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Tillage Practices and Liming: Comparative Study of Soil Properties and Forage Corn Production

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Abstract: Tillage conservation practices (CA), traditional agriculture (TA), and liming influence soil properties and crop yield. However, it is essential to demonstrate which tillage and liming practices improve soil properties and forage corn yield. This study compared soil properties and forage corn production in two tillage systems with the addition of dolomite and lime, which formed four treatments. The tillage in the first three days surpassed the TA soil CO_2 emission, with 64.8% more CO_2 than in the CA soil, and the TA hydraulic conductivity and bulk density were more suitable than those in the CA soil. The CA soil had 233 earthworms m^{-2} more than in TA. The TA green forage corn yielded 6.45 t ha^{-1} more than in CA, with a higher P, Ca, and Mg foliar content than in CA, but in the CA, the foliar N and K were higher than in TA. The liming increased soil cations (except K), highlighting the lime on dolomite with—52% Al and + 4.85 t ha^{-1} of forage corn compared to the control. Soil CO_2 emission was far lower in CA than in TA, with a slightly lower forage yield, and other soil properties were improved, meaning lower land preparation costs and time savings than in TA. Lime improved acidic soil faster than dolomite, generating higher forage yields.

Keywords: conservation and traditional agriculture; soil CO_2 emission; lime and dolomite; leaf area index; cationic relationships; forage corn yield

1. Introduction

Traditional agriculture (TA) is characterized by tillage and bare soil management, which are practices identified as the main factors of soil degradation [1–3]. In the last 40 years, one-third of productive land worldwide is estimated to have been lost due to erosive processes derived from soil tillage [4], leading to severe soil erosion through mass downslope transport due to high stocking rates and over-grazing [5,6]. The Peruvian Amazon soils present severe erosion that negatively impacts more than 300,000 ha of crops [7], producing less profitable crops each year [8]. Furthermore, unsuitable cultural practices adopted by farmers aggravate this phenomenon as they sow crops parallel to the soil slope, thereby generating higher soil vulnerability to erosion [9,10]. MIDAGRI [11] reported that the Ucayali Department only has 11.7% of suitable soil for crops under tillage, while 57.3% is for forestry production. Soil scarcity for crop production and migratory agriculture are some factors that encourage farmers to invade unsuitable soils for crop production [12], expanding the agricultural frontier and exposing those soils to intense tillage [13].

When tillage begins, soil experiences fractures that break its structure; organic matter oxidation, runoff [14], and bulk density [15] increase; and hydraulic conductivity and water content decrease, leading to soil erosion [16,17]. Furthermore, tillage creates an adverse environment for soil macrofauna due to inadequate temperature, soil humidity, and lower carbon availability, which decreases the earthworm population [18–20].

Conservation agriculture (CA) is characterized by no burning crop residues, minimum mechanical soil disturbance for sowing, and permanent cover crops, whose objective is to improve the soil's physicochemical and biological properties [21–23]. Also, CA is crucial in preserving biodiversity, especially pest control and crop yields [24,25], is a recognized method to attenuate soil erosion [3,16,17], and emerges as a friendly alternative with natural resources, showing suitable conductivity hydraulics [15,26], lower bulk density [27], and higher soil moisture [28,29] than those in TA. Organic matter oxidation is excessive in TA-tilled soil, emitting a higher CO_2 amount than in CA-untilled soil [30]. In the long term, it could reduce organic matter storage and soil fertility [31,32], disturbing the biodiversity of agroecosystems [33].

Additionally, 40–50% of the world's agricultural soils are acidic [34], with a pH less or equal to 5.5 [35], reduce macronutrients and molybdenum availability, raise Al solubilization, becoming toxic for crops [34,36,37]. This indicator added to an Al percentage higher than 25%, characterizes an acidic soil, which led to a significant decrease in corn yield [27,38,39].

Although information is available about this topic, it has not yet assessed the impact of different tillage and liming methods on soil properties in the study region, particularly in acid soils; a field study is considered the best way to answer the question of which tillage and liming practices affect soil properties the least and improve yield. We hypothesized that CA with liming to the soil is an alternative that could attenuate soil CO_2 emission, improve other soil properties, and increase forage corn yield in acid soil. The main objective of this study was to determine the dynamics of soil properties and yield of forage corn under two tillage and liming practices.

2. Materials and Methods

2.1. Location and Description

The study was set from 6 October 2022 to 28 February 2023 at the experimental field of Pucallpa Agrarian Innovation Sate Institute (INIA Pucallpa) located in Campoverde District, Ucayali Department, 8°32′31.05″ S, 74°52′41.58″ W at 193 m a.s.l. In addition, the temperatures ranged from 30.3 to 35.0 °C, 83% relative humidity, 156 $w\ m^{-2}$ solar radiation, and 0.9 $m\ s^{-1}$ wind speed. The experimental plot belonged to a plain (non-floodable low terrace) covered by *Desmodium* sp. for a long period. The soil was classified as a Typic Dystrudepts [40], with 53, 21, and 26% of sand, silt, and clay, respectively; electrical conductivity = 1.9 $dS\ m^{-1}$; $pH_{(1:1)}$ = 5.1; organic matter = 2.15%; extractable P (Bray) = 5.84 ppm; potassium (K) = 0.17 $cmol^{(+)}\ kg^{-1}$; cation exchange capacity (CEC) = 4.21 $cmol^{(+)}\ kg^{-1}$; and Al = 54%.

2.2. Experimental Design and Treatments

A split plot design with a randomized complete block arrangement was applied. The tillage system factor was established in main plots, corresponding to conservation agriculture (CA) and traditional agriculture (TA). The liming factor was set in subplots (58 days before sowing), corresponding to lime (L) and dolomite (D). Also, a control (C) treatment was included, which did not receive the liming, configuring six treatments with four replications with 24 experimental units. The main plots (20 m long × 4 m wide) consisted of two tillage systems: conservation and traditional agriculture, and the subplots (5 m long × 4 m wide) consisted of three limings: dolomite, lime, and control.

2.3. Liming and Crop Management

Before the forage corn sowing, the experimental plot was prepared by cutting *Desmodium* sp. at 5 cm height, leaving 0.24 ± 0.06 kg m^{-2} as a cover crop, homogeneously spread on the soil surface. In the TA treatment case, the soil was tilled with a hand pick before liming, and the cover crop was removed. Next, 9200 and 4416 kg ha^{-1} of L and D, respectively, were applied to the assigned subplots. The liming was carried out on the same day for both tillage systems; it was superficial and incorporated manually into the soil with a hand pick in the CA and TA, respectively. L contained 90% calcium carbonate ($CaCO_3$), and D had 30.8% calcium oxide (CaO) plus 15.7% magnesium oxide (MgO). Finally, the sowing was carried out at a row and plant distance of 0.6 and 0.2 m, respectively, with two seeds, each 0.2 m, obtaining a potential density of 166,666 plants per ha. Fertilization was applied a week after corn emergence, with a dose of 100 kg of N ha^{-1}, 80 kg of P_2O_5 ha^{-1}, and 100 kg of K_2O ha^{-1}, and 42 days later, a dose of 100 Kg N ha^{-1} was newly applied, whose sources of N, P_2O_5, and K_2O were urea, diammonium phosphate, and potassium chloride, respectively.

Desmodium sp. weeds were controlled manually during soil CO_2 emission monitoring and a day after forage corn sowing. The 0.2% cypermethrin application controlled cutworms (*Agrotis* spp., *Feltia* spp.) on the 9th day after sowing (das), an application of 0.2% cypermethrin effectively controlled cutworms (*Agrotis* spp., *Feltia* spp.). Corn earworms *Helicoverpa zea* Boddie, were managed by applying 0.2% chlorpyrifos on the 32nd and 54th das.

2.4. Measurement of Variables

2.4.1. Soil Biological Variables

Soil CO_2 Emissions

A pair of closed chamber systems were installed in each experimental unit. Inside each chamber, a 50 mL vial was placed, containing 35 mL of a NaOH solution (0.5 M) to work as a CO_2 trap, which was replaced at the same time every 3–4 days until 21 days after the first chambers' installation carried out immediately after tillage. Polypropylene chambers with 3 L volume were put inverted on the soil at 2 cm depth, and their edges were hermetically sealed with mud. CO_2 capture was determined by NaOH titration against HCl (0.1 N), using 2 mL of barium chloride ($BaCl_2$ $2H_2O$) (≥99.5%, Merck, Darmstadt, Germany) together with phenolphthalein as an indicator. The titration was carried out immediately after removing the trap solution from sealed chambers, avoiding contact with the air, and using a control trap without soil control trap installed without soil to correct the CO_2 calculated amount [41]. In addition, soil temperature and gravimetric moisture were recorded at each CO_2 trap replacement, at 5 cm depth in the soil, near the chamber's outer edge, using a digital thermometer (TP-101, WMETERS, Nanjing, China) and the cylinder method, respectively. The last method used a cylinder of 99 cm^3, where the extracted soil had the same cylinder volume, and the fresh and dry soil weights (fsw, dsw, respectively) were recorded by drying in an oven at 105 °C for 48 h, so the soil gravimetric moisture (M°) was determined by applying the following formula [42]:

$$M^\circ(\%) = \frac{(\text{fsw} - \text{dsw})}{\text{dsw}} \times 100\ \% \tag{1}$$

Earthworm Population

The earthworm number in the soil was counted (83 days after sowing (das)) at two soil depths (0–10 and 10–20 cm), each depth corresponding to a volume of a parallelepiped with a square base edge of 20 cm, 10 cm high. The amount found was multiplied by 25, obtaining the number of earthworms per m^{-2} [43].

2.4.2. Soil Physical Variables

Gravimetric Moisture (M°) and Bulk Density (Bd)

M° was determined (40 and 83 das) by the cylinder method, at two soil depths, 0–10 and 10–20 cm. After determining dry soil weight (dsw) and knowing total volume of the sampling cylinder, Bd was calculated (83dds) using the following formula [42]:

$$\mathrm{Bd}(\mathrm{gcm}^{-3}) = \frac{\mathrm{dsw}}{\mathrm{total\ volume}} \tag{2}$$

Hydraulic Conductivity (Ks)

The Ks was determined (83 das) by using a metallic ring (20 cm high and 17 cm diameter) inserted 1 cm deep into the soil after removing any cover crop residue on the soil surface. A volume of 0.15 L of water was repeatedly applied inside the ring, and the time of each infiltration (I) was recorded until the last one was very slow. The number of infiltrations with their respective accumulated times was recorded to determine the cumulative infiltration (IR) through the plot of IR vs. time, and the infiltration rate (IR) was determined by the slope trending line on the plot [44]. The Ks was defined with the formulas:

$$\mathrm{Ks}(\mathrm{mm\ s}^{-1}) = \frac{\mathrm{IR}}{0.467\left(1 + \frac{2.92}{\mathrm{r}\alpha^{*}}\right)} \tag{3}$$

where:

r(m): radius of the ring

$$\alpha^{*} = 0.0262 + 0.0035 \times \ln(\mathrm{IR}) \tag{4}$$

2.4.3. Soil Chemical Variables

Soil samples of each experimental unit were extracted from five subsamples, which were taken from 0–20 cm depth, after 58 days of the liming. The Ca, Mg, K, and Al contents were determined by the principle of atomic absorption spectrophotometry [42], using a spectrophotometer (AA500, PGInstruments, Westminster, UK) and expressed as percentages. The potentiometric method determined the pH using a potentiometer (pH7310, Inolab, Tuttingen, Germany), achieving 1:2.5 soil and water equilibrium through a saturated paste [45]. The mathematical division of such cations calculated the Ca/Mg, Mg/K, Ca/K, and (Ca + Mg + K)/Al cationic relationships.

2.4.4. Biometrics and Foliar Nutrients Content Variables

Height, Leaf Area Index, Green and Dry Forage Corn

Plant height was determined by measuring from the plant neck to the last stalk node, using a measuring tape at the complete flowering stage (48 das). The leaf area index (LAI) was determined (48 das) by the relationship between the leaf area (m^2) on its corresponding soil surface (m^2) [46]. Plants corresponding to 3 m from central sowing rows were cut at their base in a milky state (R3, 83 das) and weighed to determine green forage. Also, a sample of ten corn plants was oven-dried at 72 °C for 72 h to assess dry forage (83 das) Bazán [42].

N, P, K, Ca, Mg Foliar Content

Ten leaves opposite the top corn ear on the plant were extracted (48 das), washed, and dried at 65 °C for 72 h in an oven (UF450, MEMMERT, Büchenbach, Germany). Then, they were ground using an electric mill (FZ112, Solrimana, New Delhi, India). The foliar N was determined by the micro-Kjeldal method with a Kjeldal digestor (S2, Behr, Düsseldorf, Germany), while the K, Ca, and Mg were determined using an atomic absorption spectrophotometer (AA500, PGInstruments, Westminster, UK), and P was determined using the Olsen method [42].

2.5. Statistical Analysis

Outlier values of the analyzed variables were discarded. The earthworm population count was transformed using the factor $\sqrt{(x + 0.5)}$ to normalize the data. The variable values of soil properties, biometrics, yield, and foliar nutrient content of forage corn were processed using the analysis of variance (ANOVA). The averages were compared by the DGC test (Di Rienzo, Guzmán, and Casanoves), with a significance level of 5% ($p < 0.05$). The statistical analysis program R (version 1.3.1.) was used for statistical evaluation.

3. Results and Discussion

3.1. Soil Biological Variable

3.1.1. Soil CO_2 Emission

Soil CO_2 emission showed a significant statistical difference for the tillage system factor ($p < 0.05$) (Figure 1a). Soil CO_2 emissions ranged from 0.15 ± 0.003 to 0.25 ± 0.01 and from 0.16 ± 0.01 to 0.30 ± 0.01 g CO_2 m^{-2} h^{-1} in the CA and TA, respectively. The TA soil on the 3rd and 6th day emitted 0.12 and 0.04 g CO_2 m^{-2} h^{-1} more than in the CA, respectively, and on the 3rd day of CO_2 sampling, the closest day to the tilling, the CO_2 emission was the highest. However, on the 21st day, the CA soil significantly emitted 0.05 g CO_2 m^{-2} h^{-1} more than in the TA ($p < 0.05$) (Figure 1a). The soil CO_2 emissions in the CA and TA did not show significant differences on the 10th, 14th, and 17th days ($p > 0.05$), which showed similar soil temperatures (Figure 1b). Soil CO_2 emission in the TA and CA rhythmically increased and decreased with air temperature (Figure 1a,b). The TA soil temperature during CO_2 sampling was 0.99–5.99 °C higher than that in the CA (Figure 1b), and the CA soil moisture was 1.8–5.1% higher than in the TA (Figure 1c).

Soil CO_2 emission variation depends on soil tillage systems, and biotic and abiotic factors, which alter the soil microclimate [22,47]. Soil CO_2 emission values in the TA and CA (Figure 1a) were similar to those reported by Farhate et al. and Álvaro-Fuentes et al. [48,49], who studied the tillage effect on soil CO_2 emission. However, these values were low compared to those provided by La Scala et al. and Toufeeq et al. [23,30]. The peak of higher soil CO_2 emission (Figure 1a) in the TA could be explained by increased organic carbon oxidation after soil tilling, releasing higher CO_2 into the atmosphere [30]. In the first samplings, the TA practices showed far higher soil CO_2 emissions than in the CA, which was congruent with those reported by La Scala et al., Toufeeq et al., Silva-Olaya et al., and Álvaro-Fuentes et al. [23,30,47,49], whose experiments showed 1.26, 1.3, 0.32, and 34.8 g CO_2 m^{-2} h^{-1}, respectively, more than in the CA in this study. The CO_2 emissions did not show significant differences between TA and CA on the 10th, 14th, and 17th sampling day ($p > 0.05$), probably because both presented similar soil temperatures and because the abiotic factor was highly correlated with microbial activity [23,28], corresponding to similar CO_2 emissions.

Soil CO_2 emission with soil temperature (r = 0.76 to 0.95) and moisture (r = −0.46 to −0.73) were highly correlated on the 3rd, 6th, and 14th CO_2 sampling days (Figure 2a,b), which were analogous to the data obtained by Bilgili et al. [50]. On the contrary, those correlations only on the 21st day were negative and positive, respectively (Figure 2a,b), due to a higher decrease in soil moisture than the soil temperature (Figure 1b,c) and possibly due to cultural practices such as weed control that could alter the CO_2 emitted amount [23,47,49].

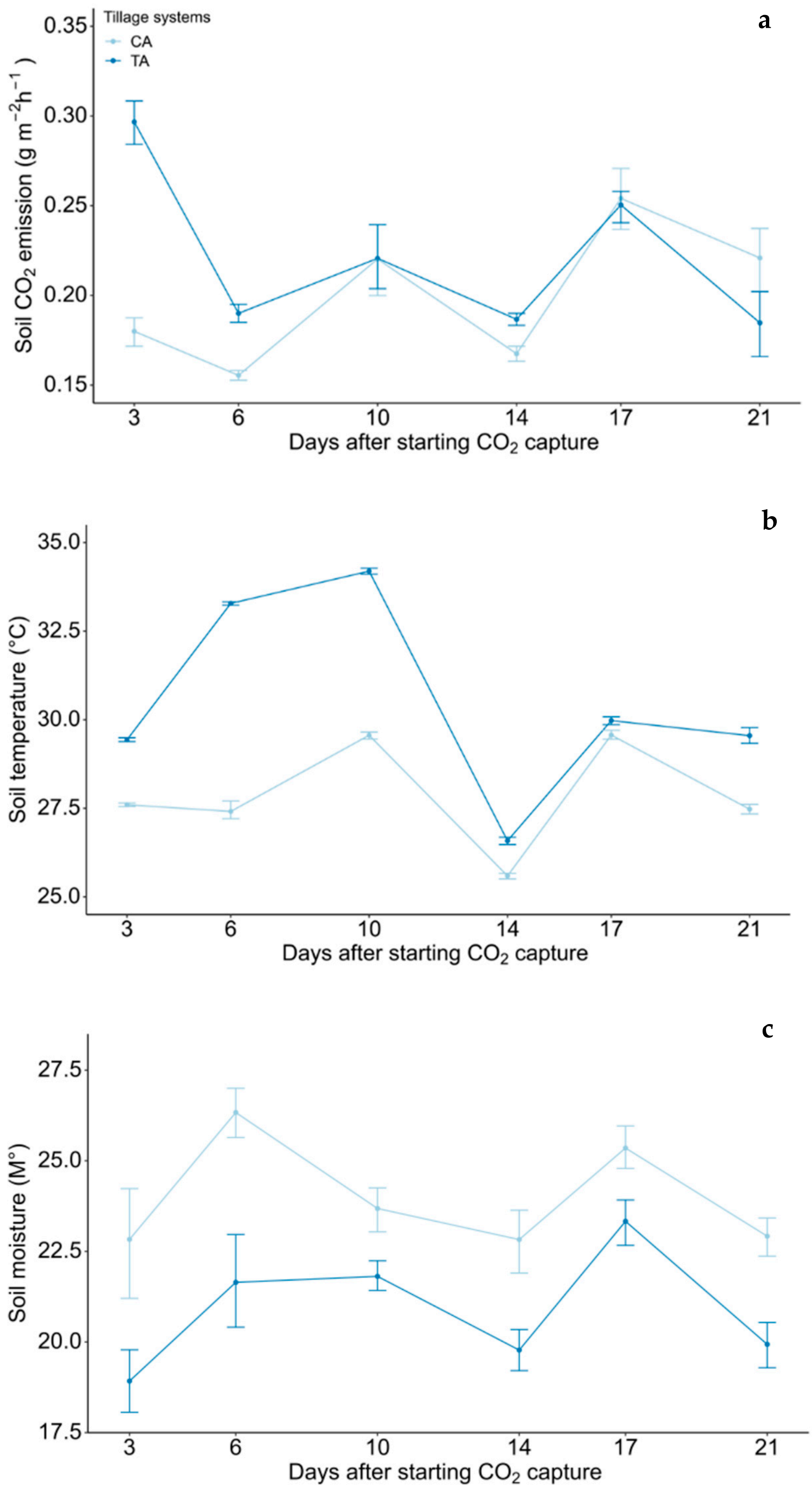

Figure 1. (**a**) Soil CO_2 emission related to (**b**) the soil temperature (T°) and (**c**) moisture (M°) with standard error for the tillage systems by 21 days. TA: traditional agriculture; CA: conservation agriculture.

Figure 2. Pearson's correlation coefficient matrix of the soil CO_2 emission with (**a**) the soil temperature (T°) and (**b**) moisture (M°). T°: soil temperature; M°: soil moisture; 3rd, 6th, 10th, 14th, 17th, and 21st: the sampling days of CO_2, T°, and M°.

3.1.2. Earthworm Population

Figure 3 shows mean values ± standard error of the earthworm population taken at 0–10 cm depth. In general, the interaction of the factors, tillage system × liming, showed significant differences ($p < 0.05$), where the CA×C, CA×L, and CA×D presented 263, 212, and 224 earthworms m^{-2} more than the TA×C, TA×L, and TA×D, respectively. Meanwhile, when the factors were evaluated separately, only the tillage system factor showed highly significant differences ($p < 0.05$), and the liming factor was not significant ($p > 0.05$), where the CA earthworm population reported 233 earthworms m^{-2} more than in the TA. Furthermore, earthworms were not found at 10 to 20 cm depth in the CA and TA, nor in the TAxD interaction at 0–10 cm depth (Figure 3).

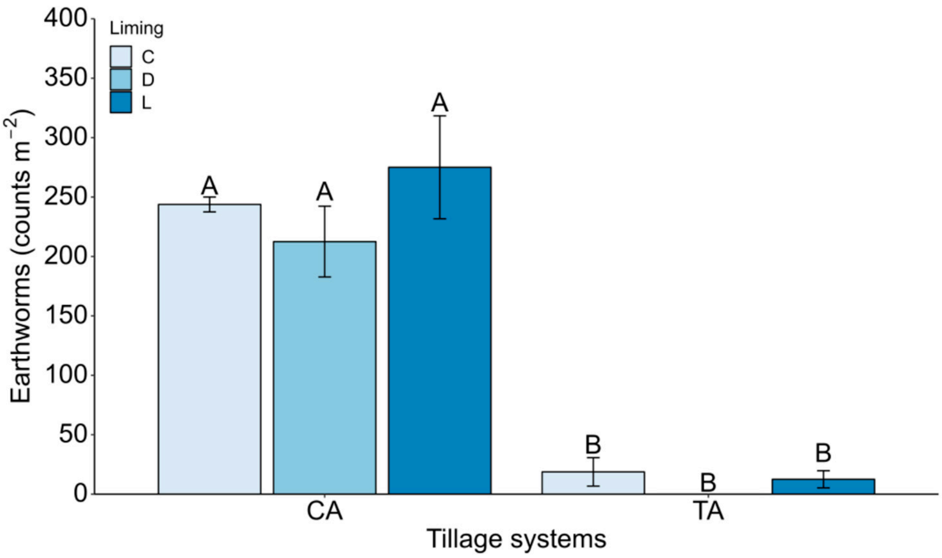

Figure 3. Arithmetic means and standard errors of the earthworm number at 0–10 cm depth, under the tillage system × liming interaction. CA: conservation agriculture; TA: traditional agriculture; C: control; D: dolomite; L: lime; A,B: different letters within the tillage systems indicate statistically significant differences according to the DGC test with $p < 0.05$.

The results showed that the CA practices increased the earthworm population compared to the TA practices due to the absence of physical damage caused by soil tillage, which was congruent with different studies [22,51,52]. It was probably due to the higher CA soil moisture [19,53,54] than in the TA, 10.89 ± 0.72 and 9.93 ± 0.51%, respectively (Figure 4), and cover crop in the CA presented 0.24 ± 0.06 kg m^{-2} of *Desmodium* sp., which served as a food source for earthworms [19]. Analogously, the number of earthworms m^{-2} reported by McInga et al., Nurul Aini et al., and Birkás et al. [18,53,55] in the CA soils was higher by 24, 17, and 52 earthworms m^{-2}, respectively, than in the TA soils, probably due to the elimination of tillage and the presence of crop stubble on the soil, conditions that provided a suitable abiotic environment for the development of earthworms [54].

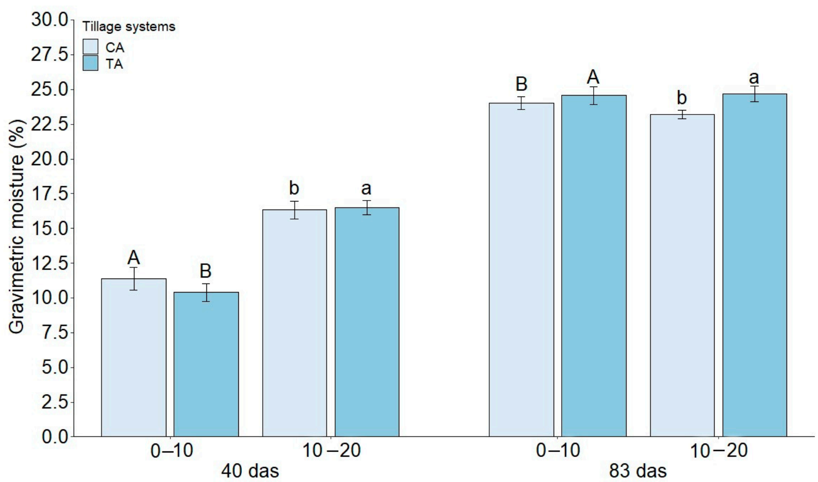

Figure 4. Arithmetic means and standard errors of the soil gravimetric moisture at two sampling times, at two soil depths. CA: conservation agriculture; TA: traditional agriculture; 0–10, 10–20: soil depths (cm); das: days after sowing; A,B/a,b: different letters within a soil depth indicate statistically significant differences according to the DGC test with $p < 0.05$.

The earthworm population with hydraulic conductivity (Ks) and bulk density (Bd) showed a negative and positive correlation (r = −0.93 and r = 0.43), respectively, probably due to a certain population of "soil compacting earthworm species" such as *Millsonia anomala* Omodeo and Vaillaud, normally found in the Peruvian Amazon [51], which could increase Bd and decrease Ks. The forage corn's foliar Ca content and the earthworm population reported a negative correlation coefficient (r = −0.41), probably because earthworm is a Ca-competing organism of soil biota [43], evidenced by the high Ca content in earthworm nests compared to agricultural soil, 5 and 3.93 ppm, respectively [56]; even in other nests, the Ca content was 2296.2 ppm, so the Ca is the element most required by earthworms (Boonchamni et al., 2019) [43].

3.2. Soil Physical Variables

3.2.1. Gravimetric Moisture (M°)

On the first and second sampling (40 and 83 days after sowing (das)), the tillage system factor expressed a significant statistical difference in the M° of the soil's two layers ($p < 0.05$). On first sampling, the M° in the CA soil was higher than that in the TA by 0.96% at 0–10 cm depth; and, at 10–20 cm depth, the M° was 0.18% higher in the TA soil than in the CA soil (Figure 4). On the second sampling, the M° in the TA soil was higher than that in the CA soil by 0.53 and 0.77%, at 0–10 and 10–20 cm depth, respectively (Figure 4). Furthermore, liming and the tillage system × liming interaction did not show significant statistical differences in soil M° at both depths and the two samplings ($p > 0.05$).

Different research studies indicate that M° is very variable when it is evaluated under different tillage systems [29,57,58]. The soil M° was higher in the CA than TA at the first layer and the first sampling because water evaporation from the CA soil was possibly lower due to the presence of a cover crop, *Desmodium* sp. [28,29]. On the contrary, the TA soil M° was higher than in the CA soil in the second layer, possibly because a clay layer below the first layer did not allow good drainage, and a greater amount of water was accumulated in the second layer. Furthermore, a "tillage floor" was formed and did not allow adequate water drainage [14]. On the second sampling, the determination of M° coincided with heavy rainfall days before, and possibly the "tillage floor" and the clay layer stored higher M° in TA soil than in CA soil.

3.2.2. Bulk Density (Bd)

The tillage systems factor was significantly different ($p < 0.05$) in Bd at 0–10 and 10–20 cm soil depth. In the first layer, the CA soil Bd was 1.54 ± 0.02 g cm^{-3}, representing 3.5% more than in the TA soil. Opposite results were reported in the second layer; the TA soil Bd showed 1.58 ± 0.02 g cm^{-3}, 0.65% more than in the CA soil (Figure 5). Furthermore, in the soil's two layers, the liming factor and the tillage system × liming did not show significant statistical differences ($p > 0.05$). However, the soils' Bd of the two types of tillage systems did not represent the ideal Bd for the sandy clay loam texture, which should be less than 1.4 g cm^{-3}, nor did they represent a restrictive Bd for the roots because they presented lower values at 1.75 g cm^{-3} [44].

Bd plays a significant role in soil because it influences soil compaction degree, movement of solutes and water, soil aeration, and drainage [22], and according to the results obtained, the tillage systems had a significant impact on soil Bd ($p < 0.05$). The CA soil Bd in the soil's first layer was higher than in the TA soil, and a similar effect was determined in analogous investigations and with soils of different textures [59–61]. However, the impact of CA and TA practices in soil Bd varied according to different studies. The low value of the TA soil Bd in the first layer could be explained by soil mechanical fracture due to tillage and reduction in soil total porosity [59,61,62] and by low clay content [27]. However, similar studies showed that at the transition beginning from TA to CA, soil Bd was not significantly different [15,29,61,63–65]. In other studies, TA soil Bd was significantly higher than in CA soil, but only in soils with a high clay percentage [27]. Furthermore, CA soil Bd was significantly lower than in TA soil through several sowings [15]. In this study, the first and second soil layers (on the 2nd sampling of M°) showed negative correlations of Bd and M° (r = −0.67 and −0.65), coinciding with other studies, probably due to when Bd increases, porosity decreases, reducing space for moisture [66,67].

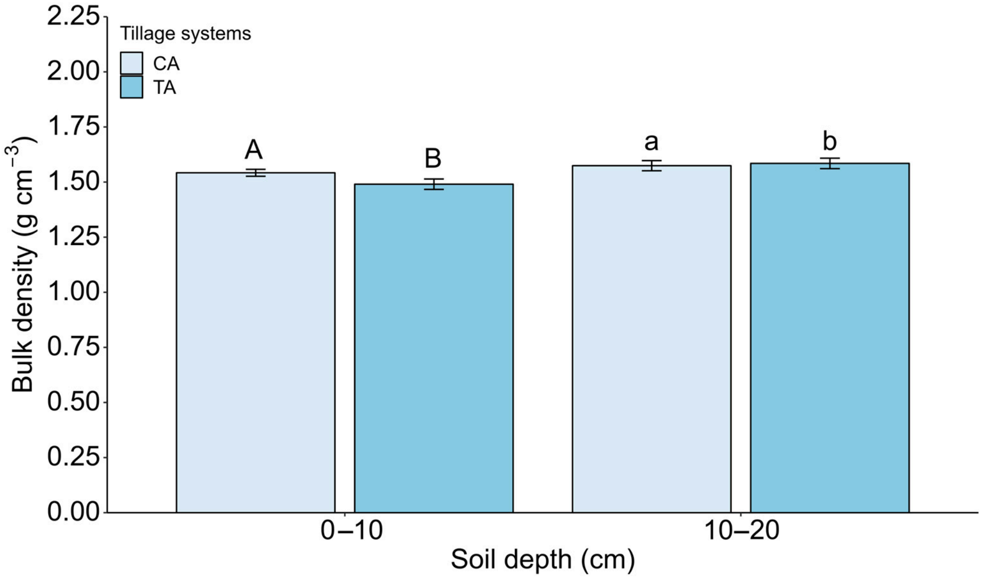

Figure 5. Arithmetic means and standard errors of bulk density under the tillage systems. at two soil depths CA: conservation agriculture; TA: traditional agriculture; A,B/a,b: different letters within a soil depth indicate statistically significant differences according to the DGC's test with $p < 0.05$.

3.2.3. Hydraulic Conductivity (Ks)

Interaction of the factors, the tillage system x liming, showed a significant difference on Ks ($p < 0.05$), where the interactions TA×C, TA×L, TA×D were 15.04×10^{-3}, 16.05×10^{-3}, and 17.40×10^{-3} mm s^{-1} more than CA×C, CA×L and CA×D, respectively (Figure 6). By analyzing the factors individually, only the tillage systems showed a significant difference ($p < 0.05$), where Ks in the TA and CA were $27.73 \pm 1.11 \times 10^{-3}$ and $11.54 \pm 0.03 \times 10^{-3}$ mm s^{-1}, respectively.

These results showed that the tillage system type strongly influenced the Ks. Ks is an essential soil property, so important for plant growth and soil life, probably because an adequate Ks increases the exchange of CO_2 with O_2 in soil, so plant roots' absorption of water and nutrients increases considerably [68]. According to Álvaro-Fuentes et al. [44], Ks was moderately fast and moderate in the TA and CA soils, respectively, where Ks in the TA soil was much higher than in the CA soil because the soil was tilled [69,70], causing the sudden increase in Ks [29]. These results were analogous to a study of conversion from TA to CA practices, where Ks in TA soil was 4.5×10^{-3} mm s^{-1} more than in CA soil [29]. However, Ks in the CA soil infiltrated 7.1×10^{-3}, 7.9×10^{-3}, and 5.3×10^{-3} mm s^{-1} faster than in the TA soil, according to Sartori et al. and Thierfelder et al. [15,26], respectively.

In other studies, the Ks did not show significant differences at the beginning of the transition from TA to CA: 42.7×10^{-3} vs. 42.2×10^{-3} and 9.1×10^{-3} versus 16.1×10^{-3} mm s^{-1}, respectively [71,72]. In this study, the low Ks in the CA soil (Figure 6) is explained by the higher Bd in the CA than in TA soil at 0–10 cm depth, 1.54 ± 0.02 and 1.48 ± 0.02 g cm^{-3} (Figure 5), respectively, evidenced through a negative correlation (r = −0.35) with the Bd (0–10 cm), because by increasing Bd, Ks decreases, probably due to a reduction in soil pore space [73]. Furthermore, the Ks and the green forage corn yield showed a medium positive correlation (r = 0.48), probably because Ks favored adequate O_2 exchange to soil [68], favoring crop yield.

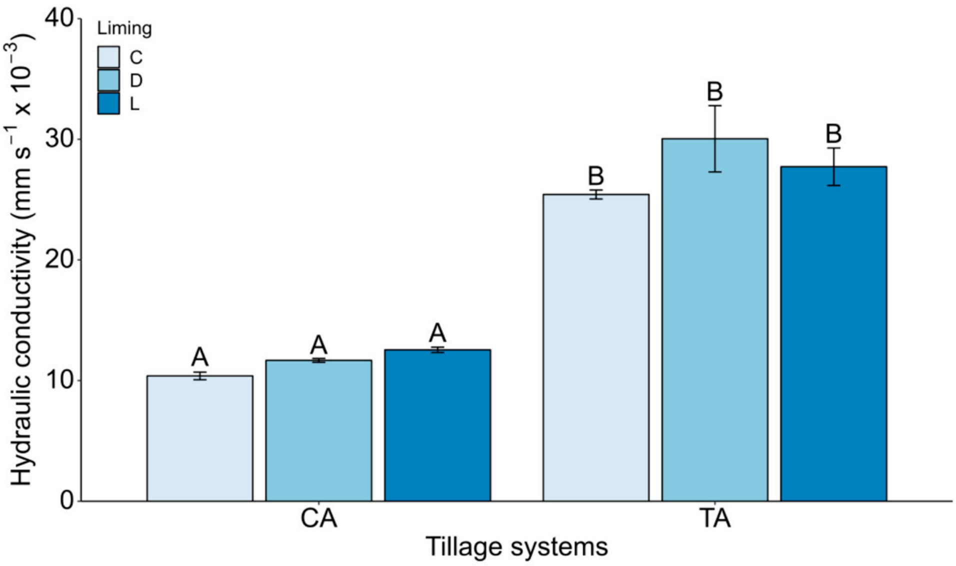

Figure 6. Arithmetic means and standard errors of the hydraulic conductivity under the interaction of tillage systems × liming; CA: conservation agriculture; TA: traditional agriculture; C: Control; D: Dolomite; L: Lime; A,B: different letters within tillage systems indicate statistically significant differences according to the DGC's test with $p < 0.05$.

3.3. Soil Chemistry Variables

Regarding the liming factor effect and the tillage system × liming, they reported significant statistical differences in the percentage of soil nutrients, cationic relationships, and soil pH ($p < 0.05$) (Table 1). The liming significantly decreased the k and Al concentrations in the soil ($p < 0.05$). The decrease in these elements was higher with the lime than with the dolomite application, having a similar repercussion on the interactions of the tillage systems with the lime vs. dolomite. Furthermore, the soil Ca concentration increased 37.8% more with the lime than with the dolomite application. Therefore, the Ca/Mg, Ca/K, and (Ca + Mg + K)/Al calcic cationic relationships increased by 6.6, 2.8, and 22.8 times more than those with the dolomite application (Table 1). Meanwhile, the dolomite application showed the highest increase in the Mg concentration and Mg/K relationship, 11.1% and 2.3 times, respectively, more than those under the lime application. Furthermore, these two variables had similar repercussions under the interaction of the dolomite × tillage systems (Table 1).

Table 1. Arithmetic means and standard errors of soil cations, cationic relationships, and pH dynamic under the tillage systems, liming, and the tillage systems × liming.

Factors	K	Mg	Ca	Al	Ca/Mg	Mg/K	Ca/K	(Ca + Mg + K)/Al	pH
	%								
Tillage systems (TS)									
CA	2.58 ± 0.25 a	7.29 ± 1.34 a	60.95 ± 7.19 a	29.18 ± 6.71 a	12.60 ± 3.00 a	2.97 ± 0.51 a	29.76 ± 6.41 a	20.55 ± 8.63 a	5.51 ± 0.15 a
TA	2.57 ± 0.03 a	8.50 ± 1.72 a	63.00 ± 6.68 a	25.93 ± 6.13 a	11.68 ± 2.67 a	3.78 ± 0.75 a	34.16 ± 7.74 a	22.53 ± 8.79 a	5.63 ± 0.15 a
Liming (Lg)									
C	3.66 ± 0.20 a	4.81 ± 0.27 b	37.93 ± 1.26 c	53.60 ± 1.55 a	8.01 ± 0.42 b	1.36 ± 0.10 c	10.49 ± 0.39 c	0.88 ± 0.05 b	4.93 ± 0.05 b
L	1.53 ± 0.12 c	3.91 ± 0.30 b	92.88 ± 0.32 a	1.68 ± 0.13 c	24.66 ± 1.73 a	2.68 ± 0.28 b	63.14 ± 4.54 a	61.06 ± 4.81 a	5.96 ± 0.10 a
D	2.52 ± 0.12 b	14.97 ± 0.65 a	55.13 ± 0.50 b	27.39 ± 0.96 b	3.74 ± 0.14 c	6.08 ± 0.49 a	22.25 ± 1.10 b	2.68 ± 0.14 b	5.96 ± 0.10 a
TS × Lg									
CA×C	3.44 ± 0.30 a	4.72 ± 0.34 c	35.82 ± 1.84 d	56.03 ± 2.24 a	7.68 ± 0.52 b	1.43 ± 0.16 d	10.58 ± 0.67 c	0.8 ± 0.07 b	4.88 ± 0.05 b
CA×L	1.69 ± 0.21 c	3.65 ± 0.33 c	92.87 ± 0.42 a	1.81 ± 0.25 e	26.10 ± 2.32 a	2.23 ± 0.10 d	57.58 ± 6.61 a	58.50 ± 9.94 a	5.87 ± 0.03 a
CA×D	2.60 ± 0.16 b	13.52 ± 0.31 b	54.18 ± 0.25 b	29.71 ± 0.19 c	4.03 ± 0.10 b	5.25 ± 0.32 b	21.13 ± 1.50 b	2.35 ± 0.03 b	5.88 ± 0.05 a
TA×C	3.89 ± 0.24 a	4.90 ± 0.47 c	40.05 ± 1.03 c	51.17 ± 1.48 b	8.35 ± 0.68 b	1.30 ± 0.12 d	10.40 ± 0.49 c	0.95 ± 0.06 b	4.98 ± 0.09 b
TA×L	1.38 ± 0.10 c	4.18 ± 0.52 c	92.89 ± 0.55 a	1.55 ± 0.05 e	23.23 ± 2.68 a	3.13 ± 0.48 c	68.70 ± 5.63 a	63.63 ± 2.17 a	6.03 ± 0.18 a
TA×D	2.44 ± 0.19 b	16.42 ± 0.69 a	56.08 ± 0.71 b	25.07 ± 0.84 d	3.45 ± 0.17 b	6.90 ± 0.75 a	23.38 ± 1.60 b	3.00 ± 0.14 b	5.88 ± 0.03 a

CA: conservation agriculture; TA: traditional agriculture; C: control; L: lime; D: dolomite; a–e: different small letters in a column indicate significant differences among TS, Lg, and TS × Lg, according to the DGC test with $p < 0.05$.

Further, the liming factor significantly increased soil pH ($p < 0.05$), and the pH values under the lime and dolomite application were equal, but they were higher by 1.03 than the control treatment. These effects were reflected in the interactions liming × tillage systems because they did not show a significant difference ($p > 0.05$) but were significantly higher than their interactions without liming ($p < 0.05$) (Table 1).

The lime supply to acidic soils is crucial to increasing Ca content and pH and decreasing Al content [73,74]. In this study, these results were corroborated, and the lime worked better than the dolomite (Table 1). Also, the soil pH with the soil Ca and Al showed high correlation coefficients, r = 0.86 and −0.87, respectively, probably because liming in acidic soil is dissociated, releasing cations such as Ca, hydroxyls, and bicarbonates, which decrease Al activity and increase soil pH [37,73,75], and because liming dissolution is blown about in soil by water infiltration, increasing nutrient availability and pH and decreasing Al saturation to 13% in TA and 27% in CA soil [36,37]. In agreement, similar results were obtained by applying 8.5 t ha^{-1} of lime [73,75] and 4 t ha^{-1} of dolomite [76].

In this study, the Ca with Al showed a strong negative high correlation (r = −0.97) due to the liming, probably due to the formation of water-soluble organic compounds and by the exchange of Ca with Al, remaining the last one inactive [36] in the precipitated form [37].

The decrease in soil K showed a strong negative correlation (r = −0.86) with the Ca due to the supply of lime and probably because they are antagonists [77]. Furthermore, the increase in leaf area index (from 3.58 to 4.72), dry matter, and the nutrient demand (N protein and Ca) could be explained through the high positive correlation between Ca, leaf area index, dry forage corn, and leaf N content (r = 0.61, 0.52, and 0.64, respectively) [78].

The positive correlation between the Ca/Mg relationship, leaf area index, dry forage corn, and leaf N index (r = 0.55, 0.57, and 0.73) suggests that higher Ca levels may be required for cell wall formation with increased leaf area and dry matter. Also, Mg is required proportionally to higher leaf N content for suitable production, transport, and use of photoassimilates, protein synthesis, and formation of chlorophyll pyrrolic rings [79]. The Mg/K relationship showed a positive correlation (r = 0.64) with foliar P content because Mg and P are synergistic, and probably an adequate balance of Mg and K is essential to increase foliar P content [77].

3.4. Biometric and Foliar Variables of Forage Corn

3.4.1. Height, Leaf Area Index (LAI), Green and Dry Forage Yield

The tillage system factor significantly influenced the plant height, green forage, and dry forage yield of the INIA 616 corn variety ($p < 0.05$). The green and dry forage corn yield under the TA practices showed 6.45 and 0.68 t ha^{-1} more than the CA, respectively (Table 2). However, the tillage system did not exhibit a significant statistical difference in the leaf area index (LAI) ($p > 0.05$).

The lime and the traditional agricultural x lime showed the highest LAI, 4.72 ± 0.26 and 5.16 ± 0.37, as well as the highest dry forage corn yields, 18.72 ± 0.80 and 19.72 ± 1.12 t ha^{-1}, respectively ($p < 0.05$) (Table 2). The lime application increased 7.35 t ha^{-1} of green forage corn more than the dolomite, and its interactions with the tillage systems did not show a significant statistical difference ($p < 0.05$).

The TA practices and lime application showed higher green and dry forage corn yields than the CA and dolomite, respectively. Crop yields compared between CA and TA are diverse. The green forage corn yield under the TA practices increased by 12.2% compared to the CA (Table 2). Similarly, Thierfelder et al. and Martinez-Gamino et al. [26,80] found that TA corn grain yield increased 29.3 and 51.08% compared to CA, respectively. It suggests that Ks and Da were more suitable in TA than CA soil [27,39], and this study obtained similar data (Figures 5 and 6). However, corn grain yield did not significantly differ between CA and TA [63]. On the other hand, corn grain yield [81] and other crops [82] did not increase significantly when lime and dolomite were applied, probably because the reaction time of the liming agents in soil was much longer than in this study. Furthermore, the higher green forage corn production under the lime application could be due to its higher solubility than dolomite [37,82,83].

Table 2. Biometric parameters of the forage corn and nutrient contents under tillage systems (TS), liming (Lg), and the interaction TS × Lg.

Factors	Height (cm)	LAI	GF	DF	N	P	K	Ca	Mg
			(t ha⁻¹)		(g kg⁻¹)				
Tillage system (TS)									
CA	1.92 ± 0.04 b	4.01 ± 0.19 a	53.01 ± 1.50 b	16.98 ± 0.41 b	52.79 ± 1.14 a	2.27 ± 0.07 b	21.67 ± 0.67 a	6.23 ± 0.28 b	1.03 ± 0.03 b
TA	1.95 ± 0.03 a	4.08 ± 0.23 a	59.46 ± 1.78 a	17.66 ± 0.59 a	50.18 ± 1.66 b	2.18 ± 0.06 a	21.31 ± 0.28 b	8.03 ± 0.47 a	1.52 ± 0.06 a
Liming (Lg)									
C	1.92 ± 0.03 a	3.58 ± 0.18 b	55.45 ± 2.26 b	16.81 ± 0.31 b	49.01 ± 1.33 b	1.99 ± 0.04 b	22.18 ± 0.43 a	6.19 ± 0.11 b	1.19 ± 0.08 a
L	1.91 ± 0.02 a	4.72 ± 0.26 a	60.30 ± 2.23 a	18.72 ± 0.80 a	56.24 ± 1.19 a	2.11 ± 0.05 b	19.89 ± 0.46 b	8.13 ± 0.68 a	1.35 ± 0.12 a
D	1.98 ± 0.05 a	3.85 ± 0.24 b	52.95 ± 1.77 b	16.41 ± 0.31 b	49.21 ± 1.49 b	2.43 ± 0.06 a	22.40 ± 0.57 a	7.08 ± 0.55 b	1.29 ± 0.12 a
TS ×Lg									
CA×C	1.91 ± 0.04 b	3.42 ± 0.23 b	51.15 ± 1.34 a	16.48 ± 0.52 b	49.93 ± 2.18 b	2.00 ± 0.08 b	22.48 ± 0.48 b	6.18 ± 0.18 b	1.00 ± 0.04 b
CA×L	1.87 ± 0.03 b	4.28 ± 0.29 b	57.14 ± 2.87 a	17.72 ± 1.02 b	59.68 ± 2.26 a	2.08 ± 0.08 b	18.80 ± 0.25 c	6.70 ± 0.79 b	1.08 ± 0.05 b
CA×D	1.98 ± 0.10 b	4.34 ± 0.36 b	50.75 ± 2.47 a	16.36 ± 0.47 b	53.53 ± 1.42 b	2.43 ± 0.12 a	23.73 ± 0.58 a	5.80 ± 0.24 b	1.03 ± 0.09 b
TA×C	1.93 ± 0.05 a	3.74 ± 0.28 b	59.76 ± 3.10 a	16.78 ± 0.44 b	54.43 ± 2.78 b	1.98 ± 0.05 b	21.88 ± 0.76 b	6.20 ± 0.16 b	1.38 ± 0.08 a
TA×L	1.94 ± 0.01 a	5.16 ± 0.37 a	63.47 ± 2.87 a	19.72 ± 1.12 a	58.40 ± 1.94 a	2.15 ± 0.06 b	20.98 ± 0.35 b	9.55 ± 0.45 a	1.63 ± 0.12 a
TA×D	1.98 ± 0.05 a	3.35 ± 0.19 b	55.14 ± 2.29 a	16.47 ± 0.49 b	47.30 ± 2.28 b	2.43 ± 0.08 a	21.08 ± 0.15 b	8.35 ± 0.51 a	1.55 ± 0.10 a

LAI: leaf area index; GF: green forage; DF: dry forage; CA: conservation agriculture; TA: traditional agriculture; C: control; L: lime; D: dolomite; a,b,c: different small letters in a column indicate a significant difference among TS, Lg, and TS × Lg, according to the DGC test ($p < 0.05$.)

Positive correlations (r = 0.52 and 0.69, respectively) were observed between the leaf area index (LAI) and dry forage corn as well as foliar N content, likely due to the increase in LAI with higher leaf N content (Table 2), resulting in increased dry forage production, a trend consistent with findings by Tian et al. [84]. The green forage corn yield showed a positive correlation with dry forage corn yield and foliar Ca content, r = 0.64 and 0.45, respectively, because dry forage corn is directly derived from green forage; and the foliar Ca was increased by the liming, which increased the green forage corn yields (Table 2), in congruence, with an increase of 35.2% when the Ca was applied at 0.06% [85]. Moreover, dry forage corn yield positively correlated with foliar N and Ca with r = 0.47 and 0.55, respectively, probably because the Ca increase in soil promoted nitrogen and calcium accumulation in the whole plant [86] and encouraged higher dry forage corn yield.

3.4.2. Foliar N, P, Ca, and Mg

The tillage system factor significantly changed the foliar nutrient concentration ($p < 0.05$). The foliar N and K from the CA treatment increased by 2.61 and 0.49 g kg^{-1}, respectively, more than in TA. Meanwhile, the foliar P, Ca, and Mg content from the TA treatment reported 0.09, 1.8, and 0.49 g kg^{-1}, respectively, more than in the CA (Table 2).

The liming factor reported a significant statistical difference in the foliar nutrient concentration ($p < 0.05$), except for Mg (Table 2). The lime application showed higher foliar N and Ca content, with 7.03 and 1.05 g kg^{-1}, respectively, more than those with the dolomite application. However, the foliar K content decreased by 2.29 and 2.51 g kg^{-1} compared to the control and dolomite, respectively. The dolomite application increased the foliar P content by 0.44 and 0.32 g kg^{-1} compared to the control and lime, respectively. Further, the interaction of the tillage system × liming was significantly different in the concentration of foliar nutrients ($p < 0.05$). The interaction lime x tillage systems showed the highest foliar N concentrations.

The foliar P content showed the highest concentrations with both interactions, the dolomite × CA and dolomite × TA; and the foliar K showed the highest concentration with the interaction between dolomite × CA. Meanwhile, the TA × control and TA × liming showed the most elevated Ca and Mg foliar concentrations (Table 2).

The absorption of some nutrients by plants is altered by tillage systems and liming, according to Tiritan et al. and Ndayisaba et al. [37,87], respectively. Leaf N was significantly higher in plants from CA soil than those from TA (Table 2), probably due to the N contribution to the soil by *Desmodium* sp. Similarly, with a *Desmodium* sp cover, the soil

N increased from 4.5 ± 0.1 to 6.3 ± 0.8 mg kg^{-1}, increasing the availability for foliar N absorption and content [87]. The TA treatment showed significantly higher P, Ca, and Mg foliar concentrations than the CA treatment ($p < 0.05$), probably because the tillage in TA supplied up to 98% more oxygen than in the CA soil [88] and the absorptions and foliar contents of those elements could increase by 63% [68]. However, in a similar study, P foliar concentrations in corn were 2.2 and 2.1 g kg^{-1} in the TA and CA, respectively, without showing a significant difference [37]. Furthermore, the lime application had an analogous effect to a similar study by Naeem et al. [89] in which leaf K decreased by 32%, Ca increased by 65%, and the leaf Mg content in corn did not increase significantly.

4. Conclusions

In comparing the soil properties, INIA 616 forage corn's biometry, yield, and nutrient content were significantly affected under the tillage systems (CA and TA) and the liming (lime and dolomite). The CA practices emitted less CO_2 from untilled soil and showed higher soil moisture content, earthworm population, and N and K foliar concentration than those under the TA practices. However, the TA practices showed adequate hydraulic conductivity and bulk density, higher leaf area index, and forage yield, with higher P, Ca, and Mg leaf concentrations than CA ones. The lime decreased the soil Al content more efficiently and increased forage yield more than dolomite. These results demonstrated that the CA practices could potentially reduce CO_2 emissions from the soil and improve some soil properties with a slightly lower forage corn yield than in the TA. Also, the lime improved the acid soil's chemical properties with increased forage yield. In future research, the tillage systems should involve analysis of stable aggregates, pore space, labile carbon, organic matter, and soil erosion over time with different crops because improving soil properties and crop yields in the transition from TA to CA is gradual. Furthermore, the liming agents should be analyzed at the laboratory level to determine soil CO_2 emission with different carbonated and silicated liming agents.

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