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QUALITY OF SOIL TILLAGE PERFORMED WITH A HYDRAULIC EXCAVATOR AND A TRACTOR IN SLOPED AREAS

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ABSTRACT

Studies addressing the mechanization of forestry in slope areas are scarce because of the difficulties to access those areas and the cost of the activity. A recent adaptation using a hydraulic excavator for soil tillage in sloped areas has shown positive results mainly obtained due to the benefits provided by the increase in subsurface area. However, little is known about its effect on the quality and efficiency of the activity. Therefore, the objective of this study was to evaluate the soil tillage quality performed by a hydraulic excavator and a subsoiler attached to a tractor during the dry and rainy seasons, in the presence (PW) or absence of a wing (AW) in the chisel of the subsoiling tines in sloped areas. We evaluated the depth, the surface width, the mobilized soil area, the profile of the tilled soil, and the quality of clod breakdown. Soil preparation in the rainy season is approximately double the prepared area compared to the second period. In addition, the presence of the wing on the tip of the subsoiler rod contributes to increase the mobilized soil area and consequently increased soil clods, thereby indicating the quality of the preparation, especially in the dry season. The hydraulic excavator mobilizes the soil with higher averages than those recommended for inclined areas due to its mechanical power, while the subsoiler maintains the preparation within the expected averages. Despite the peculiarities of each implement, they both present quality soil performances.

Keywords: Forestry; Tillage; Quality analysis

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QUALIDADE DO PREPARO DO SOLO REALIZADO COM ESCAVADEIRA HIDRÁULICA E TRATOR EM ÁREAS DECLIVOSAS

RESUMO – Estudos abordando a mecanização da silvicultura em áreas de declive são escassos, devido às dificuldades de acesso a essas áreas e ao custo da atividade. Uma adaptação recente do uso da escavadeira hidráulica no preparo do solo em áreas declivosas tem mostrado resultados obtidos principalmente devido aos benefícios proporcionados pelo aumento da área de subsuperfície. Entretanto, pouco se sabe sobre seu efeito na qualidade e eficiência da atividade. Dessa forma, o objetivo deste estudo foi avaliar a qualidade do preparo do solo realizado por uma escavadeira hidráulica e um subsolador acoplado a um trator durante os períodos seco e chuvoso, na presença (PW) ou ausência de uma asa (AW) no cinzel dos dentes subsoladores, em área de declive. Foram avaliadas a profundidade, a largura da superfície, a área de solo mobilizada, o perfil do solo preparado e a qualidade do destoroamento do solo. Na estação chuvosa o preparo do solo mobiliza aproximadaente o dobro da área preparada quando comparado ao periodo seco. Assim como a a presença da asa na ponteira da haste do subsolador contribui para o aumento da área de solo mobilizado e consequentemente aumento dos torrões do solo, reduzindo a qualidade do preparo, principalemnte no periodo seco. A escavadeira hidraulica, devido a sua potencia mecânica, mobiliza o solo com médias superiores ao sugerido para áreas declivosas, enquanto que o subsolador mantem o preparo dentro das médias esperadas. Apesar das peculiaridades de cada implemento, ambos são capazes de apresentar preparos de solo com qualidade.

Palavras-Chave: Silvicultura; Subsolagem; Análise de qualidade

1. INTRODUCTION

Soil preparation is one of the most important activities which aims to improve the quality of the site to increase or maintain the productivity of forest stands, mainly by minimizing the soil compaction generated by the traffic of forest harvesting machines, which may remain for decades (Reichert et al., 2021). However, there is still a knowledge gap to optimize tillage practices for forest environments, since the conditions and process dynamics are dependent on the soil and slope conditions of the site (França et al., 2021).

The yield and quality of the tillage activity, among several factors, depend on the soil characteristics such as texture, structure, porosity, compaction, volume, and vegetation particles, such as roots, and moisture (Cardei et al., 2020a). Cunha et al. (2021) observed that subsoiling has lower quality under low soil moisture conditions, producing smaller furrows and a higher incidence of clumps, which can present problems at the time of planting/seeding. The slope of the land is also a factor which makes it difficult to carry out the activity since there is little equipment that can be present in the conditions and it often has a high cost per hour (Souza et al., 2018).

Another factor that controls the tillage quality is the equipment that will be used. There are various brands and models of machines and equipment available for subsoiling on the market (Simões et al., 2011). A subsoiler is a consolidated and widely used implement for subsoiling in areas with slopes of up to 17°; these implements are not stable for subsoiling on sites with a slope above 17° (Cunha et al., 2021). Another piece of equipment is the hydraulic excavator, which is used in slope areas greater than 17°. It has a hydraulic arm with a tip that can be adapted with a subsoiling tine (França et al., 2021).

The proper choice for subsoiling equipment influences subsoiling performance, and it is essential to pay attention to the quality, the tine conformation, and the observation of the wing to be used (Simões et al., 2011). Askari et al. (2016) commented that the addition of wings to the chisel of the subsoiling tines increases the mobilized soil area, the relative breaking of the cutting width, and the working area. According to the authors, the use of winged chisels promotes greater soil mobilization than narrow chisels. One recurring issue is the susceptibility of the wing to wear and eventual breakage, requiring repairs (Cunha et al., 2021). This has the consequence of increasing equipment maintenance time and reducing overall production hours (Askari et al., 2019).

Despite the advantages of subsoiling, caution should be exercised in its use because it has a high cost and energy demand per unit area, and it is important to perform subsoiling within the desired quality standards (Cunha et al. 2021). The hydraulic excavator can travel in areas of up to 27º of slope, which represents an advance in forestry mechanization, however little is known about the quality of soil preparation performed by this equipment (Santos & Reichert, 2022). The first hypothesis is that the hydraulic excavator, with it is hydraulic arm adapted with a subsoiler rod, performs soil mobilization beyond the desired quality specifications, highlight the potential for its use in subsoiling activities. In contrast, the tractor coupled with the subsoiler performs soil mobilization to a level closer of quality specifications. The second hypothesis is that the presence of wings at the tip of the subsoiler increases the mobilized soil area, promoting better soil preparation for the both machines. However, its use in hydraulic excavators can be avoided due to its significant soil mobilization, which can lead to a reduction in machine maintenance time. In this context, the objective of this study was to evaluate the quality of the soil tillage performed by a hydraulic excavator and a tractor with an attached subsoiler, both with and without wings, during two seasons.

2. MATERIAL AND METHODS

The experimental site was located in the region of Nova Era, Minas Gerais, Brazil at 19°45′ S, 43°1′ W, in a predominantly mountainous area with a Cambisol soil and a Cwa climate according to the Köppen climate classification (Alvares et al., 2013). The average temperature observed was 22.02ºC, the total precipitation was 1093.4 mm, and ranged from 0 mm in the driest month to 288.3 mm in the wettest month for the year in which the experiment was conducted (Xavier et al., 2021).

The study site had previously been occupied by a *Eucalyptus* stand of the *Eucalyptus grandis* x *Eucalyptus urophylla* hybrid clone, which was planted with a 3 x 2 m spacing and had been cut at seven years. The wood was harvested using the cut-to-length system, which included felling, delimbing, topping, bucking, and debarking of the wood; these processes were performed by a harvester, and the wood was then transported to the side of the road using a forwarder. After harvesting and removing the wood, subsoiling was performed between the previous rows with either a subsoiler attached to a tractor or a hydraulic excavator.

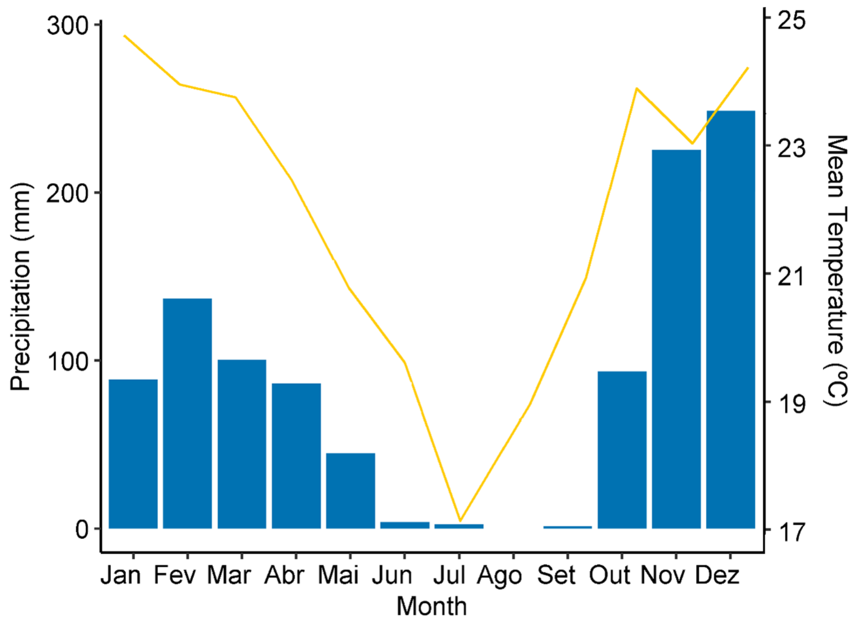

Figure 1. Mean temperature and total precipitation at Nova Era, Minas Gerais, Brazil, in the year 2017

Figura 1. Temperatura média e precipitação total em Nova Era, Minas Gerais, Brasil, no ano de 2017

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Two experiments were designed, one with each type of equipment, and were arranged parallel to the slope to cover heterogeneity in relief and soil conditions. A completely randomized block design was used in a 2 x 2 factorial design with two time periods (dry and rainy) and the presence or absence of wings on the implement for both experiments; each treatment had ten replicates, with 20 plots being evaluated for each implement/experiment. The data for each plot was obtained by the average of three points of analysis, with the plot consisting of a line 10 meters long and two meters away from the line to the side.

Experiment 1 was performed with the subsoiler attached to the tractor; a tractor model MF7140, motor 620DS/AGCO POWER, with a net power of 105.8 kW (140 hp), 2200 rpm, weight of 8.2 tons, lifting capacity at the pivot joint 46,44 kN, equipped with 4 diagonal radial panels, and an average activity yield of 2.5 h ha^{-1}. The subsoiler consisted of a cutting disc, a subsoiling rod, and four discs for finishing the furrow. The tractor followed the contour curves in the land, in the slope between 0-17º, and tilled the soil to the recommended depth. The tractor removed the tine from the soil at the end of each row, and reversed direction to start a new tillage row.

Experiment 2 was performed by a hydraulic excavator (Caterpillar 312DL), with a C4.2 ACERT™ motor , net power of 72.3 kW (97 hp), a weight of 13 t with a width between the tracks of 3.2 m, an arm's length of 6.5 m, maximum drawbar force is 114 kNm, and an activity yield of 6 h ha^{-1}. A 100 cm subsoiling tine was attached to the tip of the hydraulic arm, replacing the original bucket, to perform the subsoiling. The machine's movement followed the direction of the terrain slope (upslope and downslope), in the slope 17-27º and the planting rows were tilled following the contour of the land.

Subsoiling was performed at a distance of three meters between rows for both experiments. The standards for soil mobilization during the subsoiling were a 0.40 m depth, 0.60 m surface width, and 0.12 m² area of mobilized soil in a "V" shape (Cunha et al., 2021; Barros, 2001).

Soil moisture was also determined as a tool to help explain data variations. We collected undeformed samples by means of the Uhland volumetric ring method, by following the methodology outlined by the Brazilian Agricultural Research Corporation-EMBRAPA (1997). The samples were collected in the interrows near each sampling point of each plot, at the soil depth profile of 0-20 cm.

For experiments 1 and 2, the evaluations during the dry season occurred in September with soil moisture averages of 15.63% and density averages of 1.29 g cm^{-3}. The evaluations in the rainy season were performed in November with soil moisture averages of 22.13% and density averages of 1.24 g cm^{-3}. The quality of soil tillage was assessed for both machines with and without the presence of a 20 cm wide wing in the chisel of the subsoiling tines under both moisture conditions.

After soil tillage, the surface width, tillage depth, soil mobilization area, clod quality index, and profile of the tilled soil were evaluated for both experiments. These parameters were evaluated at the center of the subsoiling row, and each sampled row had a minimum length of five meters.

The surface width of the soil tillage was evaluated in both experiments using a rod that was inserted at either end of the tilled soil, and the distance between the ends was measured with a tape measure. At the same point, the depth of the subsoiling activity was evaluated using a profilometer, which was composed of an 81 cm bar at the base with 28 one-meter-high rods spaced three centimeters apart (Cunha et al., 2021).

The heights of the rods were measured with a tape measure and plotted to obtain the profile of the mobilized soil. The mobilized soil area was calculated as the sum of the means between the ends of the rods multiplied by 3.0 cm (the distance between the rods). The profile of the tilled soil was analyzed graphically, and the profiles were classified as either conforming or not conforming to the specifications for the subsoiling operation.

Next, the level of clod breakdown by the implement was analyzed to evaluate the quality of the finished furrow. To do so, one plot was made with a 50 x 50 cm quadrant located next to the profilometer. Then, two indices were evaluated within the quadrant: the number of clods index (NCI) and the clod diameter index (CDI). The clod quality index (CQI) was created to facilitate the qualitative analyses, which was calculated by multiplying the CDI and NCI (Table 1). The ideal value for

Table 1. Clod diameter index (CDI) and number of clods index (NCI) used for the qualitative evaluation of the furrows

Tabela 1. Índice de diâmetro do torrão (CDI) e índice de número de torrões (NCI) utilizados para avaliação qualitativa dos sulcos

CDI	Clod diameter (cm)	NCI	Number of clods
1	<0	1	0
2	0-5	2	0-5
3	5-15	3	5-10
4	15-30	4	10-15
5	>30	5	>15

the clod quality index (<4 cm), and clods with diameters (<15 cm) was based on (Cunha et al., 2021).

The means obtained using the quality indicators were tested for statistical assumptions and then analyzed using analysis of variance (ANOVA); when significant, the F-test was performed at a 5% probability of error.

Pearson's correlations between soil characteristics obtained and the tillage quality indicators (mobilized soil area, surface width and depth of the subsoiling, and clod quality index were performed. The correlation results were expressed graphically through a network of correlations. A two-dimensional network correlation was used to graphically express the functional relationship between the studied variables. The proximity between the characteristics was proportional to the absolute value of the correlation between these nodes. The positive correlations were presented in blue, while the negative correlations were presented in the yellow scale. Principal component analysis (PCA) was used to sort the soil tillage between the treatments and also identify which variables most contribute to the data variation. All analyses were processed using the R version 4.3.1 software (R Core Team, 2023).

3. RESULTS

We generally observed that both types of equipment showed good performance in the field, meeting the averages required by the technical recommendation for the mobilized soil area (0.23, 0.36 m²), surface width (0.70, 0 .8 m) and depth (0.49, 0.71 m) of the subsoiling for the subsoiler attached to the tractor and hydraulic excavator, respectively (Figure 2). The clod quality index showed values above the allowed 5.50 for the subsoiler attached to the tractor, and 4.95 for the hydraulic excavator. The variables showed a wide range of values, with some points sampled outside the standards established by the technical recommendation, in which the subsoiler attached to the tractor presented the highest number of unconformities when compared with the hydraulic excavator (area of mobilized soil and depth of the subsoiling).

The results for the subsoiler attached to the tractor showed an interaction between the factors for the mobilized soil area, depth, and surface width (P = 0.05), (Table 2). The soil tillage during the rainy season did not show significant differences between the presence and absence of the wing. The mean mobilized soil area during the dry season was higher in the presence of the wing (0.22 m²) than in the absence of the wing (0.11 m²). The same was true for depth and surface width, which were 0.49 m and 0.67 m in the presence of the wing, respectively, and 0.29 and 0.55 m in the absence of the wing, respectively.

The mobilized soil area and the depth in the presence of a wing in the tine chisel were not significantly different between the different seasons and had overall means of 0.25 m² and 0.53 m², respectively. The surface width was higher (0.78 m) during the rainy season than during the dry season (0.67 m).

The mobilized soil area (0.27 m²), depth (0.59 m), and width (0.81 m) in the absence of a wing were higher during the rainy season than during the dry season (0.11 m², 0.29 m, and 0.55 m, respectively). The values in the latter

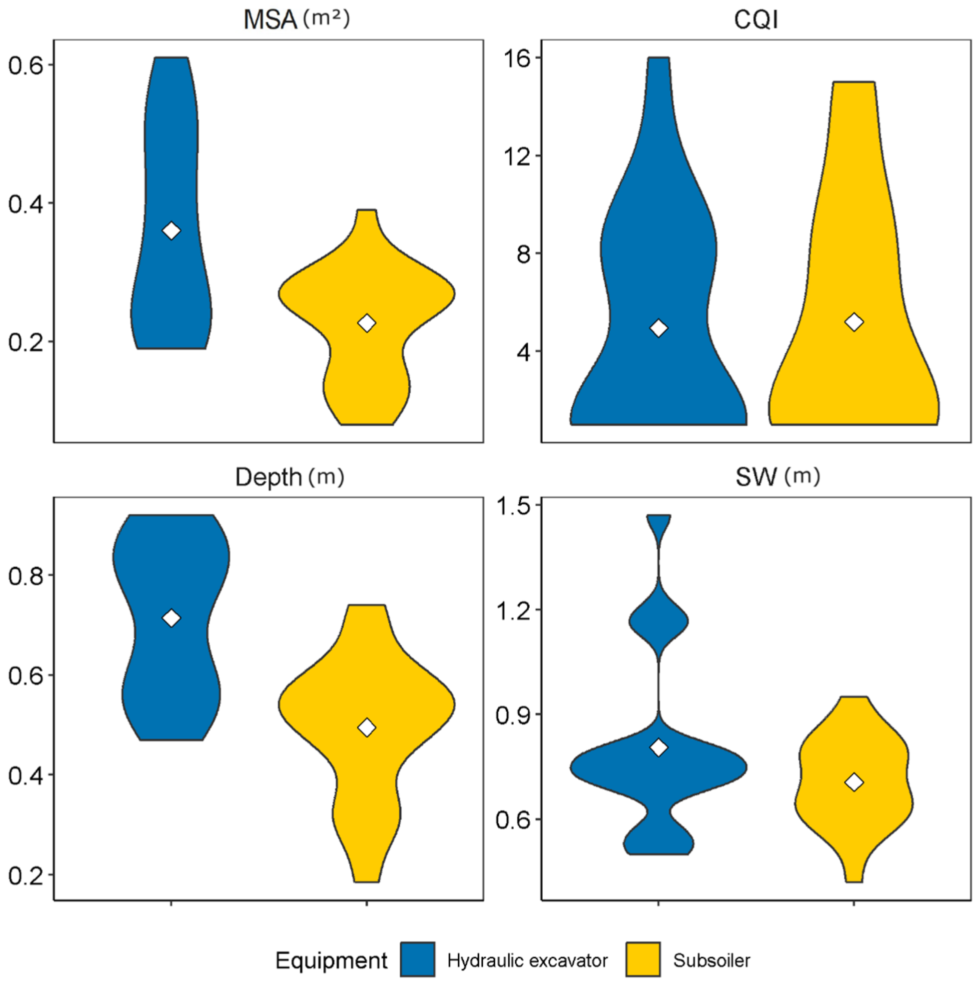

Figure 2. Amplitudes of quality indices for soil preparation carried out by subsoiler attached to the tractor (yellow) and the hydraulic excavator. MSA: mobilized soil and CQI: Clod quality index

Figura 2. Amplitudes dos índices de qualidade do preparo do solo realizado pelo subsolador acoplado ao trator (amarelo) e à escavadeira hidráulica. MSA: solo mobilizado e CQI: índice de qualidade do torrão

case were lower than those recommended for furrow tillage, as highlighted in Figure 3.

The clod quality index was satisfactory during the rainy season (1.30) compared with the dry season (9.10). The clod quality index was not significantly different between the presence and absence of the wing, the mean value was 5.2, which is considered to be above the ideal value.

With regard to the mobilized soil area, 40% and 100% of the plots did not reach the recommended value in the dry season in the presence and absence of the wing in the tine chisel, respectively. However, 100% of the plots had satisfactory values during the rainy season, regardless of the presence or absence of the wing in the tine chisel (Figure 3).

With the hydraulic excavator, the mobilized soil area, tillage depth and surface width did not show an interaction with the factors analyzed (P = 0.05) (Table 3). The response variables for hydraulic excavator met the specifications for soil tillage in all the tested treatments. The treatment with the presence of the wing (0.40 m²) had a better result for the mobilized soil area than that with the treatment with the absence of the wing (0.31 m²). Similar results were found for depth and surface width, which in the presence of the wing (0.78 cm and 0.94

Table 2. Means of the mobilized soil area, depth, and surface width as a function of the presence or absence of the wing in the tine chisel during the dry and rainy seasons for soil tillage performed with a subsoiler attached to the tractor

Tabela 2. Médias da área de solo mobilizada, profundidade e largura superficial em função da presença ou ausência da asa no cinzel de dentes durante os períodos seco e chuvoso para preparo do solo realizado com subsolador acoplado ao trator

Response Variables	Treatment	Rainy season	Dry season
Mobilized soil area (m^2)	Presence of wing	0.28Aa	0.22Aa
	Absence of wing	0.27Aa	0.11Bb
Depth (m)	Presence of wing	0.58Aa	0.49Aa
	Absence of wing	0.59Aa	0.29Bb
Surface width (m)	Presence of wing	0.78Aa	0.67Ab
	Absence of wing	0.81Aa	0.55Bb

For each response variable, means followed by the same uppercase letters in a column or the same lowercase letters in a row do not differ by the F-test at a 5% probability of error.

Para cada variável de resposta, as médias seguidas pelas mesmas letras maiúsculas em uma coluna ou pelas mesmas letras minúsculas em uma linha não diferem pelo teste F com uma probabilidade de erro de 5%.

cm, respectively) produced values that were higher than those in the absence of the wing (0.64 cm and 0.66 cm, respectively).

The mobilized soil area was higher during the rainy season (0.47 m^2) than during the dry season (0.25 cm^2). This same trend was observed for depth and surface width, which were 0.81 cm and 0.96 cm, respectively, in the rainy season and 0.61 cm and 0.65 cm, respectively, in the dry season.

The presence and absence of the wing, and the clod quality index showed satisfactory values during the rainy season (1.00 for both situ) (Table 4). The clod quality index did not significantly differ between tillage in the presence or absence of the wing during the rainy season (P>0.05), and the mean value was 1.00. The treatment without the wing had higher clod quality index (7.20) during the dry season compared with that with the presence of the wing (11.00).

When evaluating the tilled soil profile, it was observed that 100% of the plots during the rainy season had values higher than the minimum recommended value for the mobilized soil area. However, 80% of the plots did not reach the specified value when tillage was performed in the presence of the wing during the dry season, and 60% did not reach the recommended standard in the absence of the wing (Figure 4).

The network structure of soil tillage and soil conditions (Figure 5A) shows that the soil quality tillage (area mobilized soil, surface width, and depth) was positive overall, and strongly connected with each other and the soil humidity. They also had an inverse strong correlation with clod quality index and a weak inverse correlation with soil density. The soil humidity had a strong and inverse correlation with the soil density and the clod quality index.

Through a principal component analysis (PCA) (Figure 5B), we observed that the soil preparation efficiency is divided into groups according to the season of the year (rainy and dry), in which the treatments were grouped in opposite quadrants. The treatments carried out in the rainy season had greater soil moisture, mobilized soil area, surface width, and furrow depth, and also showed an inverse correlation with soil density. The opposite was observed for the treatments performed in the dry season. The soil tillage prepared in the dry season showed a strong correlation with the clod quality index. The PCA component 1 explained about 88.42% of the data, while component 2 explained about 7.58% of the data. The highest values for each axis indicate the most representative variable, thus explaining the largest portion of the variance of the original data set.

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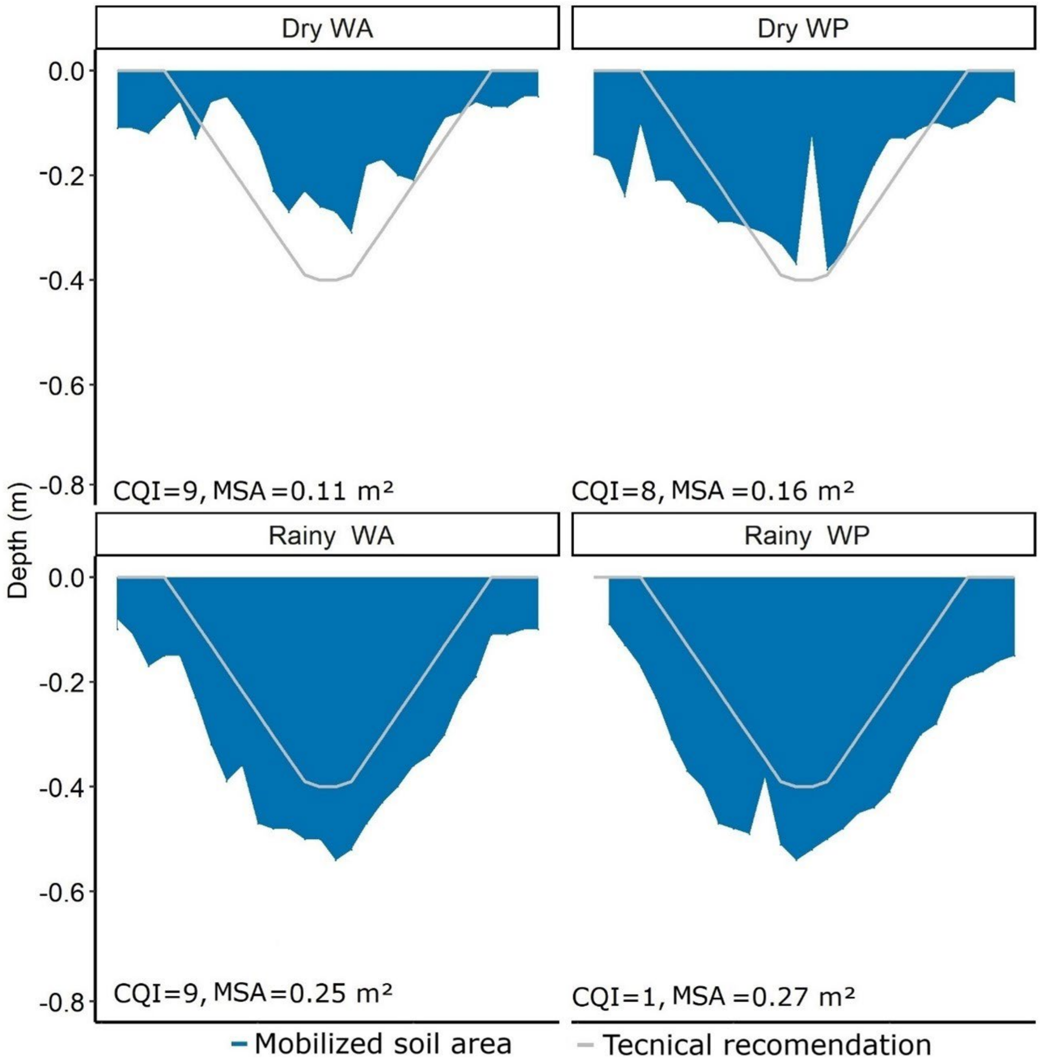

Figure 3. Profile of tilled soil obtained from subsoiling performed by the tractor with an attached subsoiler in the rainy and dry season in the presence and absence of the wing. CQI = clod quality index and MSA: of mobilized soil area

Figura 3. Perfil do solo preparado obtido da subsolagem realizada pelo trator com subsolador acoplado no período chuvoso e seco na presença e ausência da asa. IQC = índice de qualidade do torrão e MSA: da área de solo mobilizada

4. DISCUSSION

The better quality of the soil tillage in the rainy season than in the dry season is related to soil behavior, as water molecules are adsorbed with the increase in moisture, which then reduces the cohesion and tension between the soil particles and thus facilitates mobilization (Compagnon et al., 2013). Soils with low moisture have high resistance to penetration of the subsoiler, but as the water content increases, resistance decreases (Cunha et al., 2021). Therefore, regardless of the presence or absence of the wing in the tine chisel, soil mobilization was efficient during the rainy season due to less resistance to penetration of the implement in the soil.

However, it was observed that the use of tines in the presence of the wing was indispensable during the dry season to ensure that the soil preparation reached the desired minimum quality, corroborating the findings of Cunha et al. (2021). In addition, the presence of wings increases the penetration stability of the implement in the soil and allows it to reach greater depths with 22% less resistance to penetration in the soil (Askari et al., 2016),

Table 3. Means of the area of mobilized soil, depth, and surface width as a function of the presence or absence of the wing in the tine chisel during the dry and rainy seasons for soil tillage performed by the hydraulic excavator. (P<0.05)

Tabela 3. Médias da área de solo mobilizada, profundidade e largura da superfície em função da presença ou ausência da asa no cinzel de dentes durante os períodos seco e chuvoso para preparo do solo realizado pela escavadeira hidráulica. (P<0,05)

Response Variables	Wing		Season	
	Presence	Absence	Rainy	Dry
Mobilized soil area (m²)	0.40a	0.3b	0.47a	0.25b
Depth (m)	0.78a	0.64b	0.81a	0.61b
Surface width (m)	0.94a	0.66b	0.96a	0.65b

Means followed by the same letter in a row for the presence of the wing or the dry/rainy season do not differ by the F test at a 5% probability of error.

Médias seguidas pela mesma letra em sequência para a presença da asa ou estação seca/chuvosa não diferem pelo teste F com probabilidade de erro de 5%.

Table 4. Mean clod quality index for the relationship between wing condition (presence or absence) and season (dry or rainy) in the soil tillage with hydraulic excavators

Tabela 4. Índice médio de qualidade do torrão para a relação entre condição da asa (presença ou ausência) e estação (seca ou chuvosa) no preparo do solo com escavadeiras hidráulicas

Response variable	Wing	Season	
		Rainy	Dry
Clod quality index	Presence	1.00Aa	11.00Bb
	Absence	1.00Aa	7.20Ab

Means followed by the same uppercase letter in a column or the same lowercase letter in a row are not different according to the F test at a 5% probability of error.

Médias seguidas pela mesma letra maiúscula em uma coluna ou pela mesma letra minúscula em uma linha não são diferentes de acordo com o teste F com uma probabilidade de erro de 5%.

which explains the values below the technical recommendations for preparing the furrow during the dry season.

The soil mobilization values that exceed the recommended values for subsoiling, as observed with the hydraulic excavator, can be attributed to the fact that the implement has tracked wheels, which increases the contact area with the soil and the traction performed between the implement and the soil, with the engine power of 72 kW (Monteiro et al., 2011). The excavator also has a great lifting capacity with its hydraulic arm, which allows for more soil mobilization, reaching greater depths of subsoiling (Cunha et al., 2021; Souza et al., 2018).

The tilled soil profile during the rainy season met the recommended values due to the ease of soil mobilization caused by the lower cohesion of its particles and the lower resistance to soil penetration by the subsoiling tine (Cunha et al., 2021). In contrast, the dry season exhibited a high rate of non-conforming values. This finding may be attributed to the high occurrence of clods in the soil, which act as barriers to soil mobilization.

The clod quality index during the rainy season was satisfactory and influenced by soil moisture. However, it can be observed that soil tillage with the presence of the wing in the dry season has a higher correlation with the CQI (Figure 5B). According to Dexter and

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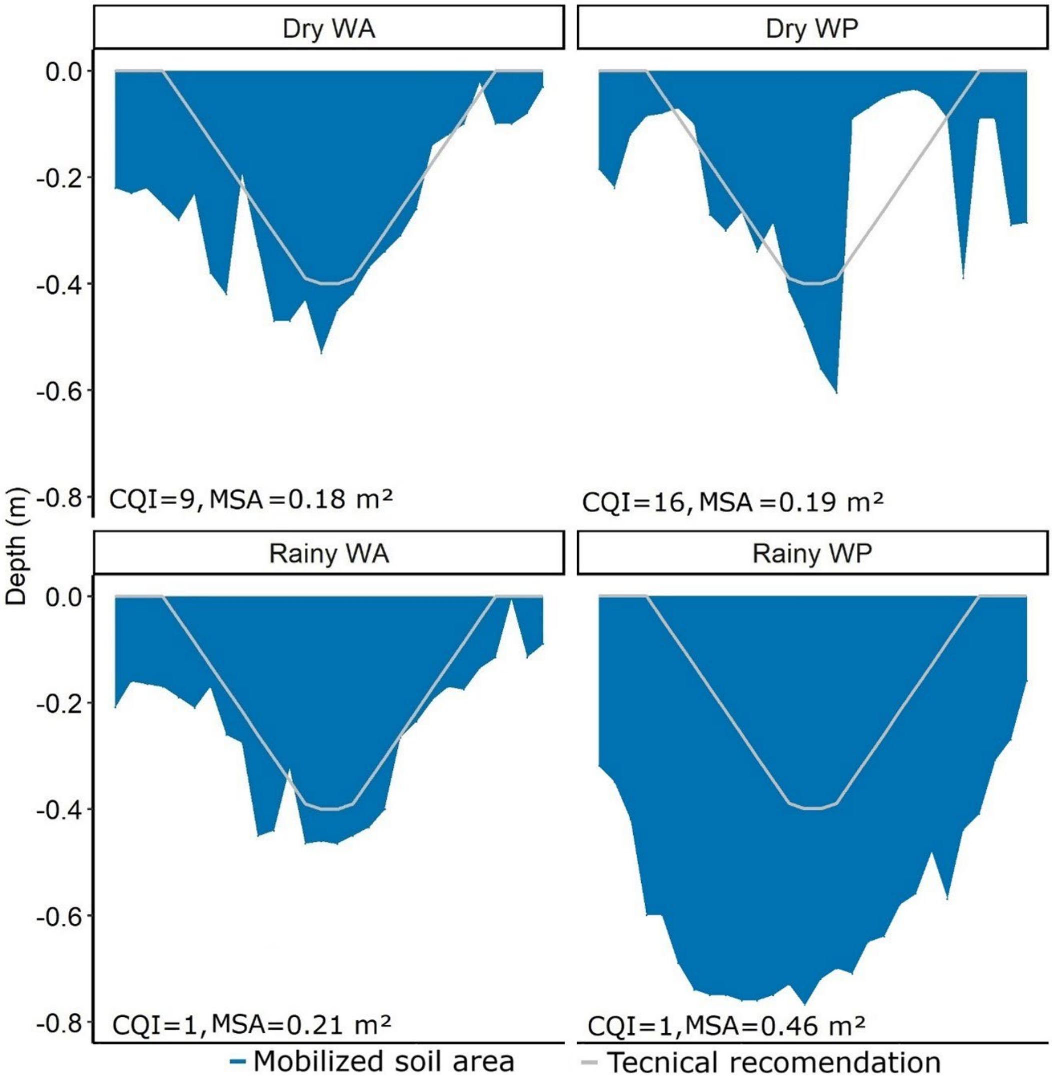

Figure 4. Profile of mobilized soil obtained during subsoiling performed by the hydraulic excavator in the rainy and dry season in the presence and absence of the wing. CQI: clod quality index and MSA: mobilized soil area

Figura 4. Perfil do solo mobilizado obtido durante a subsolagem realizada pela escavadeira hidráulica no período chuvoso e seco na presença e ausência da asa. CQI: índice de qualidade do torrão e MSA: área de solo mobilizado

Watts (2000), more humid clods may undergo plastic deformation before clod breakdown occurs, whereas low moisture levels result in a higher incidence of clods due to increased soil cohesion and particle compaction. Thus, it can be concluded that the cutting was more efficient at the shear points of the soil, which consequently increased the incidence of clods (Askari et al., 2019).

The highest index of clods in the soil was found with the hydraulic excavator, and the index was proportional to the greater soil mobilization; thus, the highest clod quality index observed was in the treatments with the presence of wings, which produce greater soil mobilization. However, Askari et al. (2019) found a higher number of clods in treatments without wings compared to treatments with wings in soil tillage performed by a tractor coupled with a subsoiler. Moreover, the higher clod quality index in this study was attributed to the absence of soil finishing systems that minimize clod formation in hydraulic excavators.

It has generally been found that a high clod index impairs the quality and efficiency

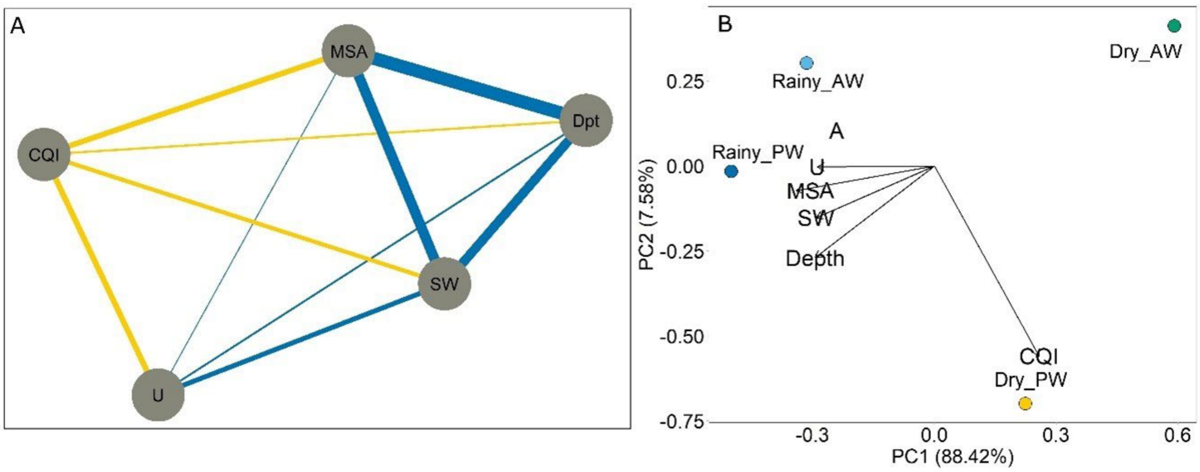

Figure 5. Network correlation (A) and Principal components analyses - PCA (B) between the quality of variables of soil tillage, depth, surface width, mobilized soil area, and CQI (Clod Quality Index). Blue lines represent positive associations, yellow lines negative ones, and the thickness and brightness of an edge indicate the association strength

Figura 5. Análises de componentes principais (PCA) e correlação de rede entre a qualidade das variáveis de preparo do solo, profundidade, largura da superfície, área de solo mobilizada e CQI (Índice de Qualidade do Torrão). As linhas azuis representam associações positivas, as linhas amarelas, as negativas, e a espessura e o brilho de uma borda indicam a força da associação

of soil tillage (Figure 5). Cunha et al. (2021) discuss that the presence of clods can obstruct the growth of the root system as it acts as a barrier in the soil, reducing the availability of water, nutrients, and oxygen to the plants. This can hinder plant survival and lead to forest inhomogeneity. One method to reduce the number of clods during soil tillage is to incorporate a furrow finishing system, such as a disc harrow, chain harrow, rolling harrow, or different types of scarifiers (Alkhafaji et al., 2018).

However, the use of a four-disc harrow with the tractor and attached subsoiler was not efficient in breaking down soil clods during the dry season, resulting in unsatisfactory results for the clod quality index. When using a hydraulic excavator, incorporating furrow finishing systems is not feasible as they can cause instability or disrupt the subsoiling operation. An alternative to reduce the clod index during excavation is to remove the wing from the tine chisel. This is because the excavator mobilizes the soil at higher levels than those required for subsoiling, regardless of the presence of the wing.

The soil tillage performed by both implements demonstrates quality subsoiling, as they reach the minimum required specifications for the activity. However, a caveat arises during the dry season, as special attention must be given to the presence or absence of the wing, as discussed in the specific details of each implement.

One of the problems with using hydraulic excavators is their low field productivity (6 h ha^{-1}) and high cost of the activity (R$ 840.00 per ha) (Souza et al., 2018). Therefore, it is recommended to employ the hydraulic excavator for soil tillage only in areas with high slopes, where the subsoiler attached to the tractor lacks the necessary stability to operate effectively.

The factors that may affect the productivity of the hydraulic excavator include the high mean mobilized soil area and depth. Cunha et al. (2021) demonstrate that subsoiling can reach depths of up to 0.80 m. Existing scientific publications show tillage depth for clayey cohesive or compacted soils might be of 0.70 m (deep subsoiling) to improve compacted soil with low microporosity and restriction to root growth, but 0.50 m (shallow) subsoiling plus ridding produce similar results (Santos and Reichert, 2022). However, Pereira et al. (2012) and Simões et al. (2011) observed that

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the higher the slope, the lower the depth that is reached during subsoiling, and the tractor performance decreases, and the cost increases. Although the slope does not negatively affect the depth reached by the hydraulic excavator, the adoption of precision systems to control the depth of the tine during subsoiling in the field is suggested to increase the operation's efficiency and to reduce the cost of the activity.

5. CONCLUSION

Both tested implements demonstrated effective soil preparation. However, the low yield and high cost associated with subsoiling activities carried out by hydraulic excavators justify their use only in sloping areas where tractors are unable to operate. Soil preparation conducted during the rainy season doubled the mobilized soil area, primarily due to favorable soil moisture conditions. The soil preparation carried out in the dry season resulted in a reduction in the mobilized soil area, mainly due to limited soil moisture. The presence of wings on the tine chisel significantly increased the mobilized soil area, which is a relevant factor, particularly in the dry season, for the tractor with the attached subsoiler. However, the hydraulic excavator did not demonstrate the necessity of the presence of the wing on the tine chisel, as it exceeded the soil preparation recommendations to a significant extent. In addition, the presence of the wing in the hydraulic excavator increased the clod quality index, reducing the quality of soil preparation.

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AUTHOR CONTRIBUTIONS

Cunha, F. L.: Conceptualization, Methodology, Validation, Investigation Formal analysis, Data Curation, Writing – original draft preparation; Nieri, E. M.: Writing – review and editing, Data Curation; Almeida, R. S.: Writing – review and editing Leite, F. P.: Conceptualization, Methodology, Funding acquisition, Project administration; Melo, L. A.: Data Curation, Writing – review and editing.

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