Hydraulic properties of clay soils as affected by biochar and charcoal amendments
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Abstract: Understanding soil hydraulic properties is crucial for planning effective soil and water management practices. A study was conducted to evaluate the effects of different biochar and charcoal treatments on soil-hydraulic properties of agricultural soils. Biochar and charcoal treatments were applied on 54, undisturbed soil-columns, extracted from three-elevation ranges, with replications along three transects. Daily weight losses of freely draining soil-columns and soil moisture contents, at five tensions, were measured. In addition, field infiltration tests and soil analyses for particle size distribution, bulk-density and organic carbon content were conducted. Moreover, five-year event precipitation data, from the watershed, was analysed and exceedance probability of rainfall intensity was computed. Results show treatments reduced soil moisture contents, for most of the cases. However, treatment effects were significant only at lower tensions (10 and 30 kPa) and within two days after saturation (p<0.05). On the other hand, relative hydraulic conductivity (Kr) coefficients, near saturation, of amended soils were higher than the control. Acidic to moderately acidic soils with high average clay (42%) and low organic carbon contents (1.1%) were dominant. Infiltration rate ranged between 1.9 and 36 mm/h, with high variability (CV = 70%). At the same time, storms with short duration (< 15 min) and high average intensity (6.3 mm/h) contributed for 68% of annual precipitation (1616mm/year). Dominant soil properties and rainfall characteristics suggest that infiltration could be a major problem on considerable number of fields, in the watershed. This implies, on such fields, constructing physical soil and water conservation structures alone will not reduce runoff and erosion effectively, unless soil infiltration and permeability rates are enhanced through integrated soil management approaches.

Media grab: Biochar and charcoal amendments can ameliorate soil-hydraulic properties of degraded soils. However, treatment effects may vary depending on dominant soil textural composition and organic carbon content.

Introduction

Despite continuous soil and water conservation efforts, since the 1980s, land degradation and drought (Amsalu and Graaff 2006) remain major threats to the predominantly rain-fed, smallholder, farming livelihood in the Ethiopian highlands. In most areas, efficiencies of soil and water conservation structures were below satisfactory. This was mainly due to inappropriate planning (Mitiku and Stillhardt 2006, Kato et al. 2011) mainly physical conservation structures. In addition, there were no previous studies conducted, with the objective of developing integrated soil management practices, tailored to address ecological and hydrological constraints.
Recently, biochar and charcoal additions on degraded soils have been suggested to improve soil physical and hydraulic conditions. In light of this, recent studies reported charcoal and biochar amendments significantly improve soil physical and hydraulic properties of degraded soils: such as moisture retention (Lehmann et al. 2006; Laird et al. 2010; Spokas et al. 2010; Karhu et al. 2011) and hydraulic conductivity (Asai et al. 2009).

However, negative results, from biochar and charcoal addition were also documented; such as reduced moisture retention (Tryon 1948) and crop yield (Kishimoto and Sugiura 1985). This indicates that the effect of biochar and charcoal, on soil physical and hydraulic properties, is highly affected by inherent field soil properties: such as textural composition and soil carbon levels (Tryon 1948, Rawls et al. 2003).

As a result, this study was conducted with two major objectives (1) to determine dominant soil physical and hydraulic properties in the watershed; and (2) to evaluate the effects of biochar and charcoal amendments on soil-hydraulic properties of cultivated soils.

**Methods**

This study was conducted in the Anjeni watershed, in the northern Ethiopian Highlands, at 10°40’ N and 37°31’ E geographic coordinates. The watershed area covers 113 ha with elevation ranges between 2407–2507 m.

Column studies were conducted, on 54 soil-cores, to evaluate the effects different biochar and charcoal amendments on moisture retention and drainage characteristics of agricultural soils. Six soil-cores were extracted adjacent from three elevation ranges (Low, Mid and High) with replicate transects (n = 3) along the toposequence. Five treatments (two biochars and three charcoals) and untreated control were randomly applied to soil-cores; Measured data include daily weights, from saturation to drying, of 54 undisturbed soil-columns (amended with five biochar and charcoal treatments and non-amended control) and soil moisture contents, at five tensions, using a pressure plate apparatus. In addition, infiltration tests (at 48 locations), laboratory analyses, on 50 soil samples, for selected soil properties (particle distribution, bulk density, organic carbon and pH) were conducted. Soil moisture retention characteristic curves (SMRC), effective saturation ($S_e$) and relative hydraulic conductivity ($K_r$) were predicted using the van Genuchten (1980) closed form soil-hydraulic equation. Moreover, five-year event precipitation data, from the watershed, were analysed and dominant storm characteristics (duration and intensity) were calculated. Similarly, watershed soil depth data was obtained from Mengistu D.A. (unpublished).

Statistical analyses and model optimization were performed using R statistical programing software for Windows, version 2.15.2. Moisture data, from saturation to dryness, violated normality and equal variance assumptions of parametric statistical test procedures; as a result, data sets from each tension were analysed separately, using Two Way ANOVA tests, with treatment (main factor) and elevation (block factor). Moreover, TukeyHSD mean comparison tests were performed for factors with significant variance tests. Non-linear least square (nls) curve-fitting package, in R, was used during model optimization.

Moisture retention data, observed at different pressures, were fitted to a set of equations according to the van Genuchten (1980) soil characteristic model.

\[
\theta(\psi) = \theta_r + (\theta_s - \theta_r) \left[ \frac{1}{1 + (\alpha \psi)^n} \right]^m \tag{1}
\]

\[
S_e = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} \tag{2}
\]

\[
K_r = S_e^l \left[ 1 - \left( 1 - S_e^{1/m} \right)^m \right]^2 \tag{3}
\]
where $\theta_r$ and $\theta_s$ are residual and saturated gravimetric soil moisture contents (g/g) and $\theta_i(\psi)$ and $\theta_f(\psi)$ are moisture content and tension respectively with $\alpha\alpha$, $n$ and $m$ are curve-fitting parameters. $\alpha\alpha$ is proportional to the inverse of air entry value; and $n$ and $m$ are related to the pore size distribution of soils. $m$ was assigned a value of one minus the inverse of $n$ (i.e. $m = 1-1/n$). $S_w$ and $K_x K_r$ represent effective saturation and relative hydraulic conductivity of soils respectively. $K_r = k/K_s K'$, where $k$ is the unsaturated conductivity and $K_s K'$ is the saturated hydraulic conductivity. $\alpha\alpha$ is a dimensionless model fitting parameter assigned a fixed value of 0.5.

Results and discussion

Soil properties show considerable variation along the elevation gradient. Soil depth varied the most ($CV = 37\%$) and differences between mean soil depth values, along the topo-sequence, were significant ($p< 0.00$). Unexpectedly, a positive correlation was observed between soil-clay levels and elevation gradient (Figure 1). Overall, acidic to moderately acidic soils (data not shown) with low carbon and high clay levels, on average 42 and 1.1%, respectively, were predominant in the watershed. In agreement with our results, Vancampenhout (2005) concluded that soil organic carbon levels, in the Ethiopian highlands, were generally low.

Figure 1. Summary results of soil properties at three elevation ranges

Rainfall intensity and soil infiltration rate

Summary result of event precipitation data, show annual rainfall was high, on average 1616.32mm/yr. However, rainfall distribution was not uniform; mainly three months (June, July and August) contributed 65% of annual precipitation (data not shown). Moreover, storm intensities varied between 0.24 and 444 mm/h (data not shown); but storms, with short durations (< 15 min) and high average intensity (6.3 mm/h) were dominant; accounted for 68% of annual precipitation (Figure 2a). Average storm intensity decreased sharply, with a slight increase in duration. For example, average intensity of storms, with duration between 30–60 min, was one-third of average intensity of storms, with duration <15 min (Figure 2a). On the other hand, steady infiltration rate ($f$) was observed between 1.9 and 36.4 mm/h; with median of 8.9 mm/h (Figure. 2b). Steady infiltration varied highly ($CV = 70\%$); but showed a decreasing pattern as elevation increased (data not shown).
The probability that storm intensity is equal or greater than the median infiltration rate was 21% (Figure 2b). Thus, much of the runoff generated during the intense storms infiltrates before reaching the outlet.

Effects of biochar and charcoal on soil moisture detention

Statistical analyses of moisture data, from pressure plate, show that treatment effects were statistically significant (p < 0.05) only at lower tensions (–10 and 30kPa) Table 1. Furthermore, mean comparison tests show Croton, Eucalyptus and Oak treatments (at 10kPa) and Croton (at 30kPa) resulted in a significant soil moisture content reduction (p<0.05). Contrary to this, Corn biochar did not reduce moisture content, at all tensions; rather, though not statistically significant, it increased moisture retention at high tensions (Table 1). In agreement with our findings, Rawls et al. (2003) suggested increased impacts of organic matter near field capacity than wilting point. Similarly, Foley and Cooperband (2002) reported that effects of organic amendments were significant only at lower tensions (30 kPa). Not only treatment effects were significant, but also block effects (elevation) was significant at lower and higher tensions: 10, 30 and 1500kPa (p<0.05). Specifically, mean moisture retention, at high elevation, was significantly low compared to low elevation, which could due soil clay content difference, (Table 1).

Table 1. Summary of treatment effects on soil moisture retention (ANOVA results) at different tensions

<table>
<thead>
<tr>
<th>Tension (kPa)</th>
<th>10</th>
<th>30</th>
<th>100</th>
<th>500</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.34 (0.01)a</td>
<td>0.32 (0.01)a</td>
<td>0.27 (0.01)a</td>
<td>0.22 (0.00)a</td>
<td>0.20 (0.00)a</td>
</tr>
<tr>
<td>Acacia</td>
<td>0.32 (0.00)a</td>
<td>0.31 (0.01)a</td>
<td>0.27 (0.01)a</td>
<td>0.21 (0.00)a</td>
<td>0.19 (0.00)a</td>
</tr>
<tr>
<td>Corn</td>
<td>0.34 (0.01)a</td>
<td>0.32 (0.01)a</td>
<td>0.28 (0.01)a</td>
<td>0.22 (0.00)a</td>
<td>0.21 (0.00)a</td>
</tr>
<tr>
<td>Croton</td>
<td>0.31 (0.00)b</td>
<td>0.30 (0.00)b</td>
<td>0.28 (0.01)a</td>
<td>0.22 (0.00)a</td>
<td>0.20 (0.00)a</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>0.32 (0.00)b</td>
<td>0.31 (0.00)a</td>
<td>0.27 (0.01)a</td>
<td>0.21 (0.00)a</td>
<td>0.20 (0.00)a</td>
</tr>
<tr>
<td>Oak</td>
<td>0.31 (0.00)b</td>
<td>0.30 (0.00)a</td>
<td>0.27 (0.01)a</td>
<td>0.22 (0.00)a</td>
<td>0.20 (0.00)a</td>
</tr>
<tr>
<td>Block effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>0.33 (0.00)a</td>
<td>0.32 (0.00)a</td>
<td>0.28 (0.00)a</td>
<td>0.22 (0.00)a</td>
<td>0.21 (0.00)a</td>
</tr>
<tr>
<td>Mid</td>
<td>0.32 (0.00)ab</td>
<td>0.31 (0.00)ab</td>
<td>0.27 (0.01)a</td>
<td>0.22 (0.00)a</td>
<td>0.20 (0.00)a</td>
</tr>
<tr>
<td>High</td>
<td>0.31 (0.00)b</td>
<td>0.30 (0.00)b</td>
<td>0.27 (0.01)a</td>
<td>0.21 (0.00)a</td>
<td>0.19 (0.00)b</td>
</tr>
</tbody>
</table>

Values are averages of replications (n = 9) and values inside parenthesis are standard errors. Different letters in the same column and treatment group, represent significant difference between treatments (p<0.05)

In agreement with our findings, Tryon (1948) reported that charcoal addition on clay soils decreased average moisture content by 11.1% and residual moisture content by 3.8%. On the contrary, the same study reported that charcoal increased moisture retention of sandy soils. Likewise, Rawls et al. (2003) reported organic matter addition decreased moisture retention of clay soils, but decreased moisture retention of sandy soils. Similarly, water-holding capacity of medium textured, boreal agricultural soil was increased by 11% shortly after biochar addition (Karhu et al. 2011).
This highlights that effects of organic amendments, including biochar and charcoal, on soil hydraulic properties, is highly affected by inherent soil properties: such as textural composition and carbon levels (Tryon 1948, Rawls et al. 2003). Moisture content reduction, on clay soils, from biochar and charcoal addition could be due to different factors: hydrophobicity of biochar and charcoal materials (Tryon 1948), improved macrospore networks, that release water easily and hence difficult to detect (Dexter 2004).

Biochar and charcoal characterization

As presented in Table 1, corn biochar affected moisture retention of soils differently than Oak biochar, Acacia and Eucalyptus charcoals, hardwood treatments. This could be due to differences in treatments composition. Overall, base cation contents of the two biochars were high; nevertheless, Corn biochar contain higher amounts of each element, particular K⁺ (Table 2). Moreover, Rao and Mathew (1995) reported that high valiancy cations increased clay flocculation and hydraulic conductivity. High Monovalent Cation Adsorption Ration (MCAR) clay dispersion can cause clay dispersion. Corn biochar has the highest MCAR 17.5 and 12.6 times higher than Acacia and Eucalyptus.

Table 2. Total elemental analyses results of biochar and charcoal treatments

<table>
<thead>
<tr>
<th>Biochar</th>
<th>pHKCl</th>
<th>Ca²⁺</th>
<th>Mg²⁺</th>
<th>K⁺</th>
<th>Na⁺</th>
<th>MCAR</th>
<th>pHwater</th>
<th>Ca²⁺</th>
<th>Mg²⁺</th>
<th>K⁺</th>
<th>Na⁺</th>
<th>MCAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>9.4</td>
<td>7317</td>
<td>8031</td>
<td>25707</td>
<td>1112</td>
<td>9.83</td>
<td>Acacia</td>
<td>8.2</td>
<td>15.9</td>
<td>11.7</td>
<td>60.1</td>
<td>2.9</td>
</tr>
<tr>
<td>Oak</td>
<td>7.5</td>
<td>1023</td>
<td>25</td>
<td>1664</td>
<td>229</td>
<td>3.23</td>
<td>Eucalyptus</td>
<td>8.7</td>
<td>13.5</td>
<td>1.6</td>
<td>51.3</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Data for Corn and Oak Biochars were taken from Edres et al. (2012).

This suggests that lower moisture retention with charcoal treated soils could be enhanced drainage and hydraulic conductivity due to increased clay particle aggregation Rawls et al. (2003).

Effects of biochar and charcoal on soil hydraulic parameters

The van Genuchten (1980) moisture characteristic model fitted observed data well; with coefficients of determination (89 to 94%) and root mean square error of (0.01 to 0.02) respectively (Table 3). However, as shown in Table 3, the model under predicated residual moisture content, for most treatments, compared with predicted value for the control and observed data at 1500kPa (estimator of residual moisture content). Of all five model fitting parameters, variability of α (inverse of air entry pressure) was high (CV = 41%, Table 3).

Table 3. Summary results of van Genuchten model fitting parameters and efficiency.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>𝜃ᵣ (g/g)</th>
<th>𝜃₅₀ (1/m)</th>
<th>α (%)</th>
<th>n</th>
<th>m</th>
<th>RMSE</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.18</td>
<td>0.34</td>
<td>0.23</td>
<td>1.59</td>
<td>0.37</td>
<td>0.02</td>
<td>89.90</td>
</tr>
<tr>
<td>Acacia</td>
<td>0.17</td>
<td>0.33</td>
<td>0.17</td>
<td>1.65</td>
<td>0.39</td>
<td>0.01</td>
<td>94.36</td>
</tr>
<tr>
<td>Corn</td>
<td>0.17</td>
<td>0.35</td>
<td>0.27</td>
<td>1.51</td>
<td>0.33</td>
<td>0.02</td>
<td>89.01</td>
</tr>
<tr>
<td>Croton</td>
<td>0.12</td>
<td>0.31</td>
<td>0.13</td>
<td>1.57</td>
<td>0.33</td>
<td>0.01</td>
<td>90.90</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>0.19</td>
<td>0.32</td>
<td>0.10</td>
<td>1.96</td>
<td>0.48</td>
<td>0.01</td>
<td>94.24</td>
</tr>
<tr>
<td>Oak</td>
<td>0.16</td>
<td>0.32</td>
<td>0.20</td>
<td>1.50</td>
<td>0.32</td>
<td>0.01</td>
<td>90.93</td>
</tr>
<tr>
<td>CV (%)</td>
<td>26.58</td>
<td>4.94</td>
<td>34.02</td>
<td>17.31</td>
<td>16.65</td>
<td>38.73</td>
<td>2.27</td>
</tr>
</tbody>
</table>
Treatments effect on soil saturation (Se) and relative hydraulic conductivity (Kr)

Treatments effect of on effective soil saturation (Se) and relative hydraulic conductivity (Kr), at different tensions (logarithmic scale), from saturation to dryness, are depicted on Figure 3. With increase in tension (≥ 1.5 cm) differences between treatment $S_e$ coefficients were increased. Between tensions (1.5–4 cm), all treatments, except Corn biochar, increased effective soil saturation (Se) compared with the control Figure 3(a). However, at high tensions (≥ 4cm), $S_e$ coefficient for Eucalyptus decreased sharply, below the control. On the contrary, at similar tensions (≥ 4cm), Corn biochar slightly increased $S_e$. On the other hand, differences between treatment $K_u$ coefficients were relatively high at low tensions (≤ 3cm); high coefficients were observed for Acacia, Croton and Eucalyptus charcoals, whilst coefficients of Corn and Oak biochars were low compared with the control Figure 3(b).

Conclusion

This study evaluated the effects of biochar and charcoal amendments on soil-hydraulic properties; and results were discussed with respect to dominant field soil physical and infiltration rates as well as rainfall characteristics.

Results show all charcoal treatments and Oak biochar decreased moisture retention for most of the cases. However, treatment effects were significant, only at lower tensions (10 and 30kPa). Moreover, observed effects of biochar and charcoal treatments, were in conformity with dominant soil textural composition and organic carbon level. Hence, it is presumable that biochar and charcoal treatments could restore soil health of degraded fields; nevertheless, research is needed to select best performing treatments, based on inherent soil properties and intended impact on soils.

Overall, findings from this study underscored the significance of considering soil physical and hydraulic conditions when planning soil and water management practices.

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References


