# Role of charcoal addition on infiltration processes and soil water content characteristics of a sandy loam soil

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**Abstract:** Terra preta (TP) is a soil amendment which is enriched with powdered charcoal, with nutrient sources from organic residues, and that constitutes a resource to improve soils for sustainable land use systems (Glaser, 2007). Terra preta-dark soil is inspired by the highly successful historic practice of soil building in the Amazon and other parts of the world. This work involves a relatively unexplored topic: the comprehension of infiltration processes and soil water content characteristics in a sandy loam soil combined with different fractions of terra preta amendments. This analysis contributes to a better understanding of the relationship between fractions of charcoal in terms of terra preta content and soil water holding capacity. First, a physical and hydraulic characterization was performed on soil samples with different charcoal content. Then, they were exposed to a rain simulation experiment under controlled conditions. A descriptive statistical analysis was applied for a quantitative evaluation of the results. It was found that as the fraction of terra preta increased, infiltration and percolation rates decreased, but water holding capacity increased. This can influence water ponding at the surface, leading to runoff formation. However, the effect on water holding capacity is an opportunity, integrated to other sustainable practices, to overcome drought effects and reduce the need for irrigation.

**Keywords:** charcoal, infiltration, sandy loam, sustainable farming, terra preta, water holding capacity

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## 1 Introduction

Land degradation reduces soil productivity, disrupts water renewal and does often cause poverty and even famine. Drylands are expanding and it is expected that they will cover half of the global land surface by the end of the century (Huang et al., 2016). Many dryland regions such as Mediterranean areas, Africa, China, Asia, and South America are the most sensitive facing climate change and are prompt to suffer soil desertification and degradation in the near future. Therefore, there is a need to look for sustainable farming practices aimed to water and soil conservation.

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In the Amazonian region, black and very fertile soils of anthropogenic origin known as “terra preta” have been studied. These soils are rich in charcoal content, and other nutrients such as nitrogen, phosphorus, potassium, and calcium (Glaser et al., 2001; Nadejda et al., 2012). Terra preta was originally produced by incorporating large amounts of burned residues into the soil together with nutrient-rich materials such as human and animal manure (rich in phosphorus and nitrogen), mammal and fish bones (rich in phosphorus and calcium), ash residues or plant biomass such as biomass wastes, compost, algae, etc. (Glaser, 2007). This mix eventually turns into a substrate which typically contains 70 times more charcoal and three times more soil organic matter, nitrogen, and phosphorous than untreated soils (Glaser, 2007). The formation of this amendment is self-regenerative and when inserted in degraded soil, it can remain stable for a long period of time (Nadejda et al., 2012). Therefore, terra preta is a resource for sustainable land management, by contributing to the restitution of organic matter and other essential nutrients in degraded soils (Glaser, 2007). The practice of converting biowaste into Terra preta can also play an important role in returning what remains of food and fodder into soil (Factura et al., 2010).

Previous studies have focused on chemical and/or biochemical characteristics of terra preta soils, with emphasis, for example,on nutrient content and availability, ion exchange, and structural stability (Lima et al., 2002; Glaser et al., 2002; Glaser, 2007; O ́Grady and Rush, 2007; Ferreira Cunha et al., 2009; Novotny et al., 2009). Some studies have found a positive correlation between soil organic matter and soil properties such as water retention, available water holding capacity, and structural stability (Glaser et al., 2002). Also, macro porosity, total porosity, and saturated hydraulic conductivity increase with higher organic matter content (Mbagwu, 1989). A study of charcoal addition to soils with different textures, made by Tryon in 1948, showed that on coarse textures (e.g. sand) the soil water retention was improved in comparison to loamy and clayey soils, which presented no changes in soil water retention with charcoal addition (Glaser et al., 2002). Effects of incorporating compost on soil physical characteristics have also been studied (Aggelides and Londra, 2000; Khan Eusufzai and Fujii, 2012; Whelan et al., 2013). Incorporation of organic matter in the form of compost has shown to improve soil hydraulic properties such as hydraulic conductivity, macro porosity, and water retention. Aggelides and Londra (2000) claimed different degrees of improvement depending on soil textures. For instance, soil properties in loamy soils were better in comparison to those in clayey soils for an equal amount of added compost. These authors reported a decrease of up to 20% on soil density and an increase up to 30% on total porosity for loamy soils. In the case of clayey soils, the increase on total porosity was below 10%. Saturated hydraulic conductivity increased up to 95% and 168% in loamy and clayey soils, respectively. Wang et al. (2009) claimed a negative correlation between the hydraulic conductivity and organic matter content in coarse soils, which suggests that a reduced ability of wetting in sandy soils occurs due to its un-aggregated structure.

The objective of this work is to contribute to the understanding of water dynamics in a sandy loam soil with added charcoal, i.e., sandy loam soil combined with different fractions of terra preta amendment. A descriptive statistical analysis is presented, where water content dynamics, infiltration characteristics, and water holding capacity are compared for soil samples with different fractions of terra preta, compost (based on household waste), and a pure sandy loam soil.

## 2 Materials and methods

When water enters in contact with the soil- represented as soil moisture $\theta$ from either rainfall or irrigation– important processes take place that influence changes in the soil water content ($d\theta/dt$). Infiltrated water (*Inf*) penetrates through the soil surface and becomes part of the water content of the soil; interflow (*Intf*) moves parallel to the surface into the first layers under unsaturated soil conditions; percolation (*Perc*) moves deeper into the lower soil layers; evapotranspiration (*Eva*) generates a loss of moisture from the direct surface; and capillary uprise (*CU*) increases soil moisture through the upward movement of fluids by capillarity. All these processes are summarized in the well-known water balance Equation (1):

$$\frac{d\theta}{dt} = Inf(t) = [Intf(t) + Perc(t)] - Eva(t) + CU(t) \quad (1)$$

In this work, evapotranspiration and capillary uprise effects were minimized in the experimental setup and assumed zero in the analysis. Infiltration was calculated by Equation (1), and soil water content and percolation were measured with the following procedure.

The soil and amendments used for the experiments were classified in two groups. *Group I* consisted of three blocks, each block containing three cylinders filled with different treatments: sandy loam (defined as control, CT), compost (based on household waste with 10% charcoal, CO), and terra preta (identified as TP). Averaged rain intensities of 22 mm h$^{-1}$ were simulated in this case. *Group II*, consisted of three blocks with cylinders filled with the same sandy loamy soil and three different addition levels of charcoal: 20% terra preta and 80%

sandy loam (20 TP), 30% terra preta and 70% sandy loam (30 TP), 50% terra preta and 50% sandy loam (50 TP). Averaged rain intensities of 15 mm $h^{-1}$ were simulated for group II samples. Soil and amendments were packed in cylinders with a height of 30 cm and a diameter of 20 cm. The analysis of variance was performed following the experimental design of split plots in space and time: evaluation of soil moisture for different fractions of terra preta amendment soil (*factor A*), with three different soil depths (*factor B*) for a rainfall simulation period (*factor C*) (Figure 1).

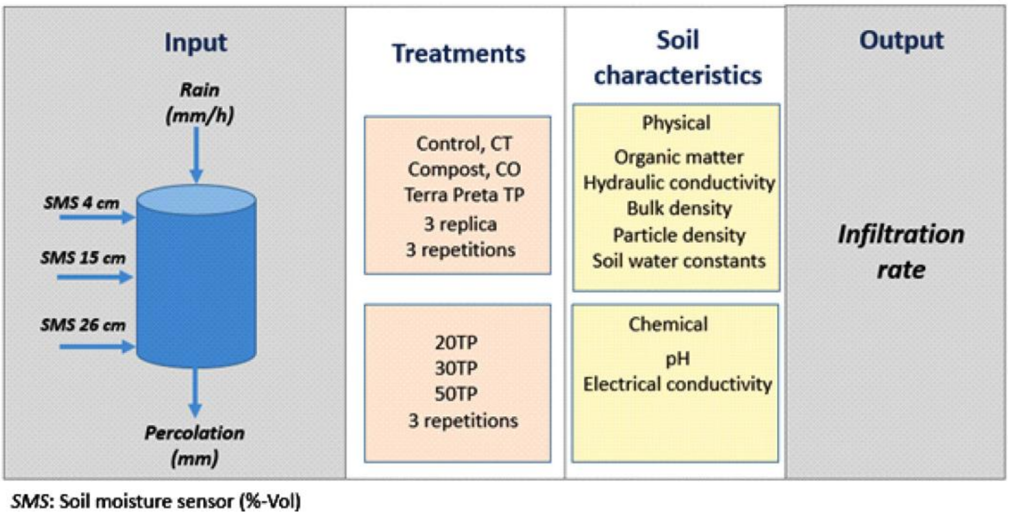


Figure 1 Representation of the experimental procedure

Three soil moisture sensors were installed (in each packed cylinder) 4, 15, and 26 cm depth. Soil moisture was registered every 3 s before, during, and after the rain simulation event. Percolation was collected at 5 min intervals and the water column height, at the surface, was measured with the same time interval as percolation.

A physical characterization of the soil samples was carried out in order to support the experimental analysis. Samples for bulk density were weighted before and after drying at 105℃ for 24 h. The dimensions of the cylinders used to take the samples had a height and diameter of 50 mm (DIN 18125-1, 2010). For organic matter, samples were dried at 105℃ for 24 h, pulverized with a mortar, and weighted before and after heating up to 550℃ for a period up to reach a constant weight, according to the norm [DIN 18128, 2002]. Soil moisture retention was obtained by the suction-plate method, following the norm (ASTM D2325-68, 2000; ASTM D6836-02, 2008).

Electrical conductivity (EC) and pH were measured for the amendment soils (CO, TP, 20TP, 30TP and 50TP), according to (ASTM-D4972, 2013), in order to corroborate soil stability. The pH was neutral for all treatments and EC ranged from 0.05 up to 0.34 dS $m^{-1}$ as terra preta fraction increased.

The non-parametric Kruskal Wallis test and the parametric analysis of variance of the soil moisture -for the treatments CT, CO, TP, 20TP, 30TP and 50TP were carried out with a significant test level of 0.05. The statistical software R (R-project, 2015) was used for the descriptive analysis of the soil water content of all treatments.

## 3 Results and discussion

The soil moisture data distribution at three different depths is shown in Figure 2. As organic matter content increases by the addition of terra preta amendment soil, soil water content not only increases, but also presents less variation of the soil moisture distribution. In Figure 2, the control treatment (sandy loam, CT) displays the lowest median soil moisture values at all depths, whereas the terra preta (TP) treatment shows the highest ones. Treatments 20TP, 30TP and 50TP show the narrowest soil moisture distribution. Outliers at the bottom bound indicate that the initial soil water conditions were below field capacity at the beginning of the experiment. Outliers at the top bound indicate saturated soil conditions at the end of the experiment. For most treatments during the experiment, the soil water content moves from values near wilting point up to saturation. At a depth of 26 cm, medians tend to stay slightly higher with respect to field capacity values. This is attributed to a delayed percolation in presence of organic matter.

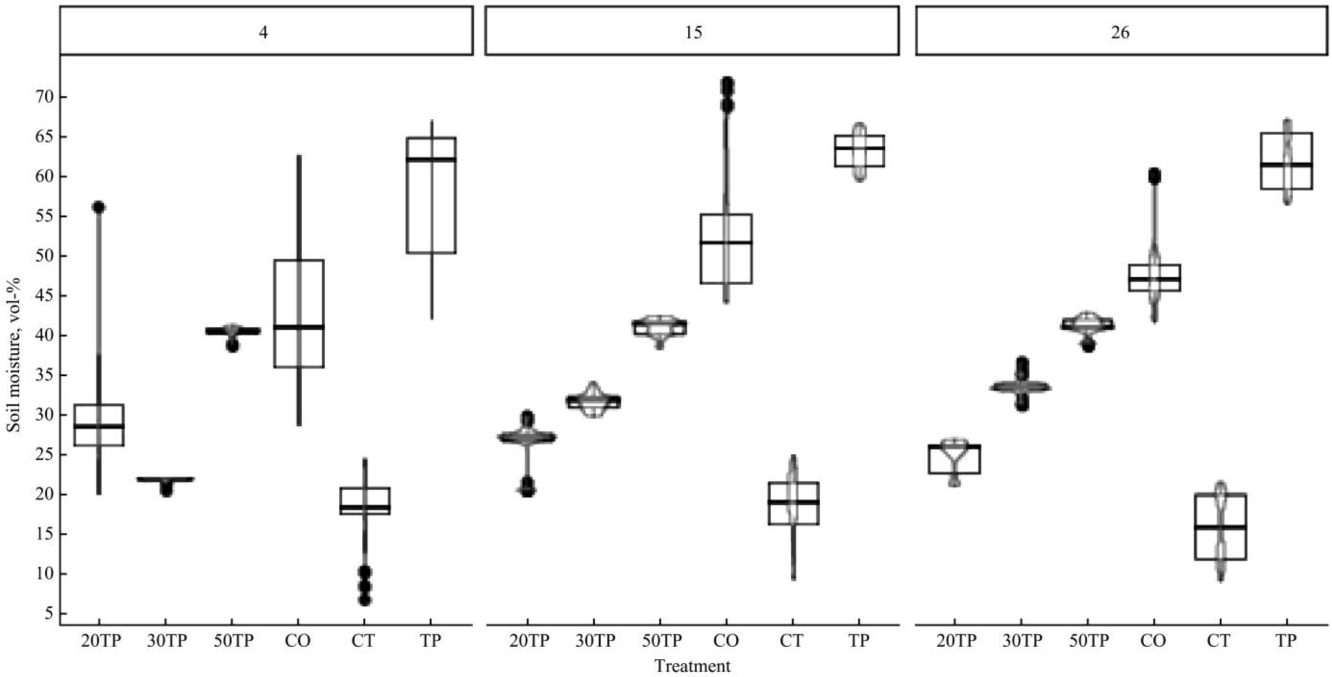


Figure 2 Blox-plot for median comparison of all treatments showing soil moisture data distribution at three different depths

Some treatments showed a higher variation of the soil moisture distribution at the surface and at the center of the soil profile. The rain impact near to the surface is linked to a relatively high soil moisture variation for all treatments.

As terra preta was added to the sandy loam soil, soil moisture constants increase (Table 1) and median values of treatments 20TP and 30TP move towards the high bound of CT. Before starting the rainfall simulation, all treatments were set to soil moisture values close to wilting point. After experiments were performed, soil moisture values for treatments 20TP and 30TP tend to move higher than field capacity.

Table 1 shows that the available water content, obtained by the suction-plate method for treatments CT and with different fractions of terra preta (20TP, 30TP, 50TP). For the treatments of Compost (CO) and Terra Preta (TP), soil water content was measured directly in the packed soil cylinders using soil moisture sensors due to their particle composition. As the fraction of terra preta increases, intervals between wilting point and field capacity increase slightly improving water available for plants.

Since there is evidence of a non-normality distribution of the residuals and heterogeneous variance of the treatments, the non-parametric Kruskal Wallis test was used to analyze the variance (Table 2). With a p-value lower than 0.05, the median ranks of the soil water content between treatments are significantly different. Tables 3 and 4 show the results of the parametric analysis of variance (ANOVA) for the soil moisture for the treatments CT, CO, TP, and 20TP, 30TP, 50TP, respectively. Both parametric and non-parametric tests provide similar results in terms of differences of the soil water content between treatments; therefore, the parametric analysis is chosen for further difference analysis, mainly due to its robustness.

**Table 1 Soil moisture constants for the studied treatments obtained by the suction-plate method**

| Treatment | Available moisture, vol-% | Saturated soil moisture, vol-% (0.0 pF*) | Field capacity, vol-% (2.54 pF[1]) | Wilting point, vol-% (4.2 pF[1]) |
|---|---|---|---|---|
| Control[2] | 5 | 47 | 19 | 14 |
| Compost[3] | 10 | 53 | 43 | 33 |
| Terra Preta[3] | 3 | 63 | 60 | 57 |
| 20TP[2] | 12 | 58 | 26 | 14 |
| 30TP[2] | 14 | 63 | 29 | 15 |
| 50TP[2] | 16 | 69 | 40 | 24 |

Note: [1]pF stands for units of y-axis of the soil retention curve, pF=0.0~.001 bar, pF=2.54~0.33 bar and pF=4.2~15 bar; [2]water content values obtained with pressure plates; [3]water content values obtained directly in the soil packed cylinder with soil moisture sensor (Echo5, Decagon Devices).

**Table 2 Kruskal Wallis test for the analysis of variance for the soil moisture (95% of confidence)**

| Treatment | *N* | *Median* | *Ave. rank* |
|---|---|---|---|
| 20TP | 171 | 26.56 | 241.4 |
| 30TP | 171 | 31.29 | 296.9 |
| 50TP | 171 | 40.85 | 541.0 |
| CT | 99 | 11.92 | 59.3 |
| CO | 9 | 46.57 | 642.3 |
| TP | 99 | 62.48 | 749.2 |
| Overall | 809 | | 405.0 |
| *H*=711.47 | *DF*=5 | *P*=0.000 | |

Note: *N*: number of elements; *Median*: median values of soil moisture; *Ave rank*: averaged rank of data from all groups; *DF*: degree of freedom; *H*: test statistics, *P*: p-value.

**Table 3 Analysis of variance (ANOVA) of the soil moisture for the treatments CT, CO and TP (95% of confidence)**

| Source of variation | Degree of freedom | *SS* | *MS* | *Fc* | *P*-value |
|---|---|---|---|---|---|
| Block | 2 | 2 241.8 | 1 120.4 | 6.3 | 0.06 |
| Treatment | 2 | 118 345.4 | 59 172.7 | 334.6 | 0.00 |
| Error a | 4 | 707.3 | 176.8 | | |
| Sub-total I | 8 | 121 293.6 | | | |
| Depth | 2 | 1 031.0 | 515.5 | 3.1 | 0.08 |
| Depth*Treatment | 4 | 3 180.3 | 795.1 | 4.8 | 0.02 |
| Error b | 12 | 1 985.7 | 165.5 | | |
| Sub-total I + II | 26 | 127 490.6 | | | |
| Time | 10 | 998.6 | 99.9 | 12.9 | 0.00 |
| Error c | 20 | 153.7 | 7.7 | | |
| Sub-total III | 32 | 3 393.1 | | | |
| Time*treatment | 20 | 83.2 | 4.2 | 0.7 | 0.83 |
| Error d | 40 | 250.1 | 6.2 | | |
| Sub-total I + III + IV | 98 | 122 779.1 | | | |
| Time*Depth | 20 | 740.9 | 37.0 | 8.4 | 0.00 |
| Treatment*Depth*Time | 40 | 162.8 | 4.1 | 0.9 | 0.60 |
| Error e | 120 | 527.3 | 4.4 | | |
| Total | 296 | 130 407.1 | | | |

Note: *SS*: sum of squares; *MS*: mean squares; *Fc*: test statistics.

**Table 4 Analysis of variance (ANOVA) of the soil moisture for the treatments 20TP, 30TP and 50TP (95% of confidence)**

| Source of variation | Degree of freedom | *SS* | *MS* | *Fc* | *P*-value |
|---|---|---|---|---|---|
| Block | 2 | 89.1 | 44.5 | 4.6 | 0.09 |
| Treatment | 2 | 18 890.2 | 9 445.1 | 966.6 | 0.00 |
| Error a | 4 | 39.1 | 9.8 | | |
| Sub-total I | 8 | 19 018.4 | | | |
| Depth | 2 | 634.2 | 317.1 | 6.4 | 0.01 |
| Depth*Treatment | 4 | 4 464.1 | 1 116.0 | 22.6 | 0.00 |
| Error b | 12 | 592.9 | 49.4 | | |
| Sub-total I + II | 26 | 24 709.7 | | | |
| Time | 18 | 228.0 | 12.7 | 2.2 | 0.02 |
| Error c | 36 | 206.6 | 5.7 | | |
| Sub-total III | 56 | 523.8 | | | |
| Time*treatment | 36 | 171.4 | 4.8 | 1.1 | 0.35 |
| Error d | 72 | 309.6 | 4.3 | | |
| Sub-total I + III + IV | 170 | 19 934.1 | | | |
| Time*Depth | 36 | 241.0 | 6.7 | 2.1 | 0.00 |
| Treatment*Depth*Time | 72 | 346.0 | 4.8 | 1.5 | 0.01 |
| Error e | 216 | 676.3 | 3.1 | | |
| Total | 512 | 26 888.7 | | | |

Note: *SS*: sum of squares; *MS*: mean square; *Fc*: test statistics.

From Tables 3 and 4, the significant differences of the soil moisture between treatments; and treatment and depths, are further analyzed, using Figure 1. The t-student test (with $\alpha/2$) and the standard error were used for determination of the confidence intervals for mean moisture values.

Figure 2 depicts the differences of soil moisture in three different depths (4, 15, and 26 cm). At 4 cm, there are significant differences between treatments, ranging from lower soil moisture values in treatment CT to higher moisture values for treatment TP. Most of the treatments tend to keep similar moisture conditions between depths of 15 and 26 cm, evidencing a slow water movement down, product of a slow percolation rate. An exception is observed for treatment CT where moisture decreases slightly at 26 cm.

The violin plot in Figure 2 also provides information of the soil moisture distribution for the treatments at three different depths. The width at each point represents the frequency of the soil moisture. At 4 cm-depth all treatments show a rapid movement of soil moisture from dry values up to saturation. At a depth of 15 and 26 cm, the treatments with sandy loam soil mixed with different fractions of terra preta amendment soil (20TP, 30TP and 50TP) show more homogeneity and frequency of moisture values near the median, than the other treatments (CT, CO, TP). Bimodality, at 26 cm-depth for treatments CT and CO, is more evident. This can be influenced by percolation which initiates earlier (Table 5).

Table 5 shows that the obtained infiltration and percolation rates, and maximum surface water depth. Averaged initial soil moisture at field capacity was set for all treatments. Simulated rainfall was configured at relative low intensities in order to understand the behavior of the soil water dynamics at low water input. Time differences between peak infiltration and peak-percolation were divided into two groups: *group 1* (~20-30 min) conformed by CT, CO, and 20TP treatments; and group 2 (~70-85 min and more) with 30TP, 50TP, and TP treatments. A higher fraction of terra preta amendment, translates in a delayed initiation of percolation. Peak infiltration rates for 20TP, 30TP, and

50TP treatments were 24%, 26%, and 44% less than the rates observed for sandy loam soil (CT), respectively. Peak percolation rates for 20TP, 30TP, and 50TP correspond to 11%, 77%, and 38% less than the rate for sandy loam, respectively. With regard to the water input in group 1, although treatment 20TP was exposed to less rain intensity than treatment CT, it had a similar peak-percolation rate delayed by 10 min. Although CT and CO had a similar time difference between peak-percolation and peak-infiltration rate, the ratio peak-percolation-rate: peak-infiltration-rate is higher for CT, and even higher for 20TP. Therefore, with treatment 20TP water content percolates more and starts percolation at similar time interval as the treatment CT. Treatment 30TP, in group 2, shows a small ratio peak-percolation-rate: peak-infiltration-rate, initiating percolation at 45 min and reaching a peak-percolation-rate at 85 min. This treatment showed a better water holding capacity than 20TP, although maximum ponded rate was higher for treatment 30TP than 20TP. Treatment 50TP shows a great delay for initiation of percolation but also great accumulation of water at the surface. As organic matter in terms of content of charcoal increases, peak-ponding-rate increases, as well as water holding capacity in terms of percolation delay.

**Table 5 Infiltration and percolation dynamics**

| Treatment | *TPI*, min | *PIR*, mm $h^{-1}$ | *TPP*, min | *PPR*, mm $h^{-1}$ | *PIn*, min | *TD**, min | *TTP*, min | *PPoR*, mm | *In*, mm $h^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| CT | 5 | 23.1 | 25 | 28.0 | 20 | 20 | 10 | 13.0 | 22 |
| CO | 5 | 24.0 | 30 | 5.0 | 30 | 25 | 15 | 12.2 | 22 |
| TP | 5 | 22.0 | >90 | 0.0** | >90 | >85 | 10 | 21.6 | 22 |
| 20TP | 5 | 17.6 | 35 | 25.0 | 20 | 30 | 10 | 7.2 | 15 |
| 30TP | 5 | 17.0 | 85 | 6.4 | 45 | 80 | 10 | 18.9 | 15 |
| 50TP | 25 | 13.0 | 95 | 17.3 | 70 | 70 | 10 | 18.0 | 15 |

Note: *Time difference is the difference between time to peak percolation and time to peak infiltration. ** Corresponds to the percolation rate during the rainfall event, percolation was observed hours after the rainfall event ended. *TPI*: Time to peak infiltration; *PIR*: peak infiltration rate; *TPP*: Time to peak percolation; *PPR*: Peak percolation rate; *PIn*: Percolation initiation; *TD*: Time difference; *TTP*: Time to ponding; *PPoR*: Peak ponded rate; *In*: Simulated rain intensity.

Table 6 summarizes the obtained values for organic matter content and bulk density of the TP treatments with respect to the reference CT treatment. Fractions from 20% up to 50% of terra preta increase organic matter content from about 300% up to 760% and reduce bulk density. The increase of organic matter enhance the water holding capacity (effect observed in Table 5). The enhancement of soil physical properties leads to better plant grow conditions, however, it also depends on water input. Large amount of water may induce to ponding at the surface, which could be problematic due to soil erosion if not combined with other countermeasures such as good vegetation coverage.

**Table 6 Organic matter content and bulk density**

| Treatment | Organic matter content, g $cm^{-3}$ | Percentage change with respect to CT, % | Bulk density, g $cm^{-3}$ | Percentage change with respect to CT, % |
|---|---|---|---|---|
| CT | 2.78 | -- | 1.33 | -- |
| CO | 37.84 | 1361 | 0.56 | -0.58 |
| TP | 52.78 | 1898 | 0,50 | -0.62 |
| 20TP | 9.00 | 323 | 0.98 | -26 |
| 30TP | 14.04 | 505 | 0.88 | -34 |
| 50TP | 21.20 | 762 | 0.76 | -43 |

## 4 Conclusions

In this work, a descriptive statistical analysis was performed in order to explore the water dynamics of sandy loam soil samples mixed with different quantities of charcoal as a terra preta amendment. Quantitative information on how infiltration and percolation processes behave was gathered. Experimental data show that soil water retention improves as soil organic matter content increases. Treatment 30TP has a better percolation: infiltration ratio than 20TP, and higher ponded depth. If combined with best farming practices such as vegetation cover, treatment 30TP could give a solution to a better water holding capacity.

Increase of charcoal, as terra preta amendment, of a mineral soil (sandy loam with 2.78% of organic matter content) reduces surface infiltration and percolation rates. As the organic matter content increases, time-to-peak percolation appears later in time, even long after the rainfall event ended. Slower infiltration rates increase ponding at the surface, which results in more runoff formation. Nonetheless, low percolation rates enhance the soil water holding capacity, since the water displacement to deeper soil layers takes place much slower.

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