Evaluation of three soil preparation technologies for small-scale producers

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Abstract: The present study aims to evaluate the quality of soil preparation using three tillage technologies, contributing to the selection of viable alternatives for small-scale family farming. Three soil preparation variants were evaluated: manual tillage with a crumbling spade, and mechanized tillage with a power tiller, one variant with a single pass of a moldboard plow and another with a rotary tiller, and the other option with only a rotary tiller. The performance of the technologies and the quality of soil preparation were determined. For the mechanized technologies, fuel consumption was also measured. The experimental research was conducted on sandy loam soil with a relative humidity of 19.78% and a bulk density of 1.38 g cm^{-3}, with vegetative residue cover between 0.66 and 2.26 kg m^{-2}. The results showed that the treatment involving tillage with the spade exhibited better work quality compared to the other two technologies, with a tillage depth of 17.94 cm, an average clod size of 2.85 mm, and post-tillage ridge differences of 6.95 cm; however, it achieved the lowest operational yield at 41.7 workdays ha^{-1}.

Keywords: dry aggregate size distribution, farm family, physical properties of soil, soil conservation, tillage.

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1 Introduction

In Ecuador, agriculture is one of the main sources of employment and income for the rural population (Morales and Mideros, 2021). It is characterized by low mechanization and a high prevalence of small productive units, where most agricultural work is carried out by family labor or through communal work (Singaña Tapia and Satama Bermeo, 2022).

According to Casanova-Ruiz et al. (2024), the type of agriculture practiced today by various producers is characterized by constant soil movement during tillage operations, for sowing preparation and weed control. These practices affect the physical, chemical, and biological properties of the soil, promoting erosion and substantially limiting crop yields. Excessive use and misuse of tillage technologies have generated soil degradation problems, among others, due to erosion

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(Somasundaram et al., 2020).

In soils destined for agriculture, the structure of the arable layer is the physical property most altered during tillage, affecting the distribution and storage of water, nutrients, and oxygen in the root development zone, which is controlled by the soil pore space (Priori et al., 2020).

Tillage depth is an important aspect for the proper development of roots and, consequently, of crops (Arzuaga et al., 2021). However, this can be affected by the presence of crop residues on the field surface. Therefore, farmers have traditionally considered crop residues as something that hinders soil preparation tasks (Sarmiento-Sarmiento et al., 2022).

Soil pulverization is also an important aspect to consider when evaluating tillage, as its increase contributes to increased porosity, allowing better movement of water and nutrients, favoring plant development and increasing crop productivity (Gavrilescu, 2021). According to Martínez Medina et al. (2021), for good production of horticultural crops, the granulometry of soil clods should be within 1 to 5 mm.

Considering the background presented, this study aims to evaluate the quality of soil preparation using three tillage technologies in terms of soil structure modification, energy demand, and fuel consumption, among many others, contributing to the selection of viable alternatives for small-scale family farming.

2 Materials and methods

The study was conducted at the La Tola Experimental Academic Teaching Field, belonging to the Faculty of Agricultural Sciences of the Central University of Ecuador. The site is located at approximately 2,400 meters above sea level, with geographical coordinates 0°13'00" S latitude and 78°25'00" W longitude. A test plot measuring 29 m long by 22 m wide was used, with sandy loam soil composed of 56% sand, 34% silt, and 10% clay. According to USDA (2004) textural classes, the soil texture of the test area is considered moderately coarse.

A randomized complete block design (RCBD) was employed to evaluate the variables of three soil preparation technologies in strips: conventional tillage 1 (CT1), one pass of the power tiller with agricultural rotary tiller; conventional tillage 2 (CT2), first a pass of the power tiller with moldboard plow followed by a pass with the agricultural rotary tiller; and manual tillage (MT) with a crumbling fork or spade (Figure 1). The data were subjected to analysis of variance (ANOVA) to determine the existence of significant differences among treatments. When significant differences were detected, the Fisher’s LSD test at $\alpha = 0.05$ was applied to compare the treatment means. Five replications of each treatment were implemented.


(a) moldboard plough (b) rotary tiller (c) crumbling spade

Figure 1 Tillage implements used

For CT1 and CT2 treatments, an MGM Lampacrescia Castoro Super power tiller with a 389 CC gasoline engine and 8.40kW power was used as the energy source. In the CT1 treatment, a rotary tiller with a working width of 0.80 m and a rotor diameter of 0.62 m was used as the working implement, featuring six discs and four curved blades distributed on both sides of the working organ's discs.

For the CT2 treatment, a single-body moldboard plow with a working width of 0.20 m and a maximum working depth of 0.15-0.20 m was used. In the MT treatment, a crumbling fork or spade was used, which is a manual tillage implement with tines that penetrate the soil, crumbling the surface through the shearing action produced when the handle is turned backward. During the experiments, the variables characterizing the test conditions were determined as follows:

Obstruction in the test plot by crop residues was determined by measuring the mass of residues in 1 m² at six points in the plot, randomly distributed along the diagonal of the test plot. The mass was determined with a KS brand digital portable hook scale with ±1 g precision.

Soil texture was determined using the Bouyoucos method (hydrometer method) at the "Julio Peñaherrera" Agricultural Chemistry and Soils Laboratory (0°13'44.1"S 78°22'18.6"W) in the Faculty of Agricultural Sciences at the Central University of Ecuador.

Bulk density was determined using the Kopecky cylinder method, which has been extensively detailed in various resources (Orzech et al., 2021). Five samples with three replicates were taken along the diagonal of the test plot. The maximum temperature for drying the samples was 60°C, taking into account the soil's organic matter content. The mass was determined on a balance with ±0.0001 g precision.

Soil moisture was determined by the gravimetric method based on dry soil (% db), following the procedure detailed in multiple resources (López-Bravo et al., 2021).

Moisture samples were taken similarly along the diagonal of the test plot, at the same points where density samples were taken. Consequently, samples were taken at five points with three replicates each. The drying temperature and mass determination methods coincide with those described in the density determination procedure.

To evaluate the operation of the equipment during use, the observed variables were working speed, fuel consumption of the power tiller, and equipment yield. Similarly, the yield of the crumbling spade was determined. Both the standard deviation and the coefficient of variation were calculated using the fundamental formulas of these statistics. The standard deviation was estimated as the square root of the variance of each set of replicates.

Working speed was determined by placing stakes along the work plot, measuring the time it took the machine to cover that distance, while fuel consumption measurement was obtained by measuring the volume of fuel required to fill the tank after each work period.

The determination of equipment and spade yield was based on the Cuban standard NC 34-37 (2003), which establishes the times and indices to be considered. Times were determined by timing the activities performed by the equipment.

To evaluate the work quality of the three tillage technologies investigated, the following were determined: tillage depth and soil fragmentation, obtaining the average clod size after tillage and Kaurichev's structuring coefficient by dry soil sieving (Rusakova, 2023).

3 Results and discussion

3.1 Experimental conditions

The determination of the experimental conditions showed that the plots had a low amount of stubble or residues during the tillage operations, with the lowest amounts found in the plot where the crumbler hoe was used (Treatment LM). However, this did not significantly affect the results, as the hoe's working principle makes it less sensitive to the presence of stubble. In the plots where the other two tillage technologies were employed, the volume of residues also did not hinder the proper execution of the work (Table 1).

Table 1 Amount of plant residues (kg m^{-2}) found in the test plots

Soil preparation treatment	Residues, kg m^{-2}
Manual implement (crumbling spade)	0.66
Power tiller + plough + rotary tiller	2.29
Power tiller + agricultural rotary tiller	1.44

Table 2 Average values of soil moisture and bulk density in the experimental plot

Soil preparation treatment	Depth, m	Moisture, % db	Bulk density, kg m^{-3}
Manual implement (crumbling spade)	0 ~ 0.10	21.75	1410
	0.10 ~ 0.20	23.86	1390
Power tiller + plough + rotary tiller	0 ~ 0.10	19.09	1300
	0.10 ~ 0.20	19.60	1350
Power tiller + agricultural rotary tiller	0 ~ 0.10	18.11	1340
	0.10 ~ 0.20	16.26	1500

The results of soil moisture and density measurements in the plots during the experimental investigations indicated (Table 2) that the soil was in suitable conditions for tillage at the time of the trials.

According to Jróbostov (1977), criteria, the soil moisture in the plot at the time of the trials (Table 2) was within suitable ranges for the operation of the implements. Soil density ranged from 1300 to 1410 kg m^{-3} in the surface layer, i.e., 0 to 0.10 m depth, and was higher in the 0.10 to 0.20 m layer, with values between 1350 and 1500 kg m^{-3}. According to the USDA's (2004) estimation table, for the bulk density of sandy loam soil, the density values range from 1550 to 1600 kg m^{-3}. The values obtained in the experimental plot were lower than these, indicating a low level of soil compaction in the test plot.

3.2 Technological and operational evaluation

The use of the crumbling spade achieved an operational yield of 30 m^2 h^{-1} (0.003 ha h^{-1}) in soil preparation, meaning that to prepare one hectare with this technology, approximately 42 eight-hour workdays are required. This yield of the spade makes it suitable for small-scale family farming. On the other hand, the yield of the power tiller with the agricultural rotary tiller was 0.019 ha h^{-1}, and with one pass of the moldboard plow plus one pass of the rotary tiller, it was 0.012 ha h^{-1}. Therefore, to prepare one hectare of land with these technologies, approximately 7 and 14 workdays are required, respectively.

The yield value achieved with the crumbling spade is similar to the 0.00318 ha h^{-1}. The yield value of the crumbling spade is lower than that achieved with the other two technologies evaluated. The average working speed during soil preparation was 1.62 km h^{-1} with the rotary tiller and 1.55 km h^{-1} with the moldboard plow (Table 3).

Table 3 Working speed and fuel consumption of the power tiller during soil preparation with the rotary tiller and mouldboard plough

Equipment	Working speed, km h^{-1}	Fuel consumption, L h^{-1}
Power tiller + rotary tiller	1.62	2.42
Power tiller + mouldboard plough	1.55	2.57

Fuel consumption during tillage with the rotary tiller showed no statistically significant differences at a 95% confidence level ($\alpha = 0{,}05$) when compared to the moldboard plow. A 9 kW power tiller has a gasoline consumption of around 2.2 L h^{-1}, which is considered moderate consumption.

The fuel consumption in both technologies during soil preparation is higher than what is required for a power tiller of this power, which may be due to the slippage of the power tiller's drive wheels, which reduces the forward speed and equipment yield, and the amount of plant residues found in the research plot, as the residues exert higher resistance during cutting, causing the machinery to use more power and therefore consume more fuel.

The differences found in the working speed of the equipment are related to the traction force, due to increased slippage. This is due to the working principle of the rotary tiller, as it has cutting blades that interact with the soil rotating in the same direction as the power tiller's drive wheels, an aspect that helps reduce the implement's traction resistance due to its thrust in the direction of movement.

The moldboard plow, however, has as its working principle the cutting of soil by shearing in the first phase, then the cut soil slides over the surface of the moldboard, and finally, in a third stage, the turning of the cut soil prism, which generates greater resistance to traction and consequently higher energy consumption.

Similarly, Daum et al. (2023) report that during moldboard tillage, wheel slippage occurs above the optimal range (considered to be 10% to 15%), and this excessive slippage can cause increased fuel consumption and low field efficiency.

3.3 Work quality

The average depth obtained by the three technologies used for soil preparation shows that with the crumbling spade, a working depth 62% greater than tillage with moldboard plow and rotary tiller (CT2) was achieved, and 85% greater in relation to tillage with only the rotary tiller (CT1). The combined use of moldboard plow and rotary tiller allowed for a 15% greater depth compared to the rotary tiller alone (Table 4).

Table 4 Working depth of the three technologies used for soil preparation

	Crumbler hoe	CT1	CT2
Average	17.94	9.53	11.06
Variance	6.00	0.66	1.93
Standard deviation	2.45	0.81	1.39
CV	13.65	8.54	12.56

The results of the tillage depth measurement show that the working depth was greater when using the crumbling spade, although its variation was higher as indicated in Table 4. This technology is followed by the use of moldboard plow + rotary tiller, while tillage with only the rotary tiller allowed for a lesser tillage depth. This is due to the constructive characteristics of these implements, as well as the interaction mechanisms of the working organs with the soil, and the failure mechanism to which the soil is subjected.

The deformation and fragmentation of the soil with the crumbling spade is carried out with tooth-type organs, which favors the formation of irregularities in the bottom of the tilled soil profile, which justifies the observation of a higher coefficient of variation in tillage depth for this technology (Table 4).

In the normality tests (Shapiro-Wilks), a *p*-value of 0.3071 was obtained for working depth and 0.6210 for average clod size, which indicates that there is normality among the residuals of the observed variable values. This result was also corroborated by Q-Q plot analysis.

In the results of the Levene's test for constant variances, a $p < 0.05$ (95% confidence level) was obtained for working depth, indicating that the variances are heterogeneous (heteroscedasticity exists), while for the average clod size this value reached 0.2109, so the variances are constant in this case.

The analysis of variance for working depth shows the existence of highly significant differences between technologies with a *p*-value less than 0.05 and a coefficient of variation of 7.45 (Table 5). The LSD Fisher mean comparison test with $\alpha = 0.05$ for this parameter appears in Figure 2.

Table 5 Analysis of Variance (ANOVA) for the working depth of the three soil preparation technologies

Source	Sum of Squares	Df	Mean Square	F-Ratio	*p*-Value
Between groups	2294.21	2	1147.11	382.98	0.0000
Within groups	500.206	167	2.99525		
Total (Corr.)	2794.42	169			

Tillage with the crumbling spade (MT) allows for obtaining the greatest working depth, followed by that performed with the power tiller, with one pass of the moldboard plow plus one of the agricultural rotary tillers (CT2), and lesser depth with a single pass of the rotary tiller (CT1). This result is associated with the presence of a greater amount of plant residues in the plot during field trials, which is consistent with the results reported by Fregoso Tirado (2008).

Regarding the average clod size, the results show that the manual implement (MT) produced clods approximately 50% larger than those obtained with the moldboard plow plus rotary tiller (CT2), and over 25% larger than those obtained with the rotary tiller alone

(CT1). The use of the power tiller with the rotary tiller resulted in a 20% greater working depth compared to the moldboard plow combined with rotary tiller (Table 6).

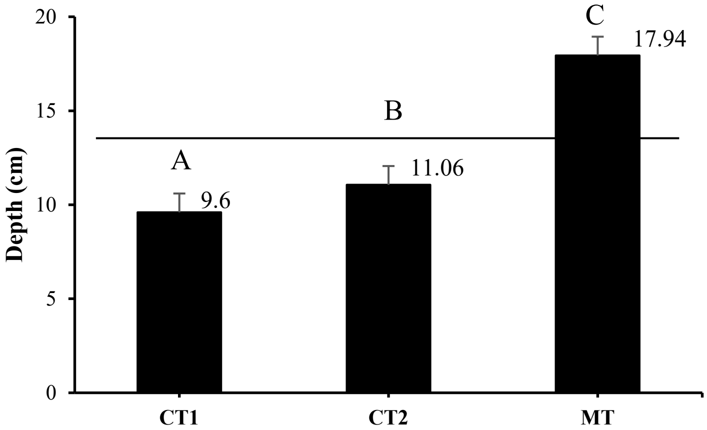

Figure 2 Average working depth with different tillage technologies

Table 6 Average clod size for the three soil preparation technologies

	Crumbler hoe	CT1	CT2
Average	2.85	2.26	1.88
Variance	0.13	0.05	0.26
Standard deviation	0.36	0.23	0.51
CV (%)	12.63	10.17	27.10

The results also indicate that the coefficient of variation (CV) was highest for the moldboard plow + rotary tiller (CT2), followed by the manual implement (MT), while the rotary tiller alone (CT1) yielded the lowest variability. This suggests that the rotary tiller produced more uniform and finely crumbled clods, resulting in better homogeneity compared to the other technologies.

The analysis of variance (ANOVA) for the average clod size revealed highly significant differences among the three tillage technologies (F = 9.75, p = 0.0019), with a coefficient of variation of 16.44% (Table 7).

Table 7 Analysis of Variance (ANOVA) for the average clod size in the soil preparation technologies

Source	Sum of Squares	Df	Mean Square	F-Ratio	*p*-Value
Between groups	2.87581	2	1.43791	9.75	0.0019**
Within groups	2.21137	15	0.14742		
Total (Corrected)	5.08718	17			

Note: ** indicates highly significant difference at α = 0.05.

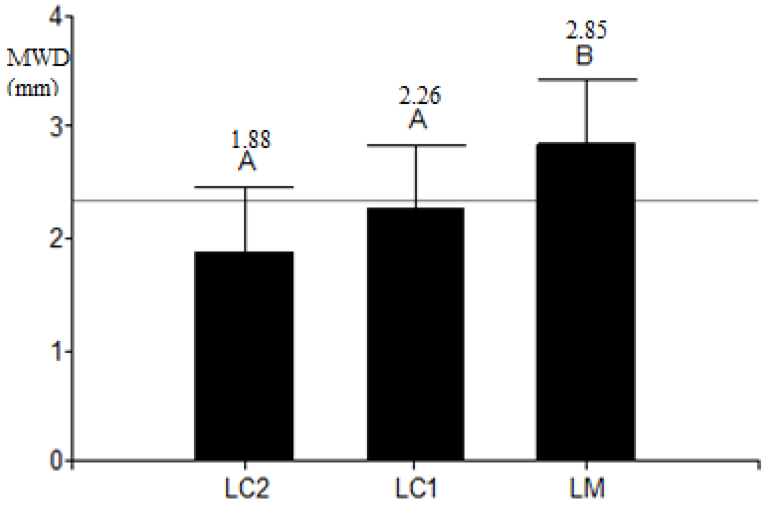

Figure 3 Comparison of means for the average clod size of each soil preparation technology

According to the Fisher’s LSD multiple range test ($\alpha = 0.05$), highly significant differences were observed between MT (2.85 mm) and both CT1 (2.26 mm) and CT2 (1.88 mm). However, no significant difference was found between CT1 and CT2 (Figure 3).

All three technologies produced clod sizes within acceptable ranges for crop development. However, CT1 and CT2 resulted in finer soil structures, which could increase the risk of soil erosion due to wind or water. In contrast, the coarser clods produced by the manual implement (MT) may help reduce erosion risk by improving surface stability.

With all three investigated technologies, average clod size values were obtained within the appropriate range for good crop development. However, with CT1 and CT2, having a smaller granulometry favors soil loss through wind or water erosion, while with the crumbling spade, a higher value was obtained, which is conducive to reducing soil loss.

The analysis of clod size distribution (%) for soil preparation (Table 8) allows us to identify those technologies using the rotary tiller, or the combination of moldboard plow + rotary tiller, produce greater soil fragmentation, obtaining between 50% to 65% of clods smaller than 1 mm. This excessive crumbling can favor erosion processes.

Table 8 Distribution of clod size and structuring coefficient (%) in soil preparation

Technologies	Sieve Diameter (mm)						Structuring Coefficient
	> 16	> 8	> 4	> 2	> 1	< 1	
Crumbler hoe	13.91	10.13	14.79	13.97	10.95	36.26	99.32
Power tiller + rotary tiller	2.49	6.47	10.80	12.23	12.69	55.32	72.95
Power tiller + mouldboard plough + rotary tiller	1.26	3.74	9.69	12.44	13.13	59.74	63.94

The structuring coefficient (Table 8), obtained as the percentage of clods with dimensions between 1 and 16 mm, in relation to clods smaller than 1 mm and larger than 16 mm, results in better structuring obtained with the crumbling spade, compared to the other two tillage technologies. This is essentially due to the high level of soil fragmentation that originates from the use of the rotary tiller in these two technologies, which makes it difficult to conserve soil properties and production sustainability (Kalogiannidis et al., 2022).

4 Conclusions

The technology with the highest operational yield is the power tiller-rotary tiller combination, requiring the equivalent of 6.6 eight-hour workdays to till one hectare. However, for the manual technology, approximately 42 workdays are required to till one hectare of soil.

The fuel consumption of the power tiller with the agricultural rotary tiller in soil preparation was 5.82% lower compared to the moldboard plow treatment, at 2.57 L h^{-1}. The estimated consumption for the power tiller is 105.26 L ha^{-1} of gasoline with the rotary tiller, and 166.67 L ha^{-1} with the moldboard plow.

From the perspective of work quality, the crumbling spade allowed for obtaining a working depth 62% greater than that obtained with the combination of moldboard plow and rotary tiller, and about 85% higher than using only the agricultural rotary tiller.

The crumbling spade also allowed for obtaining an average clod size 50% larger than tillage with moldboard plow and rotary tiller, and more than 25% larger in relation to tillage with only the rotary tiller.

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