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Influence of tillage practices and rainfall intensity on runoff and soil erosion under simulated rainfall

Influência das práticas de preparo do solo e da intensidade das chuvas no escoamento superficial e na erosão do solo sob chuva simulada

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This study aimed to evaluate the impact of various soil preparation practices, rainfall intensities and slopes using a rainfall simulator. Three land preparation methods (mulching, terracing, and terracing + ditches), three rainfall intensities (18, 50, and 73 mm h^{-1}), and three slopes (5, 10, and 15%) were examined to verify best practices of soil preparation. The exclusive use of straw (10 Mg ha^{-1}) on the surface is insufficient to prevent runoff and consequently the loss of water and soil on steep terrain and subject to high-intensity rainfall. The combination of terracing + ditches proved to be effective in reducing runoff. This study has substantial implications for the control of soil erosion for the sustainable development of agriculture in subtropical conditions.
Key-words: slope, terracing, ditches.

Este estudo teve como objetivo avaliar o impacto de diversas práticas de preparo do solo, intensidades de chuva e declives usando um simulador de chuva. Três métodos de preparo do solo (valas, terraços, e terraços + valas), três intensidades de chuva (18, 50 e 73 mm h^{-1}) e três declives (5, 10 e 15%) foram examinados para verificar as melhores práticas de preparo do solo. O uso exclusivo de palha (10 Mg ha^{-1}) na superfície é insuficiente para evitar o escoamento e consequentemente a perda de água e solo em terrenos íngremes e sujeitos a chuvas de alta intensidade. A combinação de terraços + valas revelou-se eficaz na redução do escoamento. Este estudo tem implicações substanciais para o controle da erosão do solo para o desenvolvimento sustentável da agricultura em condições subtropicais.
Palavras-chave: declive, terraços, valas.

1. INTRODUCTION

Soil erosion is globally recognized as a significant soil degradation challenge, with its management directly influencing soil and water losses [1, 2]. Soil erosion is a natural process that involves the disaggregation, transport, and deposition of soil particles, and the absence of conservationist systems can exacerbate soil erosion. Merely maintaining straw on the soil may not sufficiently protect the soil from erosion. The ecological principles of Conservation Agriculture (CA), namely permanent soil mulch cover and crop diversification [3], necessitate additional measures on sloping land, such as terraces.

Rainfall simulators have been instrumental in evaluating soil erosion and water infiltration into the soil [4]. These essential research tools allow for the visualization and analysis of soil erosion dynamics and related processes [5], thereby eliminating the irregularities and variability associated with natural precipitation. The benefits of using rainfall simulators include the ability to repeat rain events, expedite the acquisition of water infiltration results, and standardize raindrop diameters, height, and duration. Furthermore, rainfall simulators can generate and replicate rainfall of varying intensities and fundamental kinetic energy. This capability is crucial for understanding the impacts of anthropogenic actions on management changes that influence soil erodibility [6-8].

Thus, efforts to quantify the severity of these issues enable the development of conservation practices that complement soil cover [2], a crucial step in establishing soil and water conservation systems. Mulching, a process that involves covering the soil with any organic material, minimizes the soil surface area exposed to the environment. This practice helps prevent soil particle loosening and aggregate breakdown caused by rainfall. Utilizing mulch for soil surface protection can extend the beneficial effects of tillage, offering long-term control over runoff and erosion. However, in areas with steep slopes, constructing terraces is a more effective and established method for erosion control [9, 10]. Properly designed, constructed, and maintained terraces can protect soil by enhancing infiltration rates and reducing runoff and sediment production [11]. Besides terraces, level ditches, created by constructing grooves at an even level, can increase the rate of water infiltration into the soil and delay the onset of soil water flow formation [9].

Numerous studies have explored the combination of shallow soil disturbance and surface mulching as a method for controlling runoff and soil loss [12, 13]. However, no research has yet investigated the integration of these practices with the use of ditches and terraces. We propose that the amalgamation of terraces and level ditches could potentially be increasingly effective in reducing runoff and soil loss in steeplands subjected to high-intensity rainfall. Consequently, the aim of this study was to assess the impact of tillage practices, rainfall intensity, and slope using a rainfall simulator.

2. MATERIAL AND METHODS

2.1 Site description

The rain simulation experiment was conducted at the Universidade Estadual do Oeste do Paraná (UNIOESTE), Cascavel-PR, Brazil. The rain simulator has a fully detachable metal structure with a 1.0 x 1.0 x 0.3 m box, which facilitates the transport of the soil, whether intact from the field or prepared in the laboratory. Deformed soil samples were collected from the upper 0-0.3 m layer using a cutting shovel. At the time of collection, black oats were used as ground cover. The collected area has an average soil organic matter (SOM) content of 4.5% and has been conducted under a direct planting system with rotation of commercial crops and soil cover species for more than 20 years. The soil in the experimental area was classified as Dystroferric Red Latosol [14].

The chemical characterization of the soil was carried out using deformed samples from the 0-0.2 m soil layer. The following values were verified: pH ($CaCl_2$) = 4.85; P = 37.75 mg dm^{-3}; H + Al = 7.53 cmol$_c$ dm^{-3}; Al^{3+} = 0.15 cmol$_c$ dm^{-3}; Ca^{2+} = 6.84 cmol$_c$dm^{-3}; Mg^{2+} = 1.86 cmol$_c$ dm^{-3}; K^+ = 0.91 cmol$_c$ dm^{-3}; V (%) = 56.17; Al (%) = 1.81. P and K (Mehlich-1 Extractor); Al, Ca and Mg (KCl extractor 1 mol L^{-1}). The particle size values were 36, 328 and 636 g kg^{-1} for sand, silt and clay, respectively.

The rainfall simulator is equipped with a Quick FullJet full cone sprinkler nozzle.

2.2 Experimental design

We used three distinct soil preparation scenarios: mulching, terracing, and a combination of terracing + ditches. These practices were tested under three different rainfall intensities: 18, 50 and 73 mm h^{-1} and on three varying slopes: 5, 10 and 15%. Five repetitions were performed in the same scenario. Non-random experimental design was conceived due to the difficulty of removing soil from the box. 135 rain simulations were carried out. Field capacity was considered before simulations. The interval between one simulation and another was standardized, according to the surface flow in the simulator gutter to the outlet spout. As soon as the surface runoff of each repetition was stabilized, a new simulation was started.

Soybean straw, at a quantity of 10 Mg ha^{-1}, was utilized for mulching (Figure 1a). The dimensions and spacing of the terraces were determined based on a real field terracing and subsequently scaled down for the rain simulator (Figure 1b). Ditches, measuring 0.5 × 1.0 cm, were installed immediately following the terracing (Figure 1c).

Figure 1. Tillage practice and the surface configuration with (a) mulching, (b) terracing, and (c) terracing + ditches.

The hoist, assigned to the rain simulator, regulated changes in slope. These changes were subjected to three rainfall intensities, controlled by a manometer.

2.3 Parameter measurements

Following each simulated rainfall event, evaluations were conducted on runoff and soil losses. Surface runoff and soil loss samples were consistently collected using pre-weighed plastic buckets. Soil losses were quantified using pre-weighed metal cans and a precision scale. A volume of 50 mL of the drained sample was placed in these cans, shaken for uniformity and then dried in an oven at 105 °C for 24 hours before being weighed again.

2.4 Statistical analysis

Because there was no homogeneity of variance and normal distribution of data, were compared using the Kruskal-Wallis test. All statistical analyzes were carried out with a significance level of $p \leq 0.05$.

3. RESULTS

Soil tillage practices, slopes and rainfall intensities significantly influenced runoff (Kruskal–Wallis: $p \leq 0.05$). Terracing + ditches was efficient in reducing runoff compared to mulching and terracing (Figure 2a). The runoff for mulching, terracing, and terracing + ditches were 309, 250 and 130 $m^3\ ha^{-1}\ h^{-1}$, respectively (Figure 2a). In addition, slope of 15% resulted in greater runoff (Figure 2b), as well as rainfall intensities of 50 and 72 mm h^{-1} (Figure 2c).

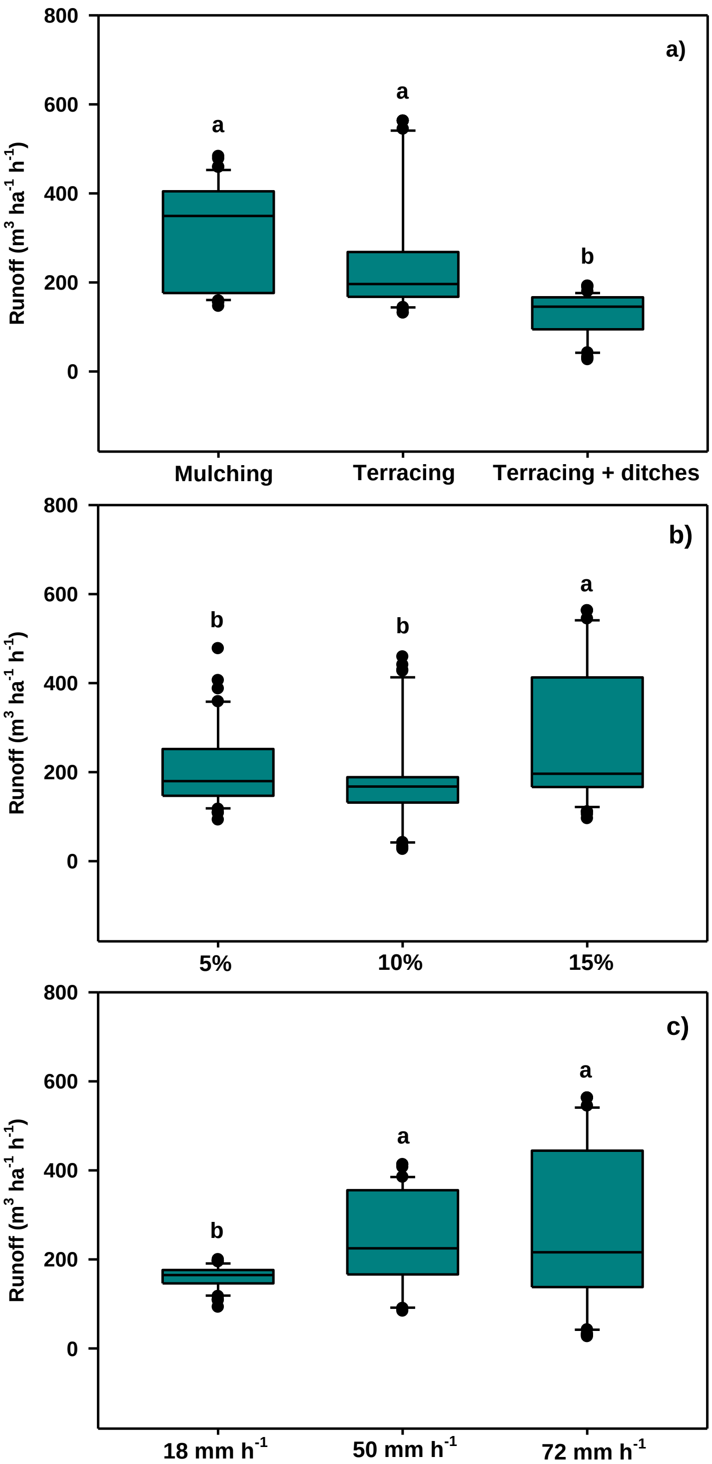

Figure 2. Runoff for tillage practices (a), slopes (b), rainfall intensity (c). Means with different letters indicate significant differences according to the Kruskall–Wallis test.

Soil tillage practices and rainfall intensities significantly influenced soil loss (Kruskal–Wallis: $p \leq 0.05$). Soil loss was notably greater in the mulching (1648 kg ha^{-1} h^{-1}) than in the terracing (424 kg ha^{-1} h^{-1}) and terracing + ditches (130 kg ha^{-1} h^{-1}) (Figure 3a). Therefore, the combined implementation of terracing and terracing + ditches management significantly reduced soil loss. No significant difference in soil losses when analyzing the different slopes (Figure 3b). However, the greatest soil losses were observed at rainfall intensities of 50 and 72 mm h^{-1} (Figure 3c).

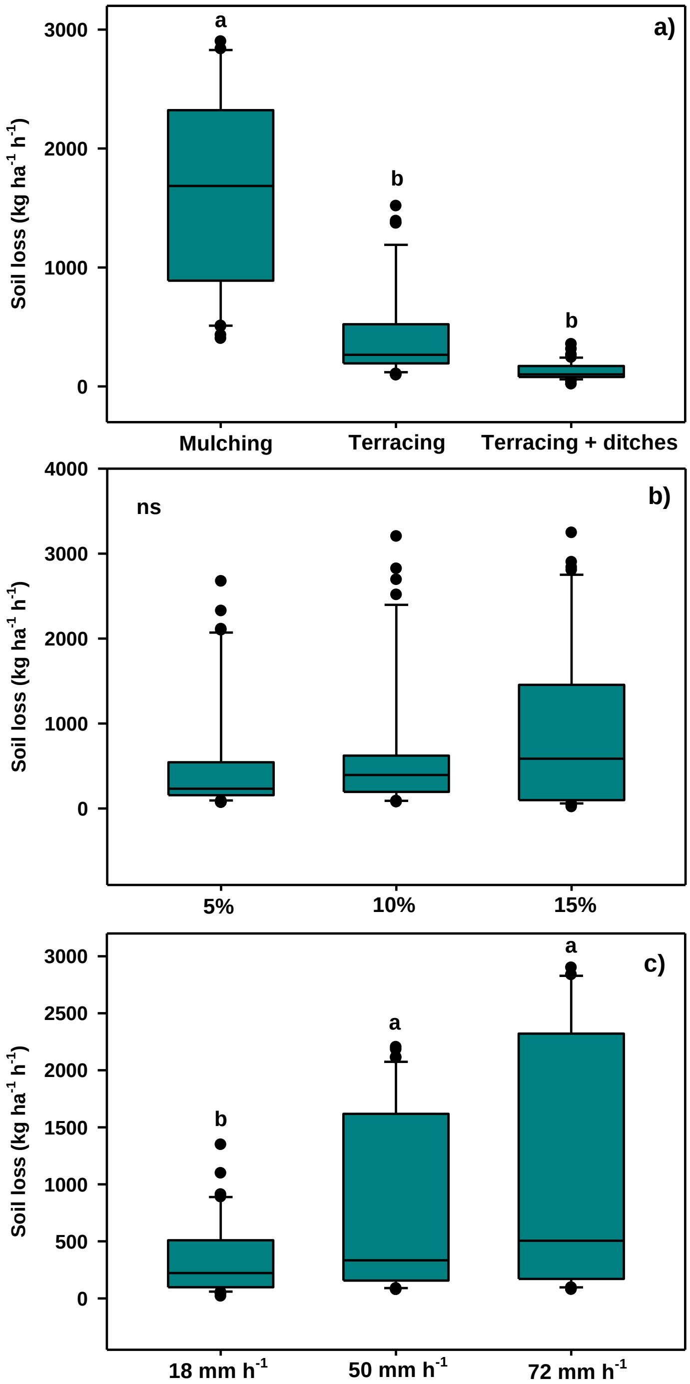

Figure 3. Soil loss for tillage practices (a), slopes (b), rainfall intensity (c). Means with different letters indicate significant differences according to the Kruskall–Wallis test. ns: not significant.

4. DISCUSSION

The combination of terracing + ditches is an extremely important support conservation practice to control surface runoff and reduce losses of water (Figure 2a) and soil (Figure 3a). Our findings indicate that mulch alone is inadequate for reducing runoff. Straw is a significant factor, it may not be the only factor in sediment reduction [15]. Lucas-Borja et al. (2019) [16] found that mulching did not influence runoff. Despite our study showing that mulching does not reduce runoff and soil losses as effectively as terracing or a combination of terracing + ditches, the benefits of mulching over bare soil are well-documented [17-19]. A majority of existing research suggests that straw mulching effectively increases slope infiltration capacities and decreases both slope runoff intensity and sediment yield [20-22].

Although mulching has been effective in controlling soil erosion, they have been less successful in reducing runoff [23-25]. Therefore, to achieve a more substantial reduction in runoff, other conservation strategies [26, 27], such as the implementation of terracing or ditches, in order to increase water infiltration into the soil and conservation of water but also improving soil quality. Grum et al. (2017) [28] demonstrated that the combination of mulch with the development of ridges and furrows could increase the soils infiltration capacity and significantly reduce surface runoff, as seen in research (Figure 2a).

The benefits of graded trenches observed in the present study align with those found by Chen et al. (2020) [9]. Characterized by superior water retention, deep infiltration, optimal soil water storage, and uniform water gathering, leveled ditches result in minimal scouring and siltation, even following rainstorms [29]. Furthermore, the structure of these ditches can mitigate the loss of organic matter and enhance soil aggregate structure, indirectly bolstering vegetation recovery and erosion resistance [29]. Duan et al. (2021) [30] found that the most successful runoff and sediment reduction was achieved through a combination of grassed taluses, front mounds, and back ditches. Chen et al. (2020) [9] found that, compared to other terracing structures, leveled ditches provided the most significant water conservation benefits, particularly on steep slopes. Niu et al. (2021) [31] recommended combinations of terracing + ditches, terracing + vegetation cover, terracing + grass on ridges, and terracing + ditches + grass on ridges as highly effective soil and water conservation strategies in citrus orchards. Feng et al. (2020) [29] noted that, following zig terraces, leveled ditches offered the second highest benefits.

The well-documented benefits of using terraces with ditches, such as enhanced infiltration are widely recognized [10, 9, 32]. Our study indicates that employing terraces is a more effective strategy than solely relying on mulching. Terracing, however, transforms the sloped surface into a horizontal plane, continuously interrupting the flow lines of slope flow and the middle stream, thereby preventing the redistribution of precipitation across the hillslopes. This approach ensures that rainfall is intercepted and infiltrated in-situ, thereby eliminating runoff and sediment flow [33]. Rutebuka et al. (2021) [34] further corroborated the immense potential of terraces in significantly reducing soil erosion rates in a sustainable manner.

5. CONCLUSIONS

This study investigated the influence of tillage practices, rainfall intensity, and slope on runoff and soil loss under simulated rainfall conditions. Our findings corroborate the hypothesis that only having straw on the surface is insufficient to prevent runoff and soil loss in steep terrains subjected to high-intensity rainfall. Tillage practices that combined terracing and mulching prove to be effective in mitigating runoff, particularly on steep slopes. The sole use of straw (10 Mg ha^{-1}) fails to prevent runoff and soil loss, except in cases of low-intensity rainfall and minimal slope. This study has substantial implications for controlling soil erosion for the sustainable development of agriculture under subtropical conditions.

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