Long-term Crop Diversity Improves Soil Chemical Attributes, Nutrient Cycling and Soybean Yield

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Abstract

Crop diversity, particularly cover crops under no-tillage, increases agricultural efficiency in the use of nutrients and the soil carbon management. The objective of the present study was to evaluate the impact of single cover crops and intercropping (MIX) under long-term no-tillage on shoot dry mass (SDM) production, nutrient cycling, soil chemical attributes, and soybean yield in the Cerrado of Mato Grosso. The treatments consisted of MC: monocropped; CS1: *Crotalaria spectabilis*; CS2: *Pennisetum glaucum* (millet); CS3: *Urochloa ruziziensis*; CS4: *Cajanus cajan* (pigeon pea); and MIX: all four crops intercropped (*C. spectabilis* + *P. glaucum* + *U. ruziziensis* + *C. cajan*). The shoot dry mass of the cover crop was evaluated at 0, 90, 105, 120, 150, 180, and 210 days after cover crop management (CM) (desiccation) in the crop years from 2014/15 to 2020/21. The chemical properties of the soil were evaluated after the 2019/20 soybean crop harvest. SDM accumulation in MIX was approximately 22% higher than that in CS2 and CS3 and 60% higher than that in MC. Soybean yields were 20% higher in MIX, CS3, and CS4 than in MC, corresponding to an increase of approximately 14 bags of soybean. MIX and CS3 improved soil chemical attributes through nutrient cycling and SDM production under long-term no-tillage. MIX, CS3, and CS4 promoted increases in soybean yield after the stabilization phase of the system. The accumulation and release of nutrients by the shoots was an important indicator of nutrient cycling under no-tillage and consequent increases in the yield of soybean in succession.

Introduction

Production costs associated with agricultural inputs have increased considerably in the last two harvests (Conab 2022). This scenario is expected to continue for crops in Brazil, emphasizing the need for changes in agricultural production management models to target energy efficiency through nutrient cycling and reduced use of mineral fertilizers and natural resources (Obour et al. 2021). Sustainable production models such as no-tillage system (NTS) prioritize the synergy of crops in rotation or succession. In particular, the diversification of species in the second harvest improves nutrient use efficiency by increasing organic matter via carbon (C) sequestration (Crusciol et al. 2021a; Baptistella et al. 2020).

Careful selection of the cover crops in the second harvest is required. In the Brazilian Cerrado, there are three cultivation periods: crop occurs between October and February, when water availability is favorable for crop development; the second crop occurs between February and June, when water availability decreases, with periods of water stress; and the off-season, which occurs between July and September and is characterized by a period of drought. Species diversification is essential in the second crop period, which is best suited to drought-tolerant species with the genetic potential for high shoot dry mass (SDM) production and nutrient cycling (Dalla Côrt et al. 2021; Pacheco et al. 2018).

Incorporating crop diversity into management practices can be difficult in the Cerrado and elsewhere in Brazil due to the dominance of the soybean-corn model, which provides high short-term profitability to the producer. Several studies have demonstrated that singly planting *Urochloa ruziziensis*, *Pennisetum* *glaucum*, *Cajanus cajan,* or *Crotalaria spectabilis* is an efficient second crop option that can improve the biophysiochemical attributes of the soil (Dalla Côrt et al. 2021; Volf et al. 2021; Bossolani et al. 2020; Ferreira et al. 2020; Franzluebbers and Gastal 2019; São Miguel et al. 2018; Pacheco et al. 2017). However, analyses of long-term effects are necessary to determine whether intercropping a mixture of cover crops in the same area can provide superior results compared with each species individually. In addition to promoting nutrient cycling, crop diversification may protect the soil against the effects of climate change by promoting atmospheric carbon sequestration via incorporation into soil organic matter (SOM), enhancing microbiological diversity, soil aggregation, and promoting water infiltration and retention in the soil with possible increases in grain yield (Obour et al. 2021; Franzluebbers and Gastal 2019; Pacheco et al. 2017).

The floristic diversity brought by a mixture of cover crops under NTS represents an innovative consortium model that prioritizes the extraction of nutrients located in deep layers of the soil, which are sometimes inaccessible to genetically improved crops. Cover crops in MIX translocate nutrients extracted from the soil to the photosynthetic apparatus to produce energy sources and carbon skeletons, which are subsequently transformed into SDM. In addition, the variety of root systems allows exploration of a greater volume of soil, formation of biopores, and the release of a diversity of mucilages and exudates, creating a specific rhizosphere for each species (Baptistella et al. 2020; Bertollo et al. 2020). Consequently, the high quality of plant materials provided by mixed cover crops favors the formation of a diverse edaphic fauna that will transform this highly labile material into stable SOM molecules, which will be protected within soil aggregates and serve as reservoirs of nutrients for successor crops. These properties of mixed cover crops suggest that it may be possible to increase soil nutrient availability by managing single or intercropped crops to increase the efficiency of the use of mineral fertilizers and other inputs.

There is a need to study of MIX of cover crops has evaluated nutrient cycling and possible changes in soil fertility and long-term soybean yield. Although the system may not express initial significant increments because it needs construction for its stabilization, long-term production is expected to increase soybean yield. So, we hypothesized that the diversity of cover crops in second crop improve the soil quality, fertility, and soybean yield in long term in no-tillage system. To provide a baseline for future research, the objective of this work was to evaluate the impact of single and intercropped cover crops under long-term no-tillage on SDM production, nutrient cycling, soil chemical attributes, and the soybean yield in succession.

Materials And Methods

1.2.1 Experimental site

The experiment was carried out in the 2013/14 to 2020/21 seasons to evaluate the evolution of the systems over 7 years of implementation. The experiment was conducted at the Experimental Station of the Federal University of Rondonópolis-MT (UFR) (16º27'41.75"S 54º34'52.55"W, altitude of 292 m)

(Figure 1). The soil in the area is classified as dystrophic Red Latosol (Santos 2018) with flat relief. Before the present study, soil sampling was performed for chemical analysis, the results of which are shown in Table 1.

The local climate is tropical, with hot and humid conditions, and is Aw according to the Köppen classification (SOUZA et al., 2013). Figure 2 provides meteorological data since the implementation of the experiment.

1.2.2 Crop systems and experimental design

The experiment was carried out in a randomized block design with six production systems and four replications, resulting in a total of 24 plots, each with dimensions of 7.40 m x 9.50 m. In the second crop, cover crops were used; in the first crop season, soybean was sown as a commercial crop. The treatments consisted of MC: monocropped; CS1: *Crotalaria spectabilis*; CS2: *Pennisetum glaucum* (millet); CS3: *Urochloa ruziziensis*; CS4: *Cajanus cajan* (pigeon pea); and MIX: all four crops intercropped (*C. spectabilis*+*P. glaucum*+*U. ruziziensis*+*C. cajan*). Figure 3 presents the treatments used since the implementation of the experiment through the 2020/21 harvest. Some systems were modified after a few years due to the adaptation of the species to the conditions of the Cerrado, but these changes were considered improvements to the trial's scope.

In the second crop each year, all crops were sown between February and March with a spacing of 0.45 m. In the treatment with sunflower+*U. ruziziensis* from 2015 to 2017, the grass was sown between the rows. With the change to MIX from 2018 to 2021, *P. glaucum* and *C. spectabilis* were sown in the same row, and *U. ruziziensis* and *C. cajan* were sown in the next row; thus, these crops were interspersed in the plots. In all production systems, soybean was sown between September and October under no-tillage after desiccation of the cover crops in June. Soybean cultivars were selected according to technical recommendations for the region and market availability. Soybean was grown with a row spacing of 0.45 m and harvested in February of the following year.

1.2.3 Fertilization

For sunflower, fertilization followed the recommendations of Souza and Lobato (2004). However, after the implementation of MIX with sunflower, fertilizers were not used. Fertilizers were not applied in plots with single cover crops. In the first five years of the study, soybean was fertilized to correct soil chemical properties. Specifically, 120 kg ha^{-1} of P_2O_5 was applied as monoammonium phosphate (MAP, with 10% N and 52% P_2O_5) in the sowing furrow, and 100 kg ha^{-1} of K_2O was applied as potassium chloride (KCl, with 60% K_2O). Half of the KCl was spread pre-sowing, and the remaining half was applied when the soybean was at the V4 phenological stage. To reflect the stabilization phase of the NTS, in the last two agricultural years (2019/20 and 2020/21), the amounts of potassium and phosphate fertilizers were reduced by half to 60 kg ha^{-1} of P_2O_5 as MAP and 50 kg ha^{-1} of K_2O as KCl as maintenance fertilization. The soybean seeds were inoculated at a dose of 150 mL of inoculant for every 50 kg of seeds with liquid inoculant Nitragin Cell Tech® HC, which contained 3x10 colony-forming units of *Bradyrhizobium japonicum* per milliliter.

1.2.4 Evaluations of SDM, nutrients, and soil properties

The shoot dry mass (SDM) of the cover crops was evaluated at 0, 90, 105, 120, 150, 180, and 210 days after cover crop management (CM). Day 0 was defined as the point of maximum accumulation of SDM and nutrients, when all cover crops were desiccated (normally in June). Therefore, SDM was collected at the second harvest in all years. The second management desiccation was carried out at 90 days of CM (September/October) for the beginning of the crop and soybean sowing. The SDM was evaluated according to the methodology described by Crusciol et al. (2005). In brief, the SDM of cover crops within an iron square measuring 50 x 50 cm was randomly collected at two sampling points per plot. The collected SDM was dried in an oven at 60°C until a constant mass to obtain the SDM and nutrients. Finally, the samples were ground in a Wiley mill and passed through a 2-mm mesh sieve before determining the concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) following the methodologies proposed by Malavolta et al. (1997).

To describe the release of SDM and nutrients from the cover crops after desiccation, the data collected at 0, 90, 105, 120, 150, 180, and 210 days after CM were fit to the exponentially decreasing mathematical model (Equation 1) described by Wieder & Lang (1982):

$$PL = Po \exp(-kt) \quad (1)$$

Where: PL is the amount of SDM and nutrients existing at time t in days (kg ha^{-1}), Po is the fraction of SDM and nutrients potentially released (kg ha^{-1}) and k is the constant for SDM and nutrient release (g g^{-1}).

The value of k was used to calculate the half-life (T½ life) of the SDM and the remaining nutrients, which represents the time required for half of the SDM to decompose and half of the nutrients to be released, using the formula T½ life = 0.693/k, as proposed by Paul & Clark (1989).

Soybean grain yield was evaluated by sampling in two 2-m lines and expressed in kg ha^{-1}, corrected for 13% moisture. For soybean yield and all shoot variables, the historical series was constructed using the averages of SDM and nutrient accumulation and release and from the 2014/15 to 2020/21 seasons to allow comparisons between crop systems under NTS over time.

Soil sampling for the analysis of chemical properties was carried out after harvesting the 2019/20 soybean crop by collecting four subsamples in the useful area of each plot (5 m x 5 m). Samples were collected with a probe-type tract at depths of 0.00-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.30 m. The soil was packed in plastic bags and taken to a greenhouse, where the bags were opened to obtain air-dried fine earth (ADFE). After drying, the samples were sieved (2-mm mesh) for complete fertility analysis according to the methodology proposed by Raij et al. (2001).

1.2.5 Statistical analysis

The results were submitted to analysis of variance, and when significant, the qualitative data were submitted to the Fisher LSD test at $p \leq 0.10$ using SISVAR 5.6 software (Ferreira, 2008). Quantitative data were fitted into decreasing exponential equations using the SIGMA PLOT 10.0 software (Systat Software Inc., San Jose, CA, USA). A multivariate analysis of shoot data was also performed as a function of soil depths using Principal Component Analysis (PCA) and Pearson's correlation using R software (R Core Team, 2020).

Results

SDM accumulation in MIX was approximately 22% higher than that in CS2 and CS3 and 60% higher than that in MC (Figure 4A). Similar patterns of differences in accumulation among the treatments were observed for all nutrients analyzed (Figure 4B, C, and D). Among the single treatments, N was highest in CS4, P was highest in CS3, and Ca was highest in CS1 in the second harvest. When comparing the efficiency of nutrient accumulation between MIX and MC, an increase in MIX of 43% for N, 22% for P and 38% for K was observed. This would represent 107 kg ha^{-1} of urea, 57 kg ha^{-1} of P_2O_5 and 224 kg ha^{-1} of K_2O that would no longer be applied in the system due to the cycling of these nutrients, generating savings for the producer.

The SDM decomposition rate was highest in CS4, with a $T_{1/2}$ of 71 days, and MIX and CS1, with an average of 93 days. The rate of nutrient release into the soil was highest in MIX (N, P, K, Ca, Mg and S), CS3 (P and Mg), CS4 (N and S), and CS1 (Ca). Soybean yield was highest in MIX, CS3, and CS4, with increases of 20% compared with the control treatment (MC), equivalent to approximately 14 bags of soybean (Figures 5 and 6).

In respect to soil chemical attributes, MIX produced superior results in terms of CEC, superficial SOM, pH up to the 0.10-0.20 m layer, and P, K, Ca, Mg and S contents (Figures 7 and 8). CS3 excelled in CEC and SOM in all layers, in pH up to a depth of 0.20-0.30 m, and in Ca and Mg contents up to a depth of 0.20-0.30 m.

Principal component analysis (PCA) for soil fertility as a function of shoot variables showed that PC1 explained 48–69% of the variation in the dataset, while PC2 explained 12–27% (Figure 9). These analyses revealed correlations of MIX and CS3 with soybean yield, shoot nutrients, and soil fertility variables at the four evaluated depths. In addition, Pearson's correlation analysis (Figure 10) demonstrated that nutrient accumulation in the aerial parts of the cover crops was highly positively correlated with soybean yield in the last two harvests (Yld6_7).

Discussion

The greater accumulation of SDM and nutrients in MIX emphasizes the importance of a diversity of crops with different phenological cycles in production systems. Each cover crop has a specific function in the system that depends on its morphophysiological characteristics. *P. glaucum* has a short cycle and contributed to nutrient accumulation in the system in the initial phase of the second crop. As water availability decreased during the second season and *P. glaucum* entered senescence, the perennial species *C. spectabilis*, *U. ruziziensis,* and *C. cajan* were able to continue vegetative growth and nutrient accumulation in SDM, which resulted in a greater quantity and quality of organic residues for soybean sown in succession.

Oliveira Jr et al. (2014) found that *U. ruziziensis* and millet have allelopathic potential and, in this study resulted in interactions between species in the MIX system may be resulted in the exudation of more diverse secondary metabolites and increased carboxylic and humic acids by the grasses. According Brandani and Santos (2016) and Moreira and Siqueira (2006), the high lignin content of grasses favors the increase microbial biomass in the soil due to the addition of SOM and proteins that reduces resistance to root growth along the soil profile. These inputs are positively reflected in the ability of this system to absorb and allocate nutrients in the organic fraction of SDM under NTS.

N content in SDM was high when *C. cajan* was cultivated as a single crop (CS4), demonstrating the importance of this legume for production under NTS in terms of N cycling, including biological fixation of atmospheric nitrogen (N_2). *C. cajan* also increased N cycling when multiple cover crops were intercropped in the MIX system, possibly by metabolites release that increase the N fixation. These observations are supported by Arantes et al. (2020), Ferreira et al. (2017), and Carvalho et al. (2022), who found that *Crotalaria* sp. and *C. cajan* increased the community of diazotrophic microorganisms responsible for the conversion of N_2 into inorganic forms that can be assimilated by plants (NO_3^-/NH_4^+) and improved the lignin:N ratio, which was associated with an increase in soil POC.

In the system in which *Urochloa ruziziensis* was grown as a single cover crop (CS3), P cycling was predominant due to the root abundance of P and probable root exudation of enzymes and organic acids (OAs) capable of solubilizing poorly labile fractions of P. According to Baptistella et al. (2021), Teutscherova et al. (2019) and Louw-Gaume et al. (2017), *U. ruziziensis* specialized to grow in environments with low available P by developing mechanisms such as greater root system development with intense colonization of mycorrhizal fungi and exudation of OAs and acid phosphatases. Almeida et al. (2020) and Louw-Gaume et al. (2017) found that *U. ruziziensis* leaches several OAs, mainly citric, oxalic, and malic acids, from the shoots or the root surface that can solubilize P and increase its availability to the grass. These organic acids make P available to plants due to their high affinity for specific minerals: oxalate releases P associated with Ca, and citrate and malate release P bound to Fe and Al oxides. Since OAs are highly energetic molecules produced by *U. ruziziensis* and are used in microbial metabolism, a cycle of the stimulation of the production and decomposition of OAs is created. Thus, the solubilization of P by OAs increases the bioavailability of P in the soil solution or bound to SOM such as phytates (Almeida et al. 2018). This P is protected from losses to the environment but is generally not available to plants.

Another important finding is the accumulation of Ca in the shoots of *C. spectabilis* (CS1). This accumulation can be attributed to the root morphology (i.e., pivot) and root physiology of the plant, which favor the absorption of Ca from the soil during the second crop. These results confirm those of Araújo et al. (2021), who found that *C. spectabilis* increased soil pH of 5.0 for 5.3 after management and thus enhanced soil Ca^{2+} and Mg^{2+} levels. These changes increased the accumulation of Ca^{2+} and Mg^{2+} in plant tissues, demonstrating that this cover crop can cycle nutrients, increase CEC and base saturation, and reduce Al content and potential acidity.

The intermediate half-life of SDM decomposition and nutrient release in MIX reflects the diversity of plants in this system (Figure 5A), which varied in their decomposition rates. Importantly, half of this SDM was still present under the soil at the time of soybean sowing. The presence of *U. ruziziensis*, whether as a single cover crop (CS3) or intercropped (MIX), was particularly important for increasing the quantity of SDM on the soil surface under NTS, as a long residue half-life of 210 days was observed in CS3. Pacheco et al. (2017) reported superior development of *U. ruziziensis* when intercropped with corn compared with oversowing with soybean; the accumulated SDM reached 18,000 kg ha^{-1}, confirming the quantitative importance of *U. ruziziensis* for soil protection in the Cerrado. Rosolem et al. (2012) also observed high persistence of SDM from *U. ruziziensis* on the soil surface and found that its root system had decomposed by only 10% at 45 days after desiccation.

The results of the present study confirm that cover crop intercropping (MIX) provides adequate quantitative maintenance of phytomass on the soil surface under NTS and more efficient nutrient cycling during the second crop. MIX was among the systems with the highest rates of nutrient release to the soil, primarily due to the inclusion of two legumes (*C. spectabilis* and *C. cajan*) that favor organic residues enriched with N. Single *C. spectabilis* (CS1) and *C. cajan* (CS4) also showed high rates of nutrient release (N, S, and Ca). According to Teodoro et al. (2011), the deep and differentiated root systems of these two legumes increase Ca and P accumulation in the Cerrado by exuding citric acid and other organic compounds that solubilize Ca-bound P and P adsorbed to Fe oxides and hydroxides. After legume cultivation, Rosa et al. (2017) observed an increase in C content in the fulvic acid fraction, which includes low molecular weight compounds, and a higher density of carboxylic groups such as organic acids and sugars, demonstrating the lability of legume tissues. Rosa et al. (2017) also noted that increasing the fulvic character of humic substances via cover crop insertion promotes humic acid and humin content and, in turn, SOM stabilization with the continued insertion of plant material in the system.

Soybean grain yield in the last two agricultural years (Yld6_7) was the most appropriate indicator of the effects of nutrient cycling promoted by cover crops. Thus, there was an initial phase of “system construction” in the first five years of the NTS. The crop diversity provided by MIX was important for obtaining high soybean yields, demonstrating that interactive nutrient cycling occurred between the crop species over time and provided a more suitable environment for the development of soybean in succession. The positive results of soybean yield in succession to single *U. ruziziensis* (CS3) highlight the importance of this species as a quantitative and qualitative promoter (P cycling) of phytomass under NTS, as reported by Baptistella et al. (2021), Almeida et al. (2020) and Almeida et al. (2018). The effect of diversity over the seasons was clear in CS4, in which *Stylosanthes* (2014) was followed by *V. unguiculata* (2015 and 2016) and *C. cajan* (2017 to 2020). Bennet et al. (2012) stated that crop diversity generally increases crop yield by 10%. Osterholz et al. (2018) emphasized that the use of diversified legumes contributes to reducing the risk of N loss through gross ammonification, that is, the gross flux of NH_4^+ produced by microbial mineralization of organic N compounds, during grain crop growth.

With respect to soil chemical attributes (Figures 7 and 8), MIX efficiently increased SOM content and CEC, mainly in the superficial layers of the soil. These increases can be attributed to the quantitative effect of the SDM of *U. ruziziensis* intercropped with the other cover crops, as similar effects were observed for the single grass (CS3) up to a depth of 0.20-0.30 m. *U. ruziziensis* has an abundant, fasciculated root system, which intensifies the contribution of organic residues to the soil, as corroborated by Carvalho et al. (2022), Rosolem et al. (2019), and Rosolem et al. (2012). In addition, but promoting the accumulation of C and N in the soil, *U. ruziziensis* increases microbial synthesis of SOM fractions and C stabilization in the soil to reduce greenhouse gases through C sequestration (Eberhardt et al. 2021; Nishigaki et al. 2020; Yao et al. 2019; Schmatz et al. 2016). The increases in SOM and CEC in deeper soil layers in CS3 are attributable to the lack of interspecific competition. The diversity of cultures in MIX also provided a better soil pH buffering effect in the layers up to 0.10-0.20 m. Weakly acidic functional groups in SOM such as carboxylic and phenolic acids form a buffer system through protonation and deprotonation, as observed by Xu et al. (2012), Latifah et al. (2017) and Shi et al. (2019). This increased buffering can reduce limestone use over time and prevent drastic changes in soil composition that can negatively affect crops and microbiota.

The results for soil nutrient contents confirmed that shoot residues in MIX promoted the cycling of nutrients, particularly P, K, Ca, Mg, and S. However, it is necessary to explain that the MIX was not fertilized, but the sunflower, previously implanted, was fertilized for three years with doses of 100 kg ha^{-1} of MAP, KCl and urea and there may still have been some residual effect of the fertilizations in this area treatment. The interaction among cover crop species proved to be a decisive factor in the nutrient cycling process, with each playing specific roles but together promoting a synergy of factors that resulted in greater efficiency in the use of nutrients. This synergy was greatest for cycling of P, K, and S. S is easily leached to depths below 0.30 m, as demonstrated by Bossolani et al. (2021b), Crusciol et al. (2019), and da Costa et al. (2018), and MIX enhanced S cycling through absorption by the roots at greater depths, allocation in organic residues and subsequent release to the soil. The effects of *U. ruziziensis* on Ca and Mg cycling at greater soil depths were also evident in CS3, besides Ca and P also stimulate the root growth of soybean in succession (Crusciol et al. 2021b; Bossolani et al. 2021a; Bossolani et al. 2021b; dos Reis et al. 2018). These effects justify the high grain yields of soybean in succession to *U. ruziziensis*, even when the latter was cropped singly.

PCA confirmed the effect of nutrient cycling, with high similarity in the data for shoot nutrients, soil fertility variables, and soybean yield detected between PC1 and PC2. The high similarity of these variables between MIX and single *U. ruziziensis* (CS3) confirms the benefits of these systems for nutrient cycling and increasing soybean yield in succession discussed above. Pearson's correlation analyses demonstrated that nutrient accumulation in the aerial part of cover crops is an important indicator of the potential of cover crop systems to promote nutrient cycling and increase soybean yield under NTS.

Conclusions

1. Intercropping cover crops (MIX) and single *U. ruziziensis* (CS3) increased all evaluated soil chemical attributes through nutrient cycling and SDM production under long-term NTS.

2. MIX, *U. ruziziensis* (CS3), and *C. cajan* (CS4) were associated with increases in soybean yield after the stabilization phase of the system, i.e., in the sixth and seventh years of NTS implementation.

3. *Crotalaria spectabilis* is an important cover crop to increase soybean yield by N fixation in the establishment phase of no-tillage system.

4. Shoot nutrient accumulation and release are important indicators of the nutrient cycling process and the potential to increase soybean yield in succession under NTS.

Abbreviations

air-dried fine earth (ADFE); atmospheric nitrogen (N_2); calcium (Ca); carbon (C); cation exchange capability (CEC); crop management (CM); crop succession (CS); Federal University of Rondonópolis (UFR); intercropped (IC); magnesium (Mg); monoammonium phosphate (MAP); monocropped (MC); nitrogen (N); no-tillage system (NTS); phosphorus (P); Principal Component Analysis (PCA); potassium (K); potassium chloride (KCl); shoot dry mass (SDM); soil organic matter (SOM); sulfur (S).

Declarations

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Tables

Table 1 - Chemical and textural characterization of the dystrophic Oxisol at the area opening for the experiment in 2013

Soil depth	**pH**	**P**	**K**	**Ca**	**Mg**	**H+Al**	**CEC**	**V**	**MO**	**Sand**	**Silt**	**Clay**
(m)	$CaCl_2$	mg dm^{-3}		_____ $cmol_c dm^{-3}$ _____				%	______ g kg ¹ _______			
0.00-0.10	4.1	5.4	55	0.5	0.2	6.8	7.6	11	17.6	450	125	425
0.10-0.20	4.0	1.4	49	0.2	0.2	7.2	7.6	5.6	19.9	500	100	400
0.20-0.30	4.1	0.2	31	0.3	0.1	6.2	6.7	7.2	13.7	500	100	400

P: available phosphorus (Mehlich 1); exchangeable K^+, Ca^{2+}, and Mg^{2+}; CEC: cation exchange capability at pH 7.0; V: base saturation; OM: Organic matter.

Figures

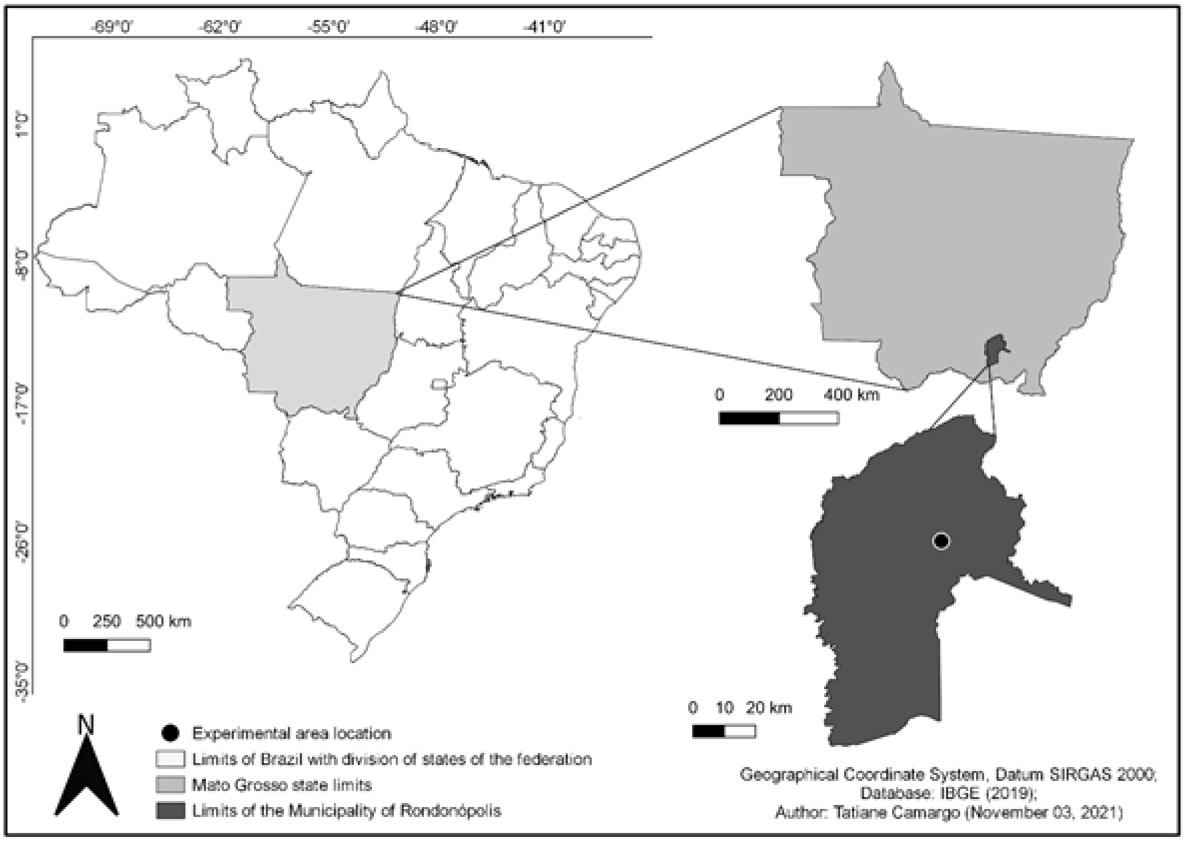

Figure 1

Graphic representation of experiment location conducted in Rondonópolis-MT in the crop years from 2013/14 to 2020/21

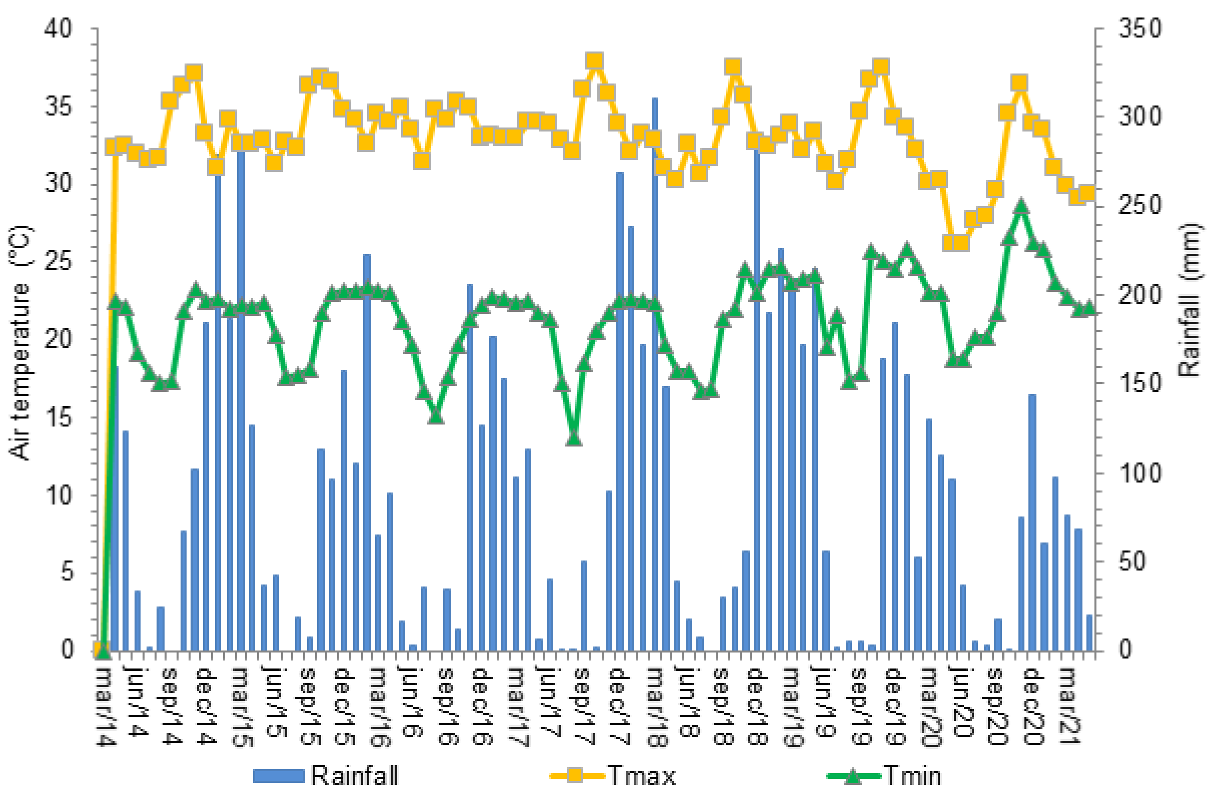

Figure 2

Accumulated monthly precipitation and average minimum and maximum air temperatures during the experiment at UFMT in Rondonópolis-MT

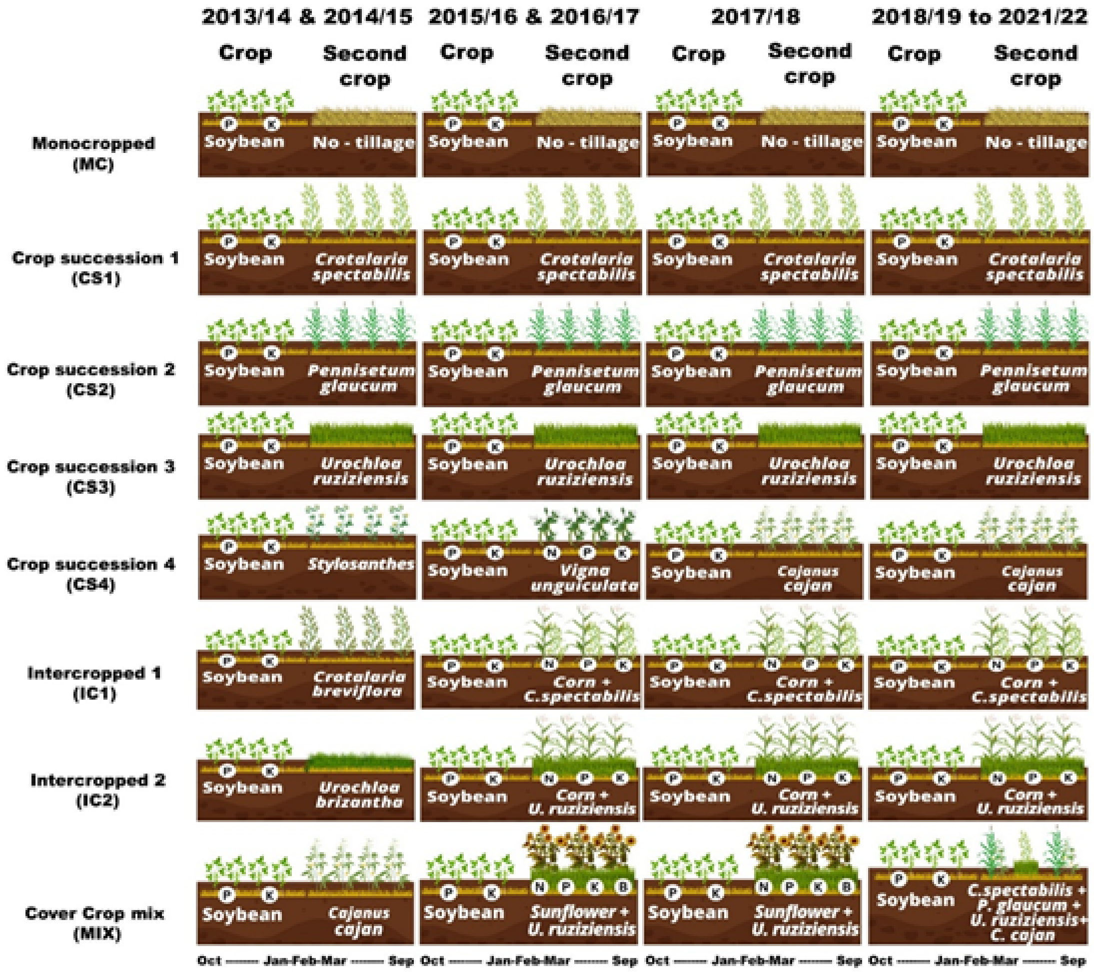

Figure 3

Crop systems characterization was implemented in the second crop in all crop years in Rondonópolis- N: nitrogen; P: phosphorus; K: potassium; B: boron representing the fertilization used on soybean and in some cover crops.

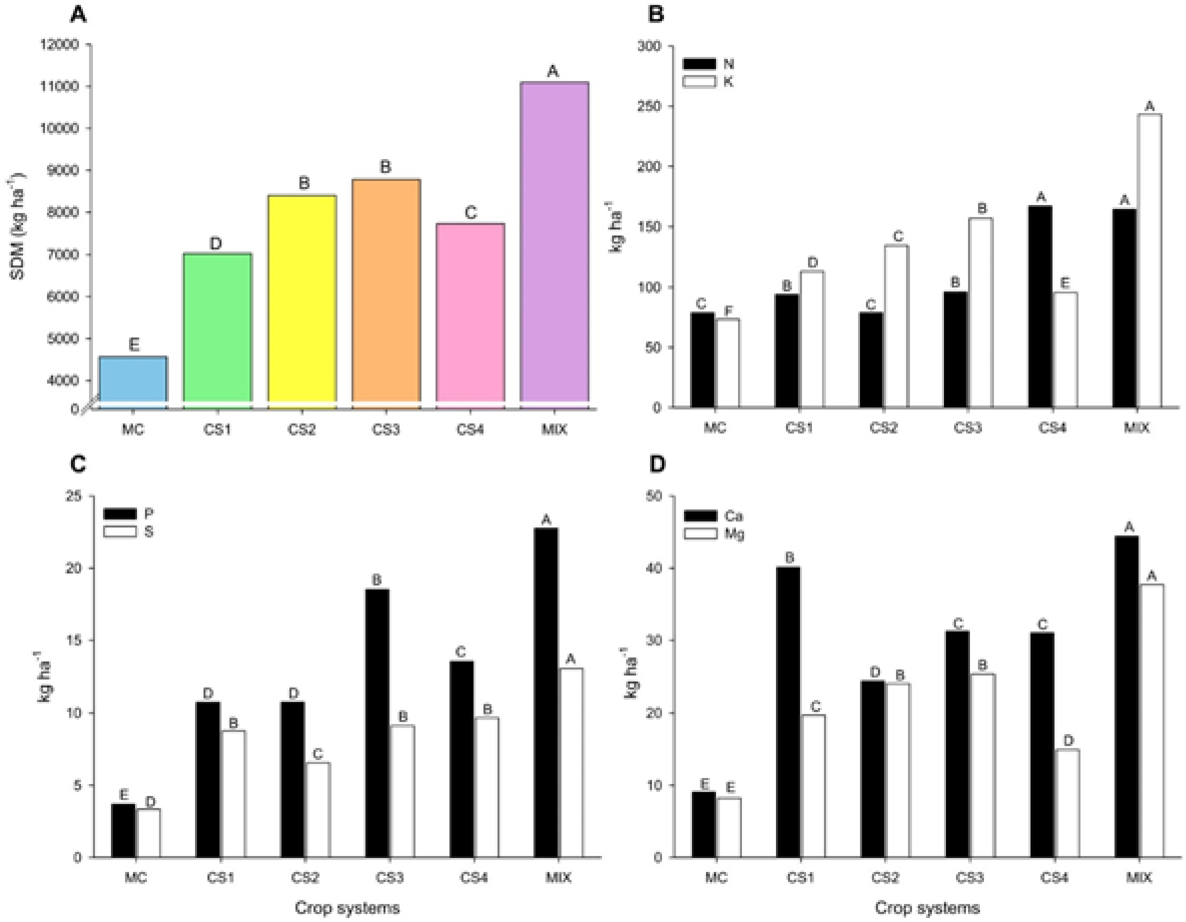

Figure 4

Seven-year average (2014 to 2020) of shoot dry mass production (A), and accumulated amounts of N, K (B), P, S (C), Ca, and Mg (D) at cover crop management (CM) at the second crop MC: Monocropped (fallow in no-tillage); CS1: Crop succession 1 (*Crotalaria spectabilis*); CS2: Crop succession 2 (*Pennisetum glaucum*); CS3: Crop succession 3 (*Urochloa ruziziensis*); CS4: Crop succession 4 (*Cajanus cajan*); MIX (*C. spectabilis*+*P. glaucum*+*U. ruziziensis*+*C. cajan*). Different letters in the column indicate significant differences between treatments by Fisher's protected LSD test at $p \leq 0.10$.

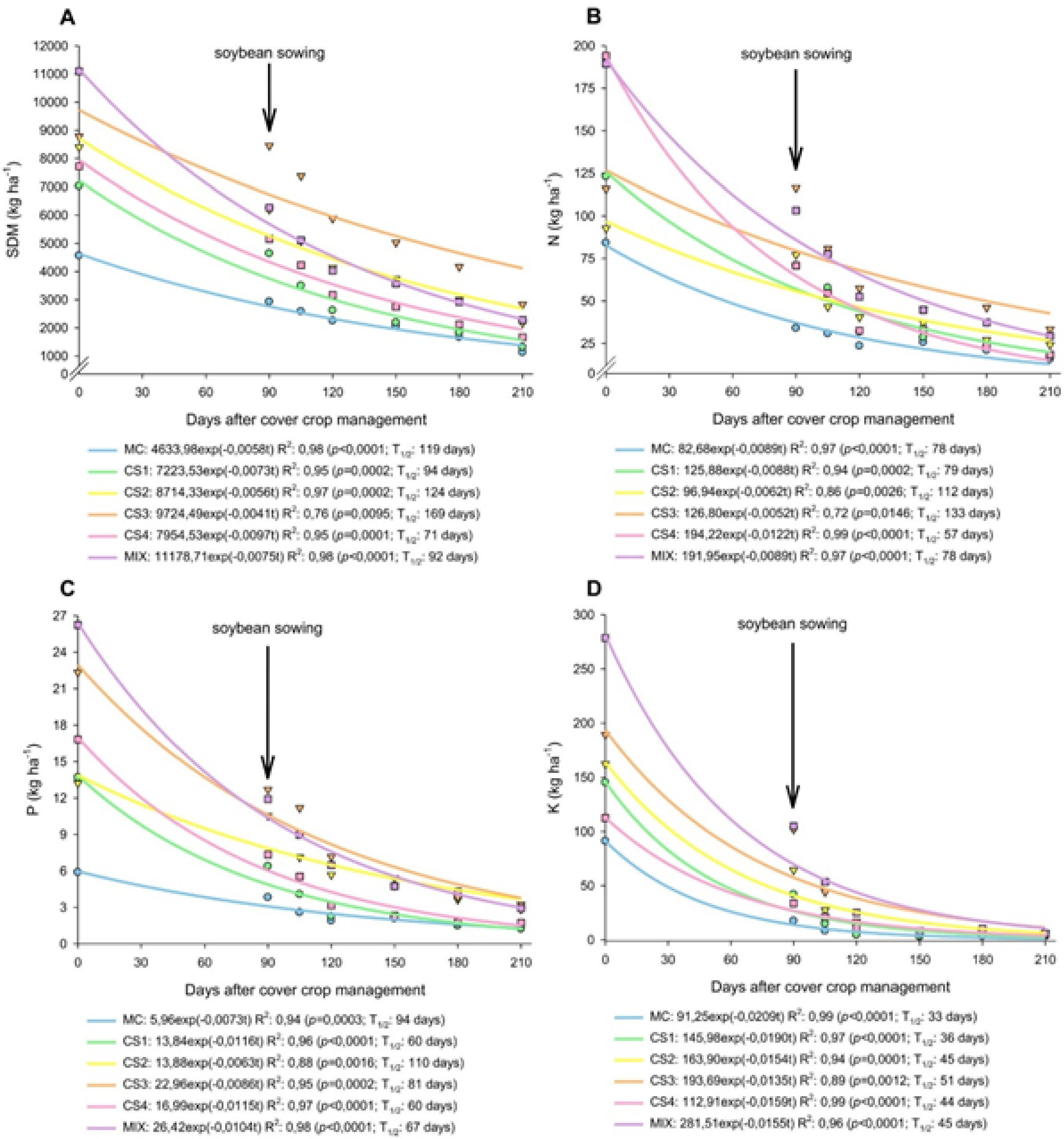

Figure 5

Seven-year average (2014/15 to 2020/21) of shoot dry mass decomposition (A) and N (B), P (C), and K (D) release after cover crop management MC: Monocropped (fallow in no-tillage); CS1: Crop succession 1 (*Crotalaria spectabilis*); CS2: Crop succession 2 (*Pennisetum glaucum*); CS3: Crop succession 3 (*Urochloa ruziziensis*); CS4: Crop succession 4 (*Cajanus cajan*); MIX (*C. spectabilis*+*P. glaucum*+*U. ruziziensis*+*C. cajan*). $T_{1/2}$: half-life time.

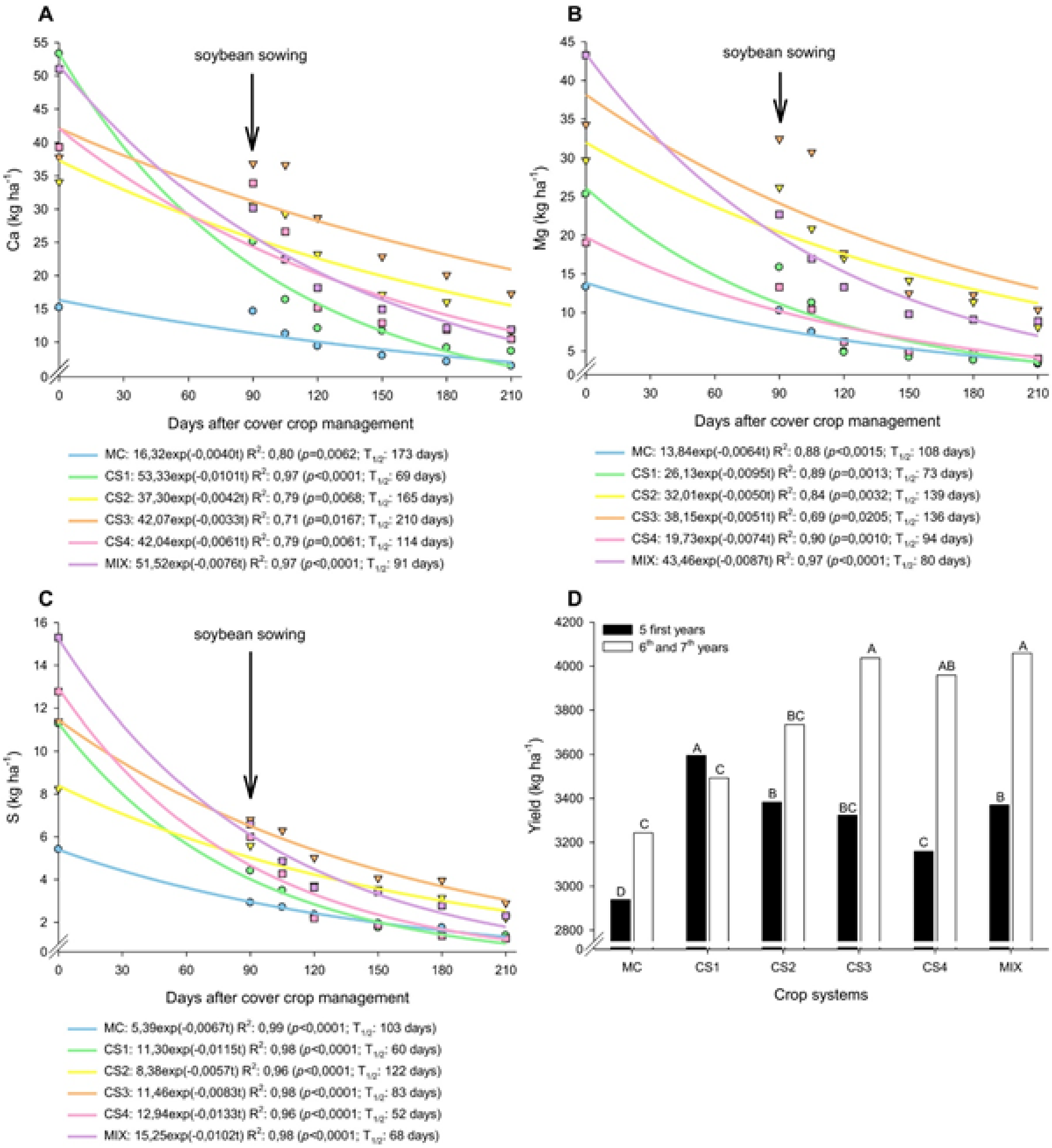

Figure 6

Seven-year average (2014/15 to 2020/21) of Ca (A) Mg (B) and S (C) release after cover crop management and soybean grain yield averages in the first five years and the 6th and 7th years MC: Monocropped (fallow in no-tillage); CS1: Crop succession 1 (*Crotalaria spectabilis*); CS2: Crop succession 2 (*Pennisetum glaucum*); CS3: Crop succession 3 (*Urochloa ruziziensis*); CS4: Crop succession 4 (*Cajanus cajan*); MIX (*C. spectabilis*+*P. glaucum*+*U. ruziziensis*+*C. cajan*). $T_{1/2}$: half-life time. For soybean yield, the different letters in the column indicate significant differences between treatments by Fisher's protected LSD test at $p \leq 0.10$.

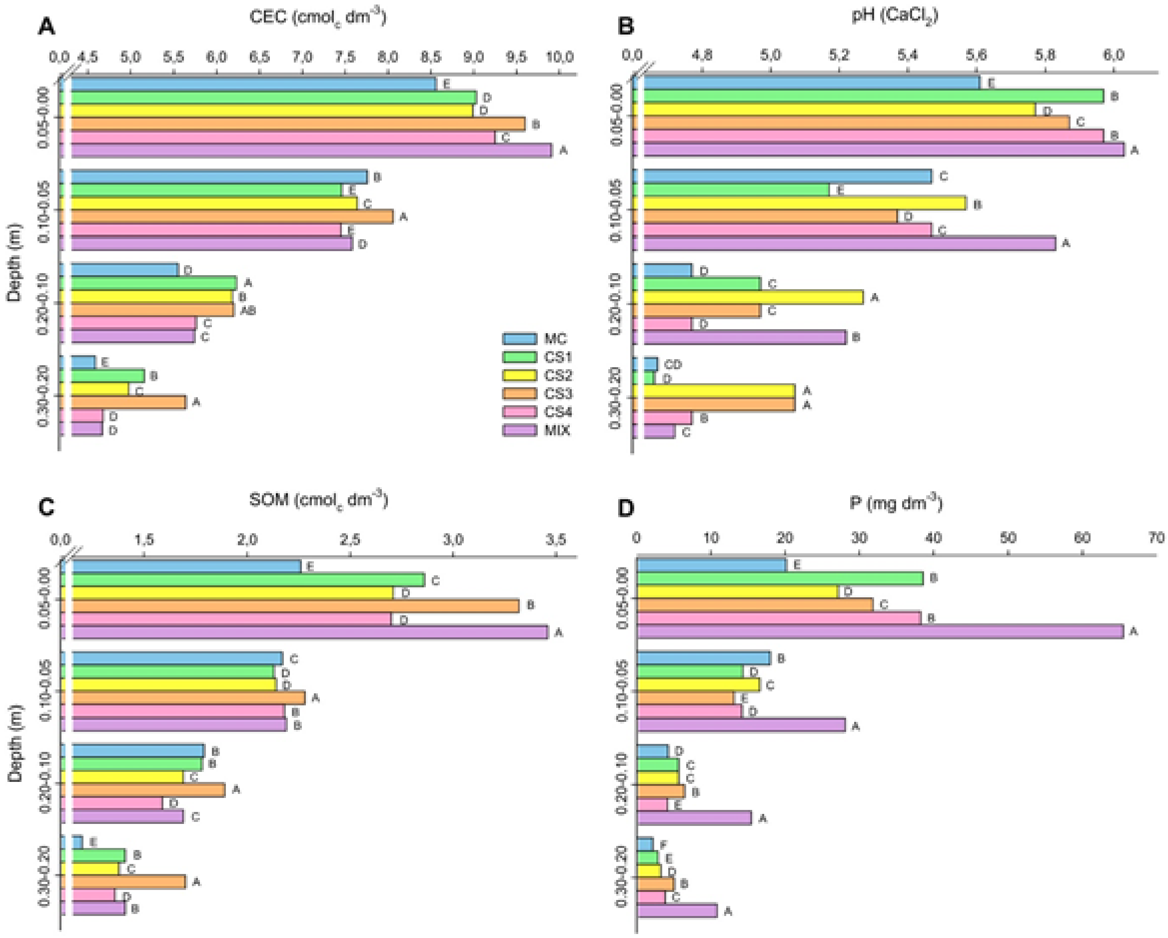

Figure 7

Soil chemical attributes and phosphorus in soil layers under cover crops after soybean harvest (crop season 2019/20) Cation exchange capability: CEC; Soil organic matter: SOM. MC: Monocropped (fallow in no-tillage); CS1: Crop succession 1 (*Crotalaria spectabilis*); CS2: Crop succession 2 (*Pennisetum glaucum*); CS3: Crop succession 3 (*Urochloa ruziziensis*); CS4: Crop succession 4 (*Cajanus cajan*); MIX (*C. spectabilis*+*P. glaucum*+*U. ruziziensis*+*C. cajan*). Different letters in the column indicate significant differences between treatments by Fisher's protected LSD test at $p \leq 0.10$.

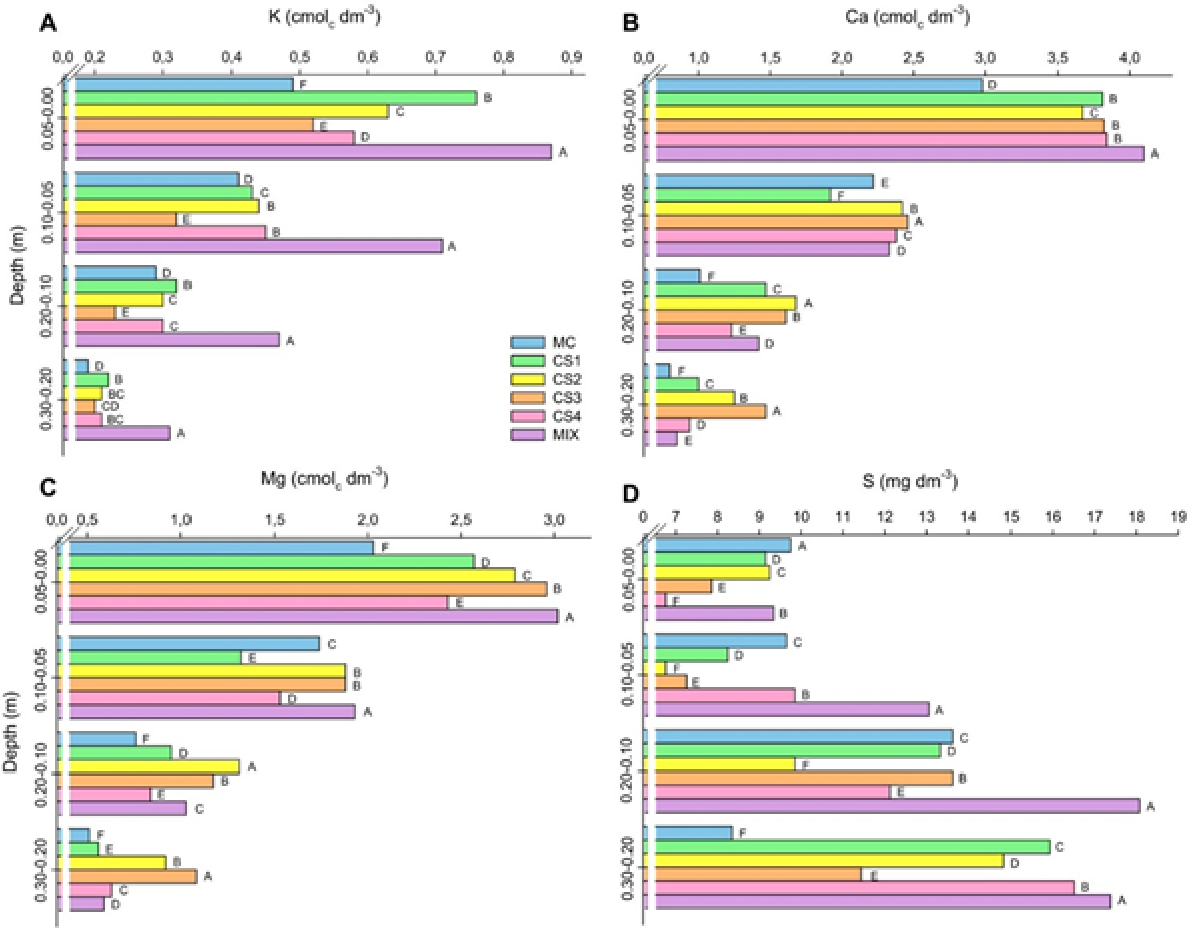

Figure 8

Soil nutrients, K (A), Ca (B), Mg (C), and S(D) in soil layers under cover crops after soybean harvest (crop season 2019/20) MC: Monocropped (fallow in no-tillage); CS1: Crop succession 1 (*Crotalaria spectabilis*); CS2: Crop succession 2 (*Pennisetum glaucum*); CS3: Crop succession 3 (*Urochloa ruziziensis*); CS4: Crop succession 4 (*Cajanus cajan*); MIX (*C. spectabilis*+*P. glaucum*+*U. ruziziensis*+*C. cajan*). Different letters in the column indicate significant differences between treatments by Fisher's protected LSD test at $p \leq 0.10$.

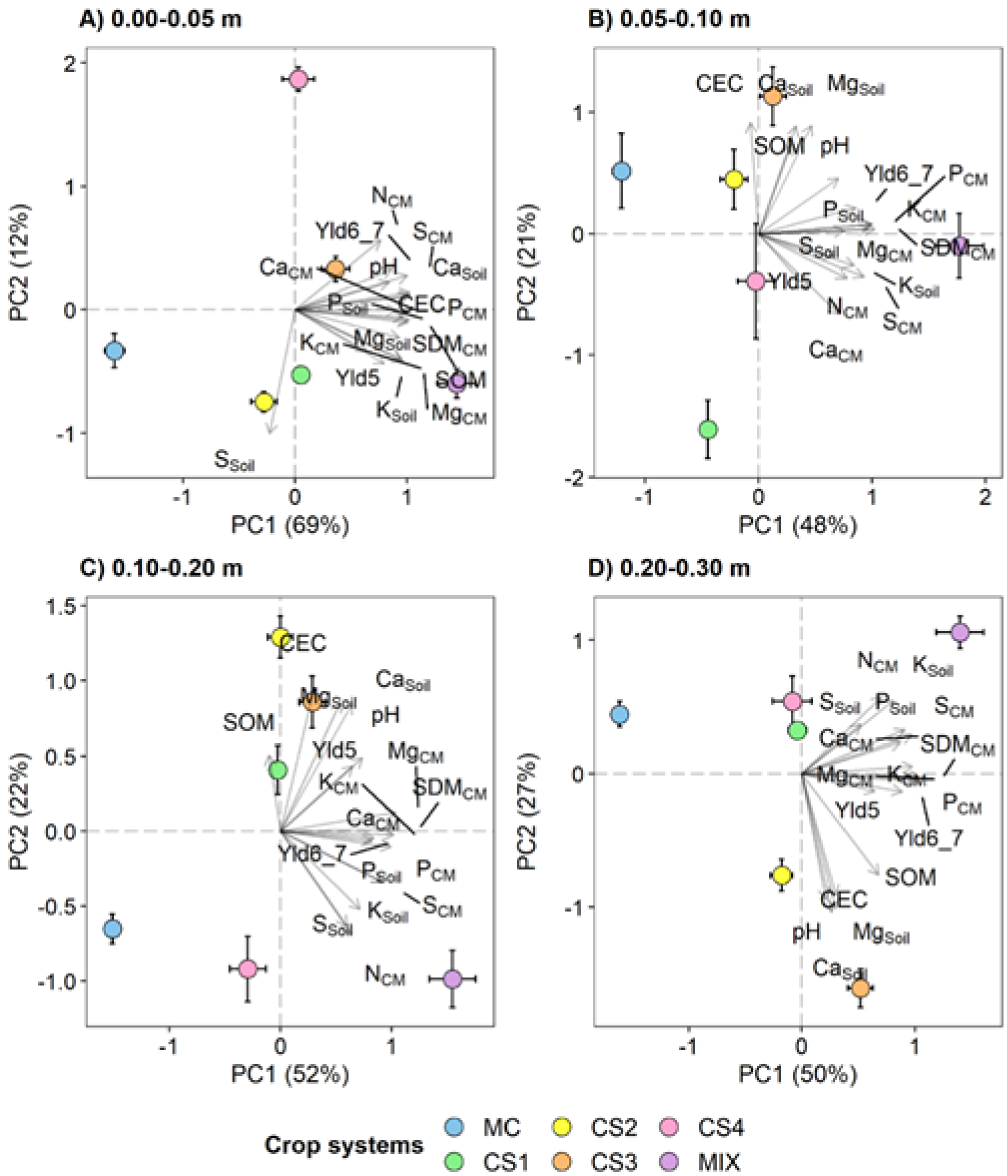

Figure 9

Principal Component Analysis of shoot dry mass production, nutrient accumulation at cover crop management (CM), soybean yield in the first five years of the experiment and the last two years (6^{th} and 7^{th}) in function of the soil layers Variables at the cover crop management (CM): Shoot dry mass: $SDM_{–CM}$; Nitrogen: $N_{–CM}$; Phosphorus: $P_{–CM}$; Potassium: $K_{–CM}$; Calcium: $Ca_{–CM}$; Magnesium: $Mg_{–CM}$; Sulfur: $S_{–CM}$; Soybean yield in the first five years of the experiment: Yld5, and 6^{th} and 7^{th} years: Yld6_7; Soil organic matter: SOM; pH; Cation exchange capability: CEC; Nitrogen: N_soil; Phosphorus: P_soil; Potassium: K_soil; Calcium: Ca_soil; Magnesium: Mg_soil; Sulfur: S_soil. MC: Monocropped (fallow in no-tillage); CS1: Crop succession 1 (*Crotalaria spectabilis*); CS2: Crop succession 2 (*Pennisetum glaucum*); CS3: Crop succession 3 (*Urochloa ruziziensis*); CS4: Crop succession 4 (*Cajanus cajan*); MIX (*C. spectabilis*+*P. glaucum*+*U. ruziziensis*+*C. cajan*).

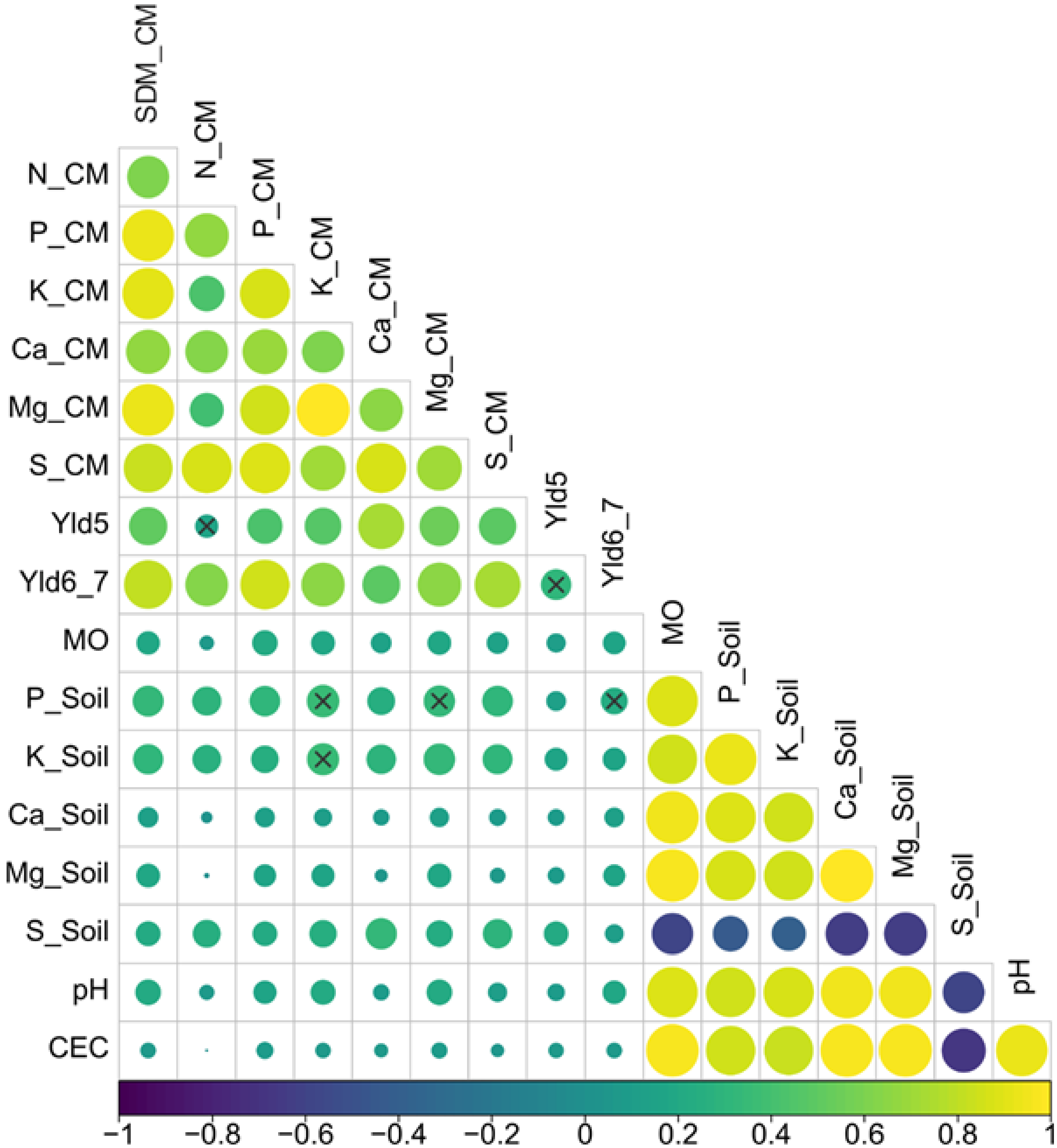

Figure 10

Heatmap correlation (Pearson) based on shoot dry mass production, nutrient accumulation at cover crop management (CM), soybean yield in the first five years of the experiment and the last two years (6th and 7th) and chemical soil attributes Variables at the cover crop management (CM): Shoot dry mass: $SDM_{–CM}$; Nitrogen: $N_{–CM}$; Phosphorus: $P_{–CM}$; Potassium: $K_{–CM}$; Calcium: $Ca_{–CM}$; Magnesium: $Mg_{–CM}$; Sulfur: $S_{–CM}$; Soybean yield in the first five years of the experiment: Yld5, and 6th and 7th years: Yld6_7; Soil organic matter: SOM; pH; Cation exchange capability: CEC; Nitrogen: N_soil; Phosphorus: P_soil; Potassium: K_soil; Calcium: Ca_soil; Magnesium: Mg_soil; Sulfur: S_soil.

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