsible for the precipitation of Al throughout the soil profile after gypsum application (Nora *et al.*, 2017). In a similar way, M system along with gypsum application or tillage systems (Table 5) resulted in the lower P contents at 0.1-0.3 m layer. This may be related to a possible response of maize as a function of gypsum, favoring this off-season crop development, therefore, exporting more P by the grains. In addition, the lower complexity of this system (only soybean and maize) and consequent lower P cycling, may have reduced the levels of this element in soil (Calegari *et al.*, 2013).

Table 3: Interaction between tillage systems (no-tillage with and without chiseling) and off-season crop systems (maize (M), maize+brachiaria (M+B), millet+crotalaria/wheat (Mi+C/W) and maize/black oats (M/O)) for soil physical attributes in the layers 0.0-0.1; 0.1-0.2 and 0.2-0.3 m of a distric Ferralsol. Cascavel, PR, Brazil

Crop systems	PR (kPa)		BD (g cm^{-3})		Macro (%)		Micro (%)		TP (%)	
	Chiseling	NT	Chiseling	NT	Chiseling	NT	Chiseling	NT	Chiseling	NT
0.0-0.1 m layer										
M	1.00 Aa[1]	0.92 Ca	1.01 Aa	0.92 Bb	17.90^{ns}	24.23 ^{ns}	45.23 ^{ns}	42.65 ^{ns}	63.12 Ab	66.85 Aa
M+B	1.17 Ab	1.53 Aa	1.07 Aa	1.03 Aa	14.97	16.70	46.50	46.48	61.45 Aa	63.18 ABa
Mi+C/W	0.90 Ab	1.02 BCa	0.97 Aa	1.00 ABa	19.57	17.13	44.87	46.17	64.47 Aa	63.30 ABa
M/O	0.87 Ab	1.28 ABa	1.00 Aa	1.05 Aa	18.92	19.82	45.02	42.12	63.92 Aa	61.97 Ba
0.1-0.2 m layer										
M	0.97 Ab	1.48 Aa	1.07 ^{ns}	1.10 ^{ns}	15.83 Aa	14.55 Aa	45.47 ^{ns}	45.68 ^{ns}	61.27 Aa	60.23 Aa
M+B	1.25 Ab	1.60 Aa	1.07	1.10	15.48 Aa	14.82 Aa	45.53	45.48	61.00 Aa	60.28 Aa
Mi+C/W	0.95 Ab	1.70 Aa	1.02	1.10	17.33 Aa	14.10 Aa	44.95	46.17	62.30 Aa	60.27 Aa
M/O	0.98 Ab	1.73 Aa	1.03	1.10	17.78 Aa	13.82 Ab	44.63	45.63	62.43 Aa	59.47 Ab
0.2-0.3 m layer										
M	1.48 ^{ns}	1.52 ^{ns}	1.13 ^{ns}	1.12 ^{ns}	8.08 ^{ns}	9.58 ^{ns}	50.32 Aa	50.15 Aa	58.38 ^{ns}	59.77 ^{ns}
M+B	1.37	1.75	1.12	1.08	10.52	11.88	49.15 Aa	48.08 Aa	59.65	59.95
Mi+C/W	1.87	1.92	1.13	1.12	9.60	9.37	49.73 Aa	49.90 Aa	59.32	59.30
M/O	1.38	1.65	1.12	1.03	11.87	10.98	48.22 Ab	50.75 Aa	60.10	61.73

[1]Capital letter compare offs-season crop systems within each soil tillage system; lowercase letters compare tillage systems within each off-season crop systems by Tukey test at 5%. ns = not significant. PR = soil resistance to penetration; BD = soil bulk density; Macro = macroporosity; Micro = microporosity; TP = total soil porosity; CV = coefficient of variation.

The use of MT resulted in lower Ca contents in the Mi+C/W at 0.0-0.2 m soil layer and in M/O at 0.2-0.3 m layer (Table 5). The non-disturbance of soil provided by the NT is the main responsible for the higher contents of this element holding it adsorbed to the soil and thus avoiding its leaching (Tiecher *et al.*, 2017). Our results differ from Cavalieri *et al.* (2008), where chiseling stimulated organic matter mineralization and thus increased Ca content in the upper soil layers. In addition, the system M/O increased P and K in depth, while M+B and Mi+C/W increased K contents in depth. This result is due to higher aboveground dry mass produced by these crops (oats, wheat and brachiaria) that enhance the addition of K and P to soil after straw decomposition (Tiecher *et al.*, 2017).

There was also a reduction of Ca in M/O and K and P in M and M+B systems in depth (0.1-0.3 m) with MT (Table 5). Results from Moreira *et al.* (2019), also showed a reduction of some nutrients, in the case of P reduction, the authors attributed to increased adsorption of P in Fe and Al oxides as chiseling was performed for 12 years, causing soil disturbance. The results of these interactions show the importance of using a diversified cropping system in the off-season (e.g. Mi+C/W), along with gypsum, to maintain or increase nutrients in soil and reduce Al levels already in the following years after establishment of the cropping systems. On the other hand, chiseling combined with exclusive cultivation of grasses in the off-season promoted reduction of cations.

Soybean yield

No interaction or treatments effects were found on soybean yield (Table 6). Zoca & Penn (2017) also observed no effects of gypsum improving soybean yield and attributed this result to high levels of Ca already present in the soil, a condition similar to that observed in this study (Table 1). Also, the low acidity (e.g., low Al levels) in our soil and the absence of water deficit in this season, may be another factor responsible for the low effects of gypsum on grain yield (Tiecher *et al.*, 2018).

The absence of response due to MT can be attributed to the lack of compacted soil layers capable of limiting soybean development, as also observed by Moreira *et al.* (2019) and Santos *et al.* (2019). A similar result was found by Secco *et al.* (2009) and Franchini *et al.* (2012), where even with some degree of soil compaction, soybean grain yield was not reduced compared to chisel tillage.

Table 4: Interaction between gypsum (0 and 3500 kg ha^{-1}) application and off-season crop systems (maize (M), maize+brachiaria (M+B), millet+crotalaria/whea (Mi+C/W) and maize/black oats (M/O)) for soil chemical attributes in the layers 0.0-0.1; 0.1-0.2 and 0.2-0.3 m of a distric Ferralsol. Cascavel, PR, Brazil

Crop systems	OM		P		K		Ca		Mg		Al	
	(g dm^{-3})		(mg dm^{-3})		(cmolc dm^{-3})							
	No gypsum	With gypsum	No gypsum	With gypsum	No gypsum	With gypsum	No gypsum	With gypsum	No gypsum	With gypsum	No gypsum	With gypsum
0.0-0.1 m layer												
M	51.81^{ns}	54.91^{ns}	22.43^{ns}	20.44^{ns}	0.46 Aa[1]	0.41 Ba	4.31 ABb	5.72 Aa	2.00 Aa	2.07 Aa	0.18 ABb	0.32 Aa
M+B	52.40	54.80	21.77	24.53	0.49 Aa	0.46 ABa	4.62 ABb	5.25 Aa	1.87 Aa	1.50 Aa	0.13 ABa	0.17 Ba
Mi+C/W	50.06	52.08	20.77	22.19	0.47 Aa	0.61 Aa	5.55 Aa	5.44 Aa	2.48 Aa	1.71 Ab	0.06 Ba	0.13 Ba
M/O	50.16	54.53	22.98	19.48	0.56 Aa	0.56 ABa	3.81 Bb	5.66 Aa	1.85 Aa	2.00 Aa	0.23 Aa	0.10 Bb
0.1-0.2 m layer												
M	47.86^{ns}	49.30^{ns}	20.82 Aa	14.04 Bb	0.40 Aa	0.20 Ab	4.26^{ns}	3.61^{ns}	1.80 Aa	1.29 Ab	0.35^{ns}	0.39^{ns}
M+B	47.55	50.70	18.26 Aa	14.94 Ba	0.39 Aa	0.26 Ab	4.91	3.86	1.55 Aa	1.38 Aa	0.31	0.52
Mi+C/W	49.10	52.12	17.02 Aa	15.11 Ba	0.35 Aa	0.36 Aa	4.11	3.77	1.69 Aa	1.35 Aa	0.38	0.56
M/O	51.76	51.39	19.01 Ab	28.19 Aa	0.28 Aa	0.24 Aa	3.58	3.61	1.81 Aa	1.38 Ab	0.38	0.36
0.2-0.3 m layer												
M	45.95^{ns}	43.45^{ns}	10.72 Aa	4.25 Ab	0.19 Ba	0.16 ABa	2.91^{ns}	3.24^{ns}	1.14^{ns}	1.04^{ns}	0.73 Aa	0.46 Bb
M+B	45.15	44.35	6.36 BCa	4.79 Aa	0.28 Aa	0.22 Ab	3.27	2.83	1.15	1.04	0.31 Bb	0.68 ABa
Mi+C/W	46.86	44.57	4.94 Ca	5.00 Aa	0.18 Ba	0.13 Ba	2.99	3.18	1.09	1.10	0.83 Aa	0.98 Aa
M/O	42.59	43.82	8.12 ABa	5.96 Aa	0.21 ABa	0.22 Aa	3.21	3.00	1.15	1.06	0.56 ABa	0.63 Aa

[1]Capital letter compare offs-season crop systems within each soil tillage system; lowercase letters compare tillage systems within each off-season crop systems by Tukey test at 5%. ns = not significant. P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Al = aluminum; CV = coefficient of variation.

Table 5: Interaction between tillage systems (no-tillage with and without chiseling) and off-season crop systems (maize (M), maize+brachiaria (M+B), millet+crotalaria/wheat (Mi+C/T) and maie/black oatsaveia (M/O)) for soil chemical attributes in the layers 0.0-0.1; 0.1-0.2 and 0.2-0.3 m of a distric Ferralsol. Cascavel, PR, Brazil

Crop systems	OM		P		K		Ca		Mg		Al	
	(g dm^{-3})		(mg dm^{-3})		(cmolc dm^{-3})							
	Chiseling	NT	Chiseling	NT	Chiseling	NT	Chiseling	NT	Chiseling	NT	Chiseling	NT
0.0-0.1 m layer												
M	52.67^{ns}	54.05^{ns}	19.82^{ns}	23.05^{ns}	0.46^{ns}	0.41^{ns}	4.98 Aa[1]	5.05 Aa	1.87^{ns}	2.20^{ns}	0.18 Ab	0.31 Aa
M+B	54.16	53.04	22.78	23.52	0.49	0.46	4.73 Aa	5.14 Aa	1.50	1.88	0.21 Aa	0.09 Bb
Mi+C/W	51.34	50.80	21.12	21.84	0.58	0.50	4.90 Ab	6.08 Aa	1.98	2.21	0.09 Aa	0.09 Ba
M/O	52.24	52.46	23.97	18.50	0.55	0.58	4.57 Aa	4.90 Aa	1.59	2.16	0.16 Aa	0.17 Ba
0.1-0.2 m layer												
M	48.82^{ns}	48.35^{ns}	19.03 Ba	15.81 Ba	0.28 Ba	0.32 ABa	3.68 Aa	4.19 Aa	1.50^{ns}	1.61^{ns}	0.29^{ns}	0.45^{ns}
M+B	49.26	48.99	12.86 Bb	20.33 Aa	0.25 Bb	0.41 Aa	3.96 Aa	3.81 ABa	1.49	1.43	0.44	0.38
Mi+C/W	49.30	51.92	14.25 Ba	17.88 ABa	0.48 Aa	0.23 Bb	3.44 Ab	4.44 Aa	1.42	1.62	1.68	0.47
M/O	50.86	52.30	28.98 Aa	18.22 Ab	0.27 Ba	0.25 ABa	4.08 Aa	3.12 Bb	1.48	1.41	0.32	0.42
0.2-0.3 m layer												
M	44.94^{ns}	44.64^{ns}	6.16 Ab	8.79 Aa	0.16 Ba	0.19 Ba	3.51 Aa	2.63 Aa	1.28^{ns}	0.90^{ns}	0.52 Ba	0.67 Aa
M+B	44.62	44.89	5.24 Aa	5.88 ABa	0.20 Ab	0.30 Aa	2.96 Aa	3.13 Aa	1.06	1.13	0.38 Ba	0.60 Aa
Mi+C/W	46.54	44.89	4.64 Aa	5.31 Ba	0.20 Aa	0.15 Ba	3.20 Aa	2.96 Aa	1.16	1.03	0.94 Aa	0.86 Aa
M/O	42.75	43.65	7.12 Aa	6.96 ABa	0.24 Aa	0.19 Ba	2.49 Ab	3.72 Aa	0.93	1.28	0.62 Ba	0.58 Aa

[1]Capital letter compare offs-season crop systems within each soil tillage system; lowercase letters compare tillage systems within each off-season crop systems by Tukey test at 5%. ns = not significant. P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Al = aluminum; CV = coefficient of variation.

Table 6: Soybean yield (kg ha^{-1}) with application of 0 and 3500 kg ha^{-1} of gypsum, under no-tillage system (NT) and no-tillage system chiseling, and soybean off-season crop systems maize (M), maize+brachiaria (M+B), millet+crotalaria/wheat (Mi+C/W) and maize/black oats (M/O) for the for the 2014/2015 harvest. Cascavel-PR, Brazil

Treatment	Soybean yield (kg ha^{-1})
0 kg ha^{-1} of gypsum	3812 ^{ns}
3500 kg ha^{-1} of gypsum	3996
CV (%)	11.69
Chiseling	3876 ^{ns}
NT	3932
CV (%)	11.64
M	3694 ^{ns}
M+B	3976
Mi+C/W	3884
M/O	4062
CV (%)	11.55

Means followed by the same letter in the column, for each factor, do not differ among themselves by the Tukey test at 5%. ns = not significant; CV = coefficient of variation.

The absence of effects on soybean yield cultivated after off-season crops was also observed by Yokoyama *et al.* (2018). According to these authors, low quality residues can affect soybean vegetative stages, but this effect is overcome during the reproductive stages due to phenotypic plasticity of soybean, resulting in similar grain production. Moreover, the off-season crops cultivation should be carried out to improve soil physical, chemical and biological conditions, as well as reducing occurrence of pests and diseases, and thus reducing production costs (Blanco-Canqui *et al.*, 2010; 2015; Calonego *et al.*, 2017; Severino *et al.*, 2006; Tiecher *et al.*, 2017). However, the direct benefits of crop rotation to soil, and subsequently to soybean yield, can be more pronounced after some years of cultivation, indicating that this practice should be carried out for the long run (Franchini *et al.*, 2012; Calegari *et al.*, 2013; Calonego *et al.*, 2017).

CONCLUSIONS

For the conditions of the present study, with moderate soil fertility and low compaction level, the soybean yield was not influenced by the application of gypsum at 3,500 kg ha^{-1} minimal tillage with chiseling and use of cover crops in the off-season.

However, the off-season management practices with minimal tillage, gypsum application and different cropping systems promoted some changes in soil physical and chemical parameters. Minimal tillage and gypsum application improved soil physical conditions by reducing soil resistance to penetration, while soil porosity was only increased after chiseling. These practices also reduced some nutrients in the soil, such as potassium, magnesium and phosphorus. Thus, recommendations of chiseling for soil decompaction, and gypsum application for aluminum reduction and calcium supply should be followed by an extra input of other nutrients. In other hand, changing the traditional soybean off-season cultivated in succession with maize to other species, including mixes and legumes, promoted benefits after one crop cycle by reducing soil aluminum and increasing potassium and phosphorus levels. Nonetheless, more years of evaluation keeping the specific management practices in each treatment, can present more consistent results in the long-term

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