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Occasional Tillage in a Field Established under Conservation Agriculture for Tomato Cropping

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Abstract

The Conservation Agriculture (CA) is a current concept drives to save natural resources for agricultural production based on the minimum soil disturbance or no-tillage, crop rotation and permanent maintenance of straw on soil surface. The increasing in soil density is a problem to achieve great copping yield under CA, so occasional one-time tillage is considered as an alternative to continuous no-tillage. In this way, this experiment was carried out to compare occasional tillage and no-tillage interacting with cover crops in a field established under conservation agriculture. Thus, the experimental treatments were set up by two tillage methods, conventional tillage and no-tillage and two cover crops, white lupin and millet setting in a randomized blocks with split plot design with four replications. The traits evaluated in the research were soil fertility, soil resistance to penetration, soil moisture and tomato agronomic performance. No-tillage was more efficient to preserve soil moisture; however soil fertility, soil resistance to penetration and tomato yield were favored by conventional tillage. Regarding to cover crops white lupin increased the soil K concentration and enhanced the tomato growth. Although occasional tillage had better performance to the soil fertility and tomato yield, we highlighted that CA is the better way to increase soil health and soil and water conservation along the time leading to so desired regenerative agriculture.

Keywords

No Tillage, Crop Rotation, Cover Crops, *Solanum lycopersicum* L.

1. Introduction

The tomato cropping in Brazil encompasses annually area around 55 thousand hectares with average yield of 68 Mg·ha^{-1} and the production of 3.810 million of tons, which incorporate high inversion of agricultural inputs to ensure economic viability due to the high investment risk. Like so, tillage is conventionality performed by plough and harrows which exposure soil to the erosive process and graduate loss of soil fertility among others environmental impacts (Guadagnin *et al.*, 2005) [1]. On the other hands, Conservation Agriculture (CA), driven to the agronomic concepts of minimum disturbance of soil or no-tillage for crop establishment, crop rotation and permanent residues on the soil surface, ensuring in an expressive way to soil erosion control and quality of water, besides improvements on soil fertility and crop resilience facing climate changes (FAO, 2024 [2]; Nouri *et al.*, 2021 [3]). The rising of soil quality from the beginning of CA adoption takes a certain time which rely on the increasing organic matter (Murillo *et al.*, 2006) [4], and that's in fact will collaborate for increasing others soil quality indexes like as soil structure, nutrient cycling, biological activity, water storing and infiltration. Wuest *et al.* (2023) [5] reported increasing in soil water holding under no-tillage compared with minimum tillage, however with subtle increase of soil carbon under minimum tillage. The maintenance of straw on soil surface contributes for reduction of soil temperature and avoids excessive evaporation and so regulating the wetting-drying status of soil (Yin *et al.*, 2023) [6]. Nevertheless, as the time goes on even in CA conditions, it is possible detected increasing in the soil bulk density especially in the crops that running an intensive flow of harvest machine which compromises root growth leading to the loosing yield (Wuest *et al.*, 2023) [5]. Soil compaction is the main justification for the use of occasional tillage in no-tillage systems (Peixoto *et al.*, 2020) [7]. In some instances, occasional one-time tillage is considered as an alternative to continuous no-tillage to address some of the challenges with no-tillage systems. Such challenges can include nutrient and C stratification and compaction risks, which can jeopardize cropping agronomic performance (Blanco-Canqui & Ruis, 2018) [8]. Results suggest that while frequent intensive tillage can lower organic soil carbon and N storage, a single occasional tillage after several years of no-tillage does not lead to soil C and N losses and soil structural instability in semi-arid drylands (Paye *et al.*, 2024) [9]. Because of this, there are questions about needs of some temporal intervention of occasional tillage for decrease soil bulk density and improve root growth and crop yield in the area under CA. Cover crops are essential for a great crop rotation strategy in CA, because they provide several environment benefits to crop field. Species like grass produce dry biomass residues on the soil surface with high carbon/nitrogen (C/N) ratio, which takes more time to decomposition of the residue and so protect the soil against solar radiation and heavy precipitation for a long time compared with others species like legume for example that have low C/N ratio. On the other hand, legumes have the capacity to incorporate nitrogen into the soil and after release to the plant, reducing N mineral fertilization (Geng *et al.*, 2023) [10]. In this context, we hypothesized if the disturbance of the soil with occasional tillage will decrease soil fertility and soil moisture content; growth and yield of tomato will benefit by occasional tillage and species of cover crop; the interaction between methods of tillage and cover crops for soil properties and tomato performance will be significant?

Nevertheless, the aim of this research was to study the impact of tillage methods (conventional and no-tillage) and cover crops (millet and white lupin) on the soil properties and tomato agronomic performance in a field established along 15 years (since 2008) under Conservation Agriculture (Branco *et al.*, 2013) [11].

2. Material and Methods

2.1. Site Description

The research was carried out at Experimental Farm of Agronomic Institute (IAC) located at geographic coordinate of 21˚12'S e 47˚51'N and 645 m above sea level. The annual average rainfall is 1.425 mm, concentrated especially from October to March with maximum average temperature of 25˚C and minimum average temperature of 19˚C. According USDA soil taxonomy soil is classified as red Oxisol (Ferralsol—World Reference Base for Soil Resources) with clay texture (sand = 276 g kg of soil$^{−1}$, silt = 332 g kg of soil$^{−1}$ and clay = 530 g kg of soil$^{−1}$) and following chemical fertility: pH = 5.5, Ca = 39.5 mmolc dm$^{−3}$, Mg = 15.1 mmolc dm$^{−3}$, K = 4,2 mmolc dm$^{−3}$, S-SO_4 = 10.5 mg dm$^{−3}$, P = 132.6 mg dm$^{−3}$, organic matter = 24.1 g dm$^{−3}$, cationic exchange capacity (CEC) = 85.1 mmolc dm$^{−3}$. The experimental site has 2.000 m^2 and it is under conservation agriculture since 2008.

2.2. Treatments and Experimental Design

The experimental treatments of the research were two tillage method, conventional, with subsoiling and harrowing (occasional tillage—just one tillage along of 16 years under no-tillage) compared with no-tillage (established along 16 years) interacting with two cover crops, millet (*Pennisetum glaucum*) and white lupin (*Lupinus albus*). Millet is a grass that has fast growth with high production of aboveground biomass besides has a fasciculate root which improves soil structure; white lupin is a leguminous that in addition to incorporating atmospheric nitrogen by biological fixation, it solubilizes phosphorus in the soil and also produce great aboveground biomass to lay down on soil surface. Both species are used as cover crops in the tropical Conservation Agriculture. Occasional tillage was characterized by conventional tillage performed before tomato transplanting and was done with subsoiling at 0.40 m of soil depth following by harrowing at 0.20 m of soil depth. For no-tillage the site was kept under conservation agriculture.

The experimental was a randomized block with split-plot design with four replicates, accounting 16 experimental unit with 4.0 m wide and 20.0 m long each one (80 m^2).

2.3. Cover Crop Growing

Cover crop was seeded in 2023 March with no-till seeder (Vence Tudo enterprise, AS-7300 model) at 0.25 m row spacing. For millet it was used 20 kg ha^{-1} of seed and 60 kg ha^{-1} for white lupin. The cover crops grew freely without any agricultural input and irrigation. Along the cover crops grown the average of minimum and maximum temperatures was 14.9˚C and 28.3˚C respectively and the total precipitation was 217 mm. This weather condition was enough to good growth of cover crops and straw production on soil surface. The cover crops were killed with a pass of roller crimper in July 2023 (110 days after seeding).

Liming was done after killing cover crops with application of 1 t ha^{-1} on the soil surface, based on the technical recommendation (Trani *et al.* 2018) [12]. Dolomitic lime (54% $CaCO_3$ and 45 $MgCO_3$) was incorporated into the soil at the conventional tillage site while in the no-tillage lime was kept on the surface, leaving the lime displace naturally in the soil profile. After killing cover crops, it was performed conventional tillage in the plots of the occasional tillage treatment.

2.4. Tomato Growing

After killing cover crops, tomato seedling (Hybrid with determinate growth from HM-Clause—HM2798) was transplanted in both, conventional tillage and no-tillage on the straw of millet and white lupin. For tomato transplanting the rows were open with the aid of the same no-till seeder (Vence Tudo enterprise, AS-7300 model) used for seeding cover crops, in both conventional and no-tillage treatments. The tomato spacing was 1.25 m between row and 0.5 m between plants.

The base fertilization of tomato was done with 40 kg ha^{-1} of N, 450 kg ha^{-1} of P_2O_5 and 150 kg ha^{-1} of K_2O, and the tomato topdressing fertilization was done with 300 kg ha^{-1} of N, 100 kg ha^{-1} of P_2O_5 ha^{-1} and 300 kg ha^{-1} of K_2O, according Trani *et al.* (2018) [12] technical recommendation.

The tomato cropping was dripping localized irrigation and the moment and quantity of irrigation was determined by tensiometer and crop evapotranspiration, respectively (Marouelli *et al.*, 1994) [13]. Biological control was performed for tomato cropping protection under integrated management of pests and diseases. Along the tomato cropping the average of minimum and maximum temperatures was 17.5˚C and 32.2˚C, respectively and the total precipitation was 162 mm, that was adequately for good performance of tomato cropping.

2.5. Traits Evaluation

The experimental traits were evaluated by cover crop dry biomass yield, soil water storing, soil fertility from 0.0 to 0.20 m of depth, soil resistance to penetration and agronomic tomato performance.

2.6. Cover Crop Dry Biomass Production

The cover crops dry biomass production was evaluated before roller crimped pass to kill cover crops. In this way, plants of 1 m^2 of each experimental unit was sampled and drying in dry forced air oven at 110˚C by 72 hours until getting constant weigh. After, dry biomass production was estimated for Mg ha^{-1}.

2.7. Soil Moisture Content

The soil moisture content was measured by gravimetric method. Thus, the procedure was done by soil sampled in the steel ring with volume of 100 cm^3 at 0.0 to 0.10 m and 0.10 to 0.20 m of soil profile at two points of each experimental unit and between row of tomato cropping, after a period of 15 days with no precipitation which provides adequate condition to evaluate soil moisture in the experimental treatments. Then, soil samples were weight and after dried in a dry forced air oven at 105˚C by 84 hours until getting constant weigh. Furthermore, it was calculated the percentage (%) of the soil moisture content by the following equation: SM = (Wu − Wd)/Wd*100, where SM = soil moisture content; Wu(g) = soil weight with moisture at moment of sampling; Wd(g) = soil weight after drying.

2.8. Soil Fertility and Soil Resistance to Penetration

Soil fertility was evaluated in two soil profile extracts at the samples taken from 0.0 to 0.10 m and 0.10 to 0.20 m depth, in two points of each experimental unit at the end of tomato cropping. The samples were sent to laboratory for soil chemical analysis of Calcium (Ca), Magnesium (Mg), Potassium (K), Sulphur ($S\text{-}SO_4$), Phosphorus (P), organic matter (OM), pH, cationic exchange capacity (CEC), bases saturation (V%). Furthermore, it was analyzed the enzymes β Glucosidase and Arylsulfatase that are important indicators of soil biological fertility. β Glucosidase act on the organic matter decomposition and soil carbon cycle and Arylsulfatase act on the Sulphur cycle in the soil making available S inorganic to the plants. The enzymatic analysis was procedure as https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1133109/tecnologia-bioas-uma-maneira-simples-e-eficiente-de-avaliar-a-saude-do-solo.

Soil resistance to penetration was measured with aid of resistance electronic meter (PLG1020—Falker enterprise) with measurement capacity until 0.60 m of soil depth, recording values in MPa at each 0.10 m. The measurements were taken in two points of each experimental unit in the row of tomato and at the end of tomato cropping.

2.9. Tomato Growth and Yield

The tomato growth was measured at 55 days after transplanting (DAT) by accounting the bunches quantity, fruit quantity, fresh fruit biomass and dry biomass of plant aerial parts (leaf, stems and fruit). For this, two plants from each experimental unit were sampled and evaluated.

The tomato root growth was measured by "mini-rhizotron" method at 55 DAT. Firstly, it was insert into the soil acrylic tubes at 0.40 m depth in one point of each experimental unit between two tomato plants. The dimension of the tubes is 60 mm diameter and 400 mm long. The root images capture was done with the Root Scanner CI-600 model from CID-Bioscience in two soil profile, 0.0 m to 0.20 and 0.20 to 0.40 m depth. Afterwards, the images were analyzed in the Winrhizotron®

software to quantify total root number, root length (cm), root volume (cm^3), root surface area (cm^2).

The tomato yield was measured by accounting marketable fruits, biomass of marketable fresh fruit and estimative of yield in Mg ha^{-1}. For this, fruits from six plants of each experimental unit were harvested, classified and recorded for tomato yield accounting.

2.10. Statistical Analysis

The statistical analysis was performed by PROC MIXED of the SAS® program (Littell *et al.*, 2006) [14]. Before the data were subjected to homoscedasticity, normality and outlier tests and then was running the variance analysis (ANOVA) followed by treatments average comparison by PDIFF test at 5% of probability.

3. Results

3.1. Yield Dry Biomass of Cover Crops

At the end of cover crops growth, millet yielded 4.8 Mg ha^{-1} of dry biomass while white lupin yielded 6.6 Mg ha^{-1} of dry biomass. This yield of dry biomass from both cover crops was adequate to performance no-tillage. Although millet had yielded less quantity of straw, the great carbon/nitrogen relation (C/N) of this specie could contributed to keep straw on soil surface for a long time, due to the slow straw decomposition. On the other hand, white lupin provided nitrogen into the soil by biological nitrogen fixation throughout bacterium symbiotic association with rhizosphere.

3.2. Soil Mineral Fertility

The results from the soil chemical analysis at 0.0 to 0.10 m depth at the end of tomato harvest are shown in Table 1. For the calcium (Ca) content and the cationic exchange capacity (CEC) had significant interaction between experimental factors, because the soil Ca content and CEC increased under white lupin cover crop and conventional tillage (Figure 1(a) and Figure 1(b)).

Table 1. Soil chemical analysis of calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), organic matter (OM), pH, cationic exchange capacity (CEC) and base saturation (V%) at 0.0 to 0.10 m of depth from the experimental treatments of cover crops, white lupin and millet and methods of tillage, conventional tillage and no-tillage.

Treatments	Ca	Mg	K	S-SO_4	P	OM	pH	CEC	V%
	mmolc dm^{-3}			mg dm^{-3}		g dm^{-3}		mmolc kg^{-1}	
Cover Crop (CC)									
White Lupin	56.4	24.7	8.1	16.5	106.0	32.6	5.8	112.9	78.6
Millet	61.2	26.5	6.1	16.1	116.4	31.2	5.9	116.1	81.1
P ≤ F	0.0609	0.0796	0.0164*	0.7542	0.1992	0.2950	0.1571	0.3280	0.1695

Continued

Methods of Tillage (T)									
Tillage	63.6	27.6	7.6	15.7	120.7	33.2	6.0	119.9	83.4
No Tillage	54.4	23.6	6.6	16.9	101.6	30.6	5.7	109.1	77.4
P ≤ F	0.0044*	0.0015*	0.2009	0.3580	0.0310*	0.0628	0.0012*	0.0076*	0.0153*
Interaction (CC × T)	0.0098*	0.2881	0.4061	0.4705	0.1803	0.3867	0.3303	0.0529*	0.2118

*Significant differences by the variance analysis (ANOVA) at 5% of probability.

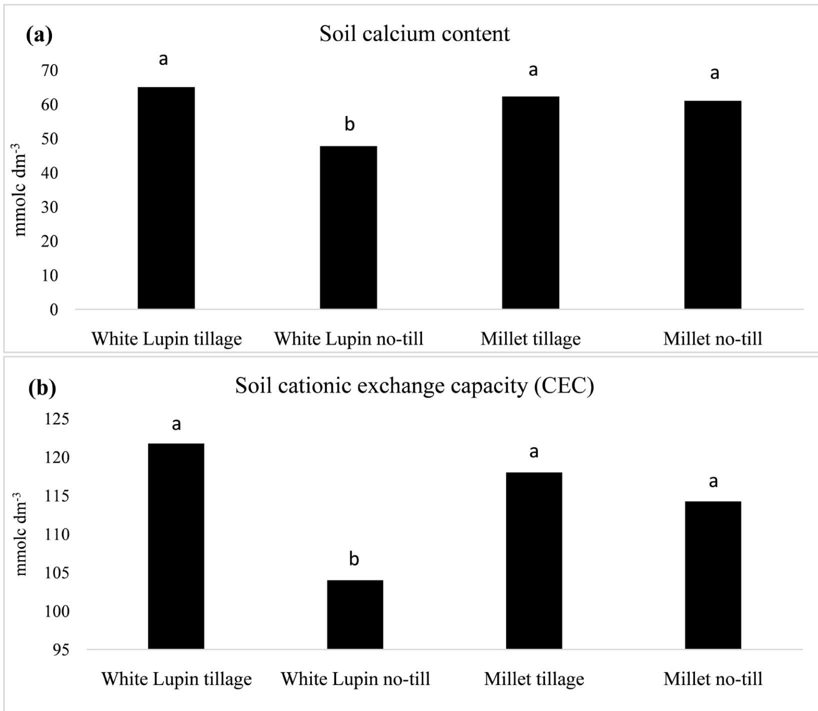

Figure 1. (a) The soil calcium (Ca) content; (b) cation exchange capacity (CEC) in soil of the experimental treatments at 0.0 - 0.10 m depth.

The soil magnesium (Mg) concentration at 0.0 to 0.10 m depth had no difference between cover crop, millet and white lupin. However, the soil Mg concentration in the conventional tillage (27.6 mmol dm^{-3}) was larger than no-tillage (23.6 mmol dm^{-3}).

The soil potassium (K) concentration increased in white lupin crop rotation with 8.1 $mmol_c$ dm^{-3} regarding to soil under millet cover crop, that's recorded 6.1 mmol dm^{-3}. There is no difference between tillage methods for soil K concentration at 0.0 to 0.10 m depth.

The soil sulfur (S) concentration had no difference between experimental treatments of cover crops and soil tillage methods. The soil phosphorus (P) concentration at 0.0 to 0.10 m depth there is no difference between cover crops, but in the conventional tillage the soil P concentration (120 g dm^{-3}) increased compared to no-tillage (101 g·dm^{-3}).

The experimental treatments had no significant effect on the soil organic matter at 0.0 to 0.10 m depth. Regarding soil pH, conventional tillage increased pH compared to no-tillage.

The results of the soil chemical analysis from 0.10 m to 0.20 m depth are shown in **Table 2**. For the soil chemical traits evaluated in the research there was no interaction between experimental factors, cover crops and soil tillage methods.

Table 2. Soil chemical analysis of calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), organic matter (OM), pH, cationic exchange capacity (CEC) and base saturation (V%) at 0.10 to 0.20 m of depth from the experimental treatments of cover crops, white lupin and millet and methods of tillage, conventional tillage and no-tillage.

Treatments	Ca	Mg	K	P	OM	pH	CEC	V%
	mmolc dm^{-3}			mg dm^{-3}	g dm^{-3}		mmolc kg^{-1}	
Cover Crop (CC)								
White Lupin	48.2	21.0	4.9	64.4	27.2	5.7	99.5	74.5
Millet	45.1	19.9	4.2	58.0	25.6	5.6	94.2	73.1
P ≤ F	0.2042	0.2495	0.0724	0.3992	0.0280*	1.000	0.1015	0.4319
Methods of Tillage (T)								
Tillage	50.4	22.1	5.0	69.0	28.2	5.7	104.2	74.1
No Tillage	43.0	18.7	4.2	53.4	24.6	5.7	89.5	73.5
P ≤ F	0.0103*	0.0050*	0.0466*	0.0582*	0.0003*	0.4690	0.0006*	0.7171
Interaction (CC × T)	0.1467	0.2495	0.6463	0.1743	0.1950	0.2861	0.1739	0.4319

*Significant differences by the variance analysis (ANOVA) at 5% of probability.

The Ca, Mg, K, P soil concentration and soil CEC increased under the conventional tillage regarding no-tillage. However, there is no difference for these soil nutrients between white lupin and millet at 0.10 to 0.20 m depth. White lupin increased soil organic matter regarding to millet as well as conventional tillage compared to no-tillage. The soil pH at 0.10 to 0.20 m depth there is no difference between treatments.

3.3. Soil Enzymatic Activity

The results of soil enzymatic activity are shown in **Table 3**. The experimental treatments of cover crop, white lupin and millet did not differ for soil activity of β Glucosidase enzyme. Meanwhile, conventional tillage increased the activity of β Glucosidase enzyme regarding to no-tillage, recording values of 102.6 and 62.2 ug p-nitrophenol/g/h, respectively.

The experimental treatments of cover crops, white lupin and millet and tillage methods, conventional and no-tillage did not differ for Arylsulfatase soil activity, which had average value of 57.0 ug p-nitrophenol/g/h.

Table 3. β Glucosidase e Arysulfatase activity at 0.0 to 0.10 m depth at the experimental treatments of white lupin and millet cover crops interacting with tillage methods, conventional (subsoiling and harrowing) and no-tillage.

Treatments	β Glucosidase	Arysulfatase
	ug p-nitrofenol/g/h	
Cover crops (CC)		
White lupin	87.5	59.9
Millet	78.1	54.2
P ≤ F	0.1619	0.4046
Tillage methods (T)		
Tillage	102.6	60.0
No-tillage	62.2	54.1
P ≤ F	<0.0001*	0.3848
Interaction (CC × T)	0.2719	0.8062

*Significant differences by the variance analysis (ANOVA) at 5% of probability.

3.4. Soil Moisture Content

Regarding to soil moisture content at 0.0 to 0.10 m depth, cover crops did not differ between them, which had recorded average value of 20.5 g H_2O 100 g solo^{-1}, but soil tillage methods differed between them that's no-tillage stored more water with 22.1 g H_2O 100g soil^{-1} against 18.7 g H_2O 100 g soil^{-1} from conventional tillage, which means 18.2% more water in soil under no-tillage at top soil 0.0 to 0.10 m depth (**Table 4**).

Table 4. Soil moisture content at 0.0 to 0.10 m and 0.10 to 0.20 m depth at the experimental treatments of white lupin and millet cover crops interacting with tillage methods, conventional (subsoiling and harrowing) and no-tillage.

Treatments	Soil moisture 0.0 - 0.10 m	Soil moisture 0.10 - 0.20 m
	g H_2O 100 g solo	
Cover crops (CC)		
White lupin	20.4	21.1
Millet	20.7	20.8
P ≤ F	0.6355	0.5576
Tillage methods (T)		
Tillage	18.7	19.6
No-tillage	22.4	22.2
P ≤ F	0.0002*	0.0008*
Interaction (CC × T)	0.3717	0.0631

*Significant differences by the variance analysis (ANOVA) at 5% of probability.

At 0.10 to 0.20 m depth, it was not recorded no difference between cover crops for soil moisture content which average value was 20.1 g H_2O 100 g soil^{-1} for both, white lupin and millet. Meanwhile, under no-tillage the soil moisture content was 13.3% larger than conventional tillage which was recorded 22.2 g H_2O 100g soil[1] and 19.6 g H_2O 100 g $soil^{-1}$, respectively.

3.5. Soil Resistance to Penetration (RP)

Soil resistance to penetration did not differ for cover crop treatments, but regarding to tillage methods conventional tillage decrease soil resistance for penetration especially up to 0.00 to 0.20 m depth compared to no-tillage. For soil depths below 0.20 m there was not significative difference between conventional and no-tillage (**Figure 2**).

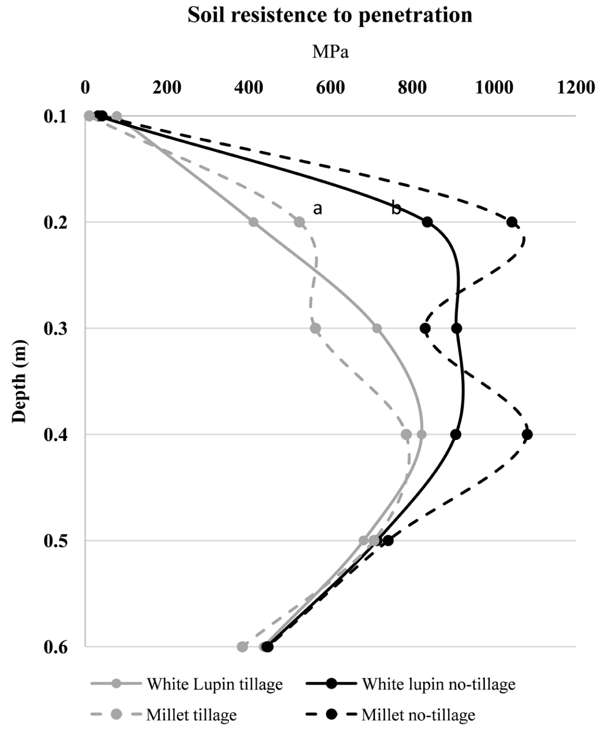

Figure 2. Soil resistance to penetration at 0.00 to 0.60 m of depth from the experimental treatments.

3.6. Tomato Aboveground and Root Growth

The cover crops treatments were significant for quantity of tomato brunch accounted at 55 days after transplanting (DAT), where tomato grown successively to white lupin produced 16 fruit bunches against 11 produced in succession of millet (**Table 5**).

The same result was recorded for the quantity of tomato fruits and to the tomato fruit fresh biomass, because in succession to white lupin, tomato produced 35 fruit per plant against 21 fruits per plant from the succession of millet and produced 1535.7 g $plant^{-1}$ of fruit fresh biomass in successive grown to white lupin against 998.8 g $plant^{-1}$ at millet succession.

Table 5. Quantity of fruit bunches (QFB), quantity of fruits (QF), fruit fresh biomass (FFB) and plant dry biomass (PDB) of tomato plants at 55 days after transplanting under experimental treatments of white lupin and millet cover crops interacting with tillage methods, conventional (subsoiling and harrowing) and no-tillage.

Tratamentos	QFB	QF	FFB	PDB
	quantity		g	
Cover crops (CC)				
White lupin	16	35	1535.7	141.6
Millet	11	21	998.8	148.1
P ≤ F	0.0287*	0.0102*	0.0439*	0.8029
Tillage methods (T)				
Tillage	14	29	1292.5	168.8
No-tillage	13	26	1242.1	120.8
P ≤ F	0.7189	0.5126	0.8310	0.0901
Interaction (CC × T)	0.9042	0.9120	0.7221	0.8702

*Significant differences by the variance analysis (ANOVA) at 5% of probability.

The experimental treatments of cover crops and tillage methods had not significative effect on the tomato aboveground dry biomass evaluated at 55 DAT.

There was no significative difference among experimental treatments of cover crops and tillage methods for root quantity, root length, volume and area of soil explored by tomato roots measured at 55 days after transplanting at 0.00 to 0.20 m of soil depth (**Figure 3**). The same results of tomato root growth parameters were recorded at 0.20 to 0.40 m measurement that's any experimental treatments were not efficient to differ on root growth parameters (**Figure 4**).

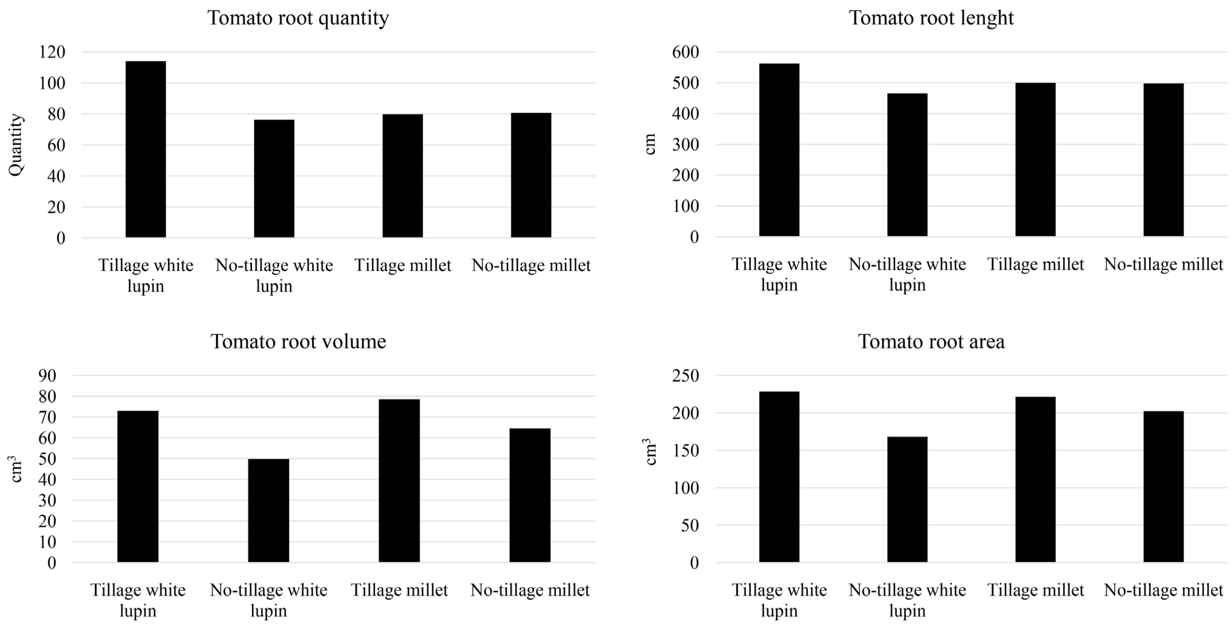

Figure 3. Tomato root growth at 0.0 to 0.20 m depth under experimental treatments.

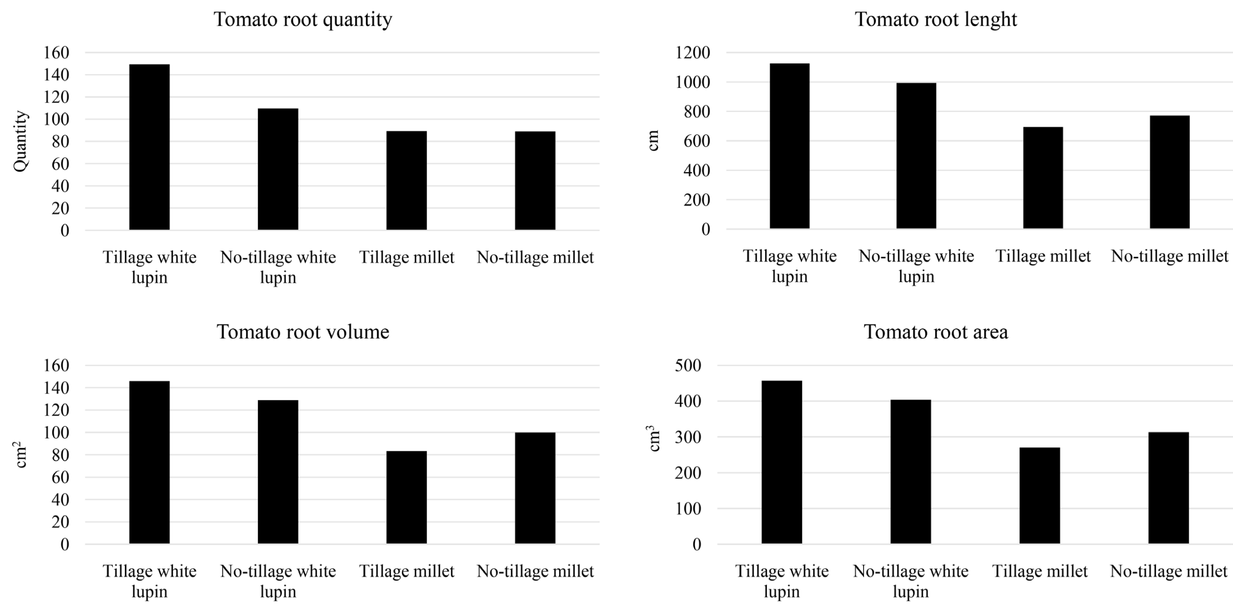

Figure 4. Tomato root growth at 0.20 to 0.40 m depth under experimental treatments.

3.7. Tomato Yield

The cover crops treatments did not differ between them for tomato yield, but for tillage methods, conventional tillage with 70.4 $Mg \cdot ha^{-1}$ of tomato yield was greater than no-tillage which had 56.5 $Mg \cdot ha^{-1}$ (**Table 6**).

Table 6. Tomato yield at the experimental treatments of white lupin and millet cover crops interacting with tillage methods, conventional (subsoiling and harrowing) and no-tillage.

Treatments	Tomato yield Mg ha^{-1}
Cover crops (CC)	
White lupin	68.5
Millet	58.5
$P \leq F$	0.1181
Tillage methods (T)	
Tillage	70.4
No-tillage	56.5
$P \leq F$	0.0397*
Interaction (CC × T)	0.4069

*Significant differences by the variance analysis (ANOVA) at 5% of probability.

4. Discussion

The conventional tillage was the treatment that improved the chemical soil analysis as well as the tomato yield. Ca and Mg concentrations at 0.0 to 0.20 m depth in conventional tillage were bigger than no-tillage, owning the fact of soil tillage with subsoiling and harrowing had provided better distribution of lime along this soil profile. Thus, the better distribution of lime in the conventional tillage reflected in the improvement of soil cation exchange capacity (CEC). So, it is need to highlight that under no-tillage the soil Ca and Mg concentration and pH were kept in adequate concentration for tomato growth. This fact proves that the environment built by conservation agriculture along the time has contributed to the lime displacement in the soil profile (Caires *et al.*, 2005) [15]. In this way, soil under the conservation tillage increases their capacity to reduce the loss potential of calcium carbonate ($CaCO_3$) along the time, which leads to improvement of soil acidity in the field (Murillo *et al.*, 2006) [4].

The soil phosphorus (P) content also was larger in conventional tillage by the same fact of Ca and Mg, because these nutrients have low mobility in soil and so the mechanism of tillage provide a better distribution of these nutrients in soil profile owing the soil disturbance. However high concentration of P was reported in field grown with maize under no-tillage compared with minimum tillage (scarification at 0.20 m) fact that was attributed by the better growth plant and great P exportation by maize under minimum tillage which results in decreasing of P concentration in the soil regard to no-tillage (Behnke *et al.*, 2020) [16].

Conventional tillage increased soil organic matter at 0.10 to 0.20 m depth owing the fact tillage have had incorporated cover crop residues into the soil at greater depth. It is known that tillage increase soil organic matter oxidation and consequently decrease it concentration, but in this work the field have been cultivated for a long time under no-tillage and just one occasional tillage did not enough to decrease soil organic matter, but indeed it increase soil organic matter in short term due to the incorporation into the soil.

No-tillage is soil conservation method which promotes increasing in soil organic matter especially when embraced crop rotation with cover crops in the cropping system (Yan *et al.*, 2024 [17]; Thomazini *et al.*, 2015 [18]). However occasional tillage with minimum soil disturbance (chiseling and subsoiling) in suitable season, especially in low precipitation, provide great cropping yield maintaining high levels of soil carbon (He *et al.*, 2021 [19]; Wuest *et al.*, 2023) [5].

Although the soil fertility level has been increased in the occasional tillage we must not fail to report that in no-tillage the soil fertility has shown with high levels of fertility both in the concentration and balance of nutrients and as well as in organic matter.

Along 5 years of study comparing conventional tillage, minimum tillage with just subsoiling and no-tillage, Yan *et al.* (2024) [17] reported larger carbon and nutrients availability under no-tillage and minimum tillage at the 0.0 to 0.40 m depth. So, it turns clear that high frequency of tillage along the time leads to decrease of soil fertility besides to expose soil to run-off.

The cover crops, white lupin and millet had little differences between them at the soil fertility, exception to potassium (K) because white lupin provide large concentration especially at 0.0 to 0.10 m depth.

The conventional tillage increased biological activity of β Glucosidase due to that fact of tillage has improved organic matter in the soil profile which provided substrate to elevate β Glucosidase activity, since this enzyme it relates to final step of organic matter decomposition. As conventional tillage increased the organic matter into the soil at 0.0 to 0.20 m it has led to increasing in β Glucosidase activity. Soil with good health present higher enzymatic activity and provides better cropping yield. Soils under native vegetation and Conservation Agriculture presented higher activities levels of Arylsulfatase and β Glucosidase compared to conventional tillage. Under no-tillage Arylsulfatase had 50 ug p-nitrofenol/g/h compared to 25 ug p-nitrofenol/g/h under conventional tillage and β Glucosidase presented 140 ug p-nitrofenol/g/h under no-tillage against 60 ug p-nitrofenol/g/h under conventional tillage (Barbosa *et al.*, 2023) [20]. More information about the soil health and bioanalysis can be find at link (https://www.embrapa.br/en/busca-de-noticias/-/noticia/91047236/soil-bioanalysis-and-health-get-online-course-in-english-and-spanish).

The soil moisture content increased with no-tillage at 0.0 to 0.20 m depth regard conventional tillage owing to maintenance of the straw on soil surface as well as to have preserved the structural soil integrity which avoid excessive soil evaporation as happen under conventional tillage (Wuest *et al.* 2023) [5]. In this way, it is possible to reduce the amount of water by irrigation leading to reduction in energy costs and water consumption when tomatoes are grown under conservation agriculture. Yin *et al.* (2023) [6] also reported that the straw maintenance on the soil surface increased soil moisture content at 0.0 to 1.20 m depth regard to conventional tillage which improved soil thermal and hydric conditions and then in better performance of wheat yield. In vegetable cropping, eggplant and cabbage, under no tillage and kept straw on the soil surface produced by cover crops in tropical conditions contributed to improve soil moisture content and thus save water irrigation (Thomazini *et al.*, 2015) [18].

Conventional tillage reduced soil resistance to penetration (RP) at 0.20 m depth owing subsoiling and rotary tillage mechanic performance. However, the tomato root has grown similarly between tillage methods, which shown that even with high values of RP under no-tillage compared to conventional tillage was not prevented to adequate tomato root growth. Tomato root growth is more resilience to compaction in clay soil (Tracy *et al.*, 2013) [21] and this corroborate so that there would be no significant difference to root growth between conventional tillage and no-tillage because the clay texture of the experimental soil (530 g kg of soil^{-1}) despite reduction of the soil RP in conventional tillage at 0.0 to 0.20 m. According Peixoto *et al.* (2020) [7] occasional tillage improved soil physical properties (penetration resistance, soil bulk density, macro porosity, and total porosity), with persistence, generally, greater than 24 months.

The tomato aboveground growth at 55 days after transplanting was similar between tillage methods, however regard cover crops tomato had better fruit bunches quantity and fruit fresh biomass when grown after white lupin, most likely because it was benefited by nitrogen from the biologic fixation provided by symbiotic relation between bacterium and white lupin rhizosphere.

The tomato cropping is benefited by prior growing of legume cover crops, especially by nitrogen availability from the biological fixation which is taking along the growth of tomato enhancing nutrition and cropping yield (Sugihara *et al.*, 2016 [22]; Muchanga *et al.*, 2017 [23]; Branco *et al.*, 2013 [11]). In this way, Geng *et al.* (2023) [10] also reported beneficial effect of crop rotation with legume cover crop with wheat which contributed to improvement of 8.6% of crop nitrogen use efficiency that's leaded to increase yield wheat about 21% to 31% and reduce nitrogen fertilization. For processing tomato cropping, Ardenti *et al.* (2024) [24] reported benefits of Conservation Agriculture to improving soil health without a negative impact on tomato yield, supporting tomato production under climatic change scenarios.

Tomato yield was better under conventional tillage that was corroborated by the fact that tillage have made available larger nutrient quantity and also has increased the biological activity of the β Glucosidase enzyme which contributed for enhancement of tomato yield. However, it is necessary highlighted that's no-tillage avoid soil erosion efficiently (Nouri *et al.*, 2021) [3], increase the stability production besides to saving natural resources and to enhance crop resilience facing climatic changes (Guerra *et al.*, 2021) [25]. The Conservation Agriculture in Brazil and South America have been adopted in large scale by extensive cereal growers due the benefits bring to the environment and cropping. So, is need highlighted the availability of high technology supported by the enterprises to development of CA. However, for smallholder is still little the support of enterprise in offer machinery for this proposal. So, we have seen a great development of self-production of machinery by smallholders which are enough to guarantee quality in sustainable crop production under CA in smallholder situation in tropical conditions. In this sense there is a great opportunity for establishment of startups to meet the needs of CA for smallholders.

5. Conclusions

This study demonstrated that no-tillage was more effective to storing water in the soil, however conventional tillage increased soil fertility regarding to nutrients levels, enzymatic activity of β Glucosidase and organic matter besides to release soil resistance to penetration at 0.0 to 0.20 m depth which contribute to increase tomato yield.

Regarding to cover crops white lupin increased the soil K concentration and enhanced the tomato growth.

Despite occasional tillage had better results for the soil fertility and tomato yield, we highlighted that Conservation Agriculture is the better way to increase soil health and soil water storage. When decision-making is drive to conventional tillage to reduce soil compaction, we suggest do it in a season with low precipitation to avoid soil loss by run-off and reduce environmental impact.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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