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Assessing the potential of biochar and charcoal to improve soil hydraulic properties in the humid Ethiopian Highlands: The Anjeni watershed

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ABSTRACT

Biochar has shown promise for restoring soil hydraulic properties. However, biochar production could be expensive in the developing world, while charcoal is widely available and cheap. The objective of this study is therefore to investigate whether some of the charcoal made in developing countries can also be beneficial for improving soil hydraulic properties, and explore whether charcoal could potentially restore the degraded African soils. Laboratory and field experiments were conducted in the Anjeni watershed in the Ethiopian highlands, to measure soil physical properties including soil moisture retention and infiltration rates. Soils were dominantly clayey with pH in the acidic range, low organic carbon content, and steady infiltration rates ranging between 2 and 36 mm/h. Incorporation of woody feedstock (Acacia, Croton, and Eucalyptus) charcoals significantly decreased moisture retention at lower tensions (10 and 30 kPa), resulting in an increase in relative hydraulic conductivity coefficients at these tensions. While wood (oak) biochar decreased moisture retention at low tensions, corn biochar increased retention, but effects were only slight and not significant. Surprisingly, available water content was not significantly affected by any of the amendments. Overall findings suggest that wood charcoal amendments can improve soil hydraulic properties of degraded soils, thereby potentially reducing runoff and erosion.

1. Introduction

Smallholder farm productivity in the Ethiopian highlands is constrained by land degradation due to accelerated soil erosion (Bewket and Sterk, 2003; Demelash and Stahr, 2010; Temesgen et al., 2012) and recurrent droughts (Amsalu and Graaff, 2006; Biazin et al., 2011; Hugo et al., 2002; Mouazen et al., 2007). To meet increasing food demand for growing populations, typically all types of land including grazing and forest fields are extensively cultivated for crop production (Feoli et al., 2002; Lu et al., 2007; Taddese, 2001). While annual precipitation is high in most African highland areas, its distribution is variable both in space and time (Bewket and Sterk, 2005; Biazin et al., 2011; McHugh et al., 2007). Water scarcity therefore prevails for 8–9 months every year (Bewket and Sterk, 2005; Biazin et al., 2011), while much rainfall is lost to runoff during the rainy monsoon season, causing erosion on the already degraded fields. To mitigate these negative impacts, soil and water conservation structures were built in most highland areas in Ethiopia. While these conservation efforts have considerably reduced surface runoff and soil erosion in some areas (Hurni et al., 2005; Nyssen et al., 2010), expectations were achieved only partially in most areas (Herweg and Ludi, 1999; Kato et al., 2011; Temesgen et al., 2012). The reason for this frequent lack of success may lie in that soil and water conservation practices often attempt to tackle symptoms of the problems (runoff and erosion) rather than their root causes (such as poor soil permeability). Moreover, conservation efforts primarily use structural measures, regardless of apparent variations in edaphic, topographic, and hydrologic factors (Amsalu and Graaff, 2006; Kato et al., 2011; Shiferaw and Holden, 2000; Temesgen et al., 2012). These structural measures may, unless excess water is drained (Bayabil et al., 2010), cause field waterlogging and accelerated erosion when conservation structures on degraded soils are breached (Temesgen et al., 2012).

One of the ways to improve soil physical properties that has received increased attention recently is biochar, that is produced when biomass is thermally decomposed at a preset temperature with no or low supply of oxygen (Lehmann et al., 2011). Biochar amendments have been reported to improve soil bulk density, porosity, water retention, and hydraulic conductivity (Abel et al., 2013; Asai et al., 2009; Atkinson et al., 2010; Jeffery et al., 2011; Karhu et al., 2011; Laird et al., 2010). Several authors have also reported that biochar amended soils retained more nutrients (Dexter, 1991; Glaser et al., 2002; Joseph et al., 2007; Kookana et al., 2011; Major et al., 2010; McHenry, 2011; Oguntunde et al., 2004; Steiner et al., 2007; Verheijen et al., 2009). Despite the potential benefit of biochar amendment, lack of capital and poor

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infrastructure may prevent smallholder farmers to get access to pyrolysis kilns needed for biochar production. This poses considerable challenges on the use of biochar in rural Africa. Wood charcoal may be a good alternative as it is widely produced in most rural areas of Africa (Lehman et al., 2006), using simple soil pits instead of high-tech kilns. Moreover, charcoal has been reported to have similar beneficial effects as biochar, as it can improve retention of both soil moisture (Glaser et al., 2002; Kameyama et al., 2010) and nutrients (Lehmann et al., 2011; Oguntunde et al., 2004; Steiner et al., 2007).

The objective of this study was to characterize soil hydrology and dominant runoff mechanisms in the Ethiopian highlands, and investigate whether biochar and wood charcoal can be used to improve soil hydraulic properties and potentially decrease surface runoff and erosion.

2. Materials and methods

2.1. Site description

This study was conducted in the Anjeni watershed in northwest Ethiopia (Fig. 1). The watershed is one of the experimental watersheds established under the Soil Conservation and Research Program (SCRP) of the Ethiopian Ministry of Agriculture in collaboration with the Swiss Agency for Development and Cooperation (Hurni et al., 2005). Mean daily temperature in this region ranges from 9 °C to 23 °C, and mean annual rainfall is 1690 mm with a unimodal rainy season, which lasts from the middle of May to the middle of October. The Anjeni watershed drains a total catchment area of 113 ha, its gauging station is located at 10°40′ N, 37°31′E (Tilahun et al., 2011). The watershed is oriented north–south and flanked on three sides by plateau ridges — elevation in the watershed ranges from 2407 to 2507 m (Herweg and Ludi, 1999). Finally, land use is mostly small scale agriculture, and soils have developed from basalt and volcanic ash, with Alisols, Nitisols, and Cambisols covering more than 80% of the area (Zeleke, 2000). The deep Alisols cover the bottom part of the watershed; moderately deep Nitisols cover the mid-transitional, gently sloping parts, and shallow Regosols and Leptosols cover the high, steepest areas. While the middle area of the watershed is covered by moderately deep Dystric Cambisols (Legesse, 2009; Zeleke, 2000).

2.2. Soil physical properties

We assessed soil physical and basic chemical characteristics across the Anjeni watershed by measuring bulk density, soil moisture characteristics, soil texture, organic carbon content, pH, and infiltration rates. Moreover, runoff processes were determined by comparing infiltration rates with rainfall intensity computed using five-year rainfall records (1989–1993).

Since soils in the Ethiopian highlands vary with elevation (Amare et al., 2013), soil samples were taken and infiltration tests were performed at three elevation ranges (‘low’ 2407–2430 m, ‘mid’ 2431–2460 m, and ‘high’ 2461–2507 m a.s.l.), along a set of 16 downslope transects across the watershed. The sampling design yielded 48 sampling locations (‘soil samples’, Fig. 1c). A distance of 125 m was maintained between transects, except when locations were inaccessible and samples were taken from adjacent locations that were accessible. In addition, transects in the northern part of the watershed lacked sampling locations in the low elevation range, hence more samples were collected from the lower elevation ranges of transects in the southern part of the watershed and to balance sample sizes between elevation ranges.

At each sampling location, we conducted in situ infiltration tests, extracted undisturbed soil samples (0–5 cm depth, using 91.2 cm^3 cores) to determine bulk density, and collected bulk soil samples (0–20 cm depth) for analyses of soil texture, organic carbon content (OC) and pH. Though organic carbon and pH are not soil physical parameters per se, they were measured because of their effects on parameters and processes like aggregate stability, clay flocculation/dispersion, and thus their effect on soil physical properties.

Infiltration tests were done during the dry season, in March 2012, and to minimize water requirements, tests were conducted using a single ring infiltrometer (25 cm tall, 30 cm diameter). A wooden board was put on top of the infiltrometer and the infiltrometer was driven ~15 cm into the soil using a hammer. For each measurement, the drop in water level was measured at 5 min intervals using plastic rulers and a stopwatch. After each measurement, the ring was refilled with water to its initial level; and the test continued until the drop in water level was constant.

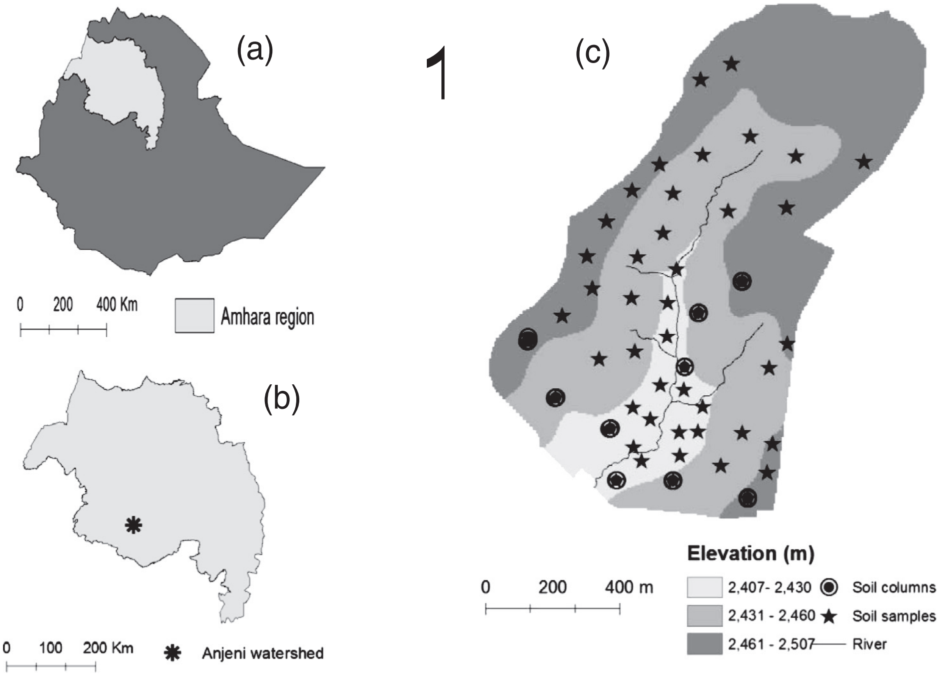

Fig. 1. Map of Ethiopia (a) with the Amhara region (b) indicating the location of the Anjeni watershed (c). Sampling locations are indicated in (c).

In addition, five-year (1989 to 1993) rainfall records were obtained from the Amhara Agricultural Research Institute (ARARI) that contained 8651 storm records from which we calculated storm duration, intensity (volume divided by duration), and frequency. The dominant runoff generation mechanism in the watershed (saturation vs. infiltration excess runoff) was subsequently identified using exceedance probabilities of storm intensity, by comparing five-year storm intensity values with the 25th, 50th, and 75th percentiles of measured infiltration rates.

2.3. *Effect of biochar and charcoal on soil water retention*

The effect of biochar and charcoal on soil water retention was assessed in the laboratory by incorporating biochar and charcoal into soils taken from the field.

For this, undisturbed soil columns (30 cm tall, 12 cm diameter) were extracted along three of the sixteen transects surveyed ('soil columns', Fig. 1c). At each elevation range (low, mid, high) of the three transects, six replicate soil columns were extracted along the contour, yielding 54 soil columns in total. These columns were lined with cheesecloth and transported to the office station (in the watershed) and left to dry in the sun for 20 d before their dry weights were determined.

Since the effect of biochar and charcoal varies with feedstock source (Abel et al., 2013; Enders et al., 2012), we tested the effect of incorporation of two biochars (prepared from corn stover and oak) and three wood charcoals (*Eucalyptus camaladulensis*, *Acacia abyssinica*, and *Croton macrostachyus*) compared to a non-amended control. The two biochars (corn and oak) used in this study were previously used by Enders et al. (2012) as 'corn 450 °C' and 'oak 450 °C'. They were produced by Best Energies Inc. (Cashton, WI, USA) by pyrolyzing predried corn and oak feedstocks in the Daisy Reactor, a uniformly heated chamber at 450 °C, for 80 to 90 min (Enders et al., 2012). All wood charcoals used were prepared in the Anjeni watershed following local farmers' practices. For this, trunks of each feedstock type (acacia, eucalyptus, and croton) with an approximate diameter of 20–30 cm were chopped into short logs (<50 cm), placed inside separate pits (1 m deep, 1 m diameter) that had been excavated on open grounds, and were set on fire. To avoid complete combustion of biomass into ash, each pit was then covered by a layer of corn stubble, and backfilled with the excavated soil. The whole charring process took on average 3 to 5 d depending on the moisture status of both the feedstocks and the surrounding soils. After this, the charred biomass (charcoal) was extracted and manually crushed to obtain relatively uniform particle sizes (~2 mm diameter).

A fixed amount of biochar and charcoal (5 g/kg soil, or 0.5% by weight) was randomly added to columns in a randomized complete block design (Fig. 1), by manually mixing the material into the top 20 cm of soil. Because cultivation alone, even with no amendment, can also change soil properties, we also manually mixed the top 20 cm of the non-amended control columns.

To allow for aggregation of biochar and charcoal particles with the soil matrix, all columns including the control were put under wetting and drying cycles for 30 d, by leaving them outside in the sun without any shade with regular (every 7 d) supply of irrigation water. Subsequently, columns were taken inside the laboratory and put on a mesh, 50 cm above the ground, and they were irrigated until they became saturated. Afterwards, daily weights of the freely draining columns were measured for 6 d (with 24-h interval), until weights were constant. Finally, 54 bulk soil samples (~250 g) were taken by mixing the top (0–20 cm) of amended and control columns for laboratory moisture tests at different tensions.

2.4. *Laboratory analyses*

Soil samples were transported to Adet Agricultural Research Center for laboratory analyses. Soil bulk density was determined after oven drying soil cores for 24 h at 105 °C, and particle size distribution was determined using the Bouyoucos hydrometer procedure (Sahlemedihn and Taye, 2000). Organic carbon content was determined following the Walkley and Black method (Sahlemedihn and Taye, 2000), and soil pH was measured with the pH-water method using a 1:2.5 soil to water mixture (Sahlemedihn and Taye, 2000). Soil water retention measurements were conducted on 54 disturbed samples taken from biochar and charcoal treated and control columns. Moisture retention measurements were performed at five tensions (10, 30, 100, 500, and 1500 kPa) using a pressure plate apparatus.

In addition, in 2010, before conducting the column experiments, charcoal samples from different batches of *Eucalyptus* and *Acacia* biomass purchased from local markets near the Anjeni watershed were chemically analyzed at the Cornell University Soil and Water Lab. pH was determined with the pH-water method using a 1:2.5 charcoal to water mixture, and exchangeable base cation (Na^+, K^+, Ca^{2+}, Mg^{2+}) contents determined using inductively coupled plasma (ICP) spectrometry. Because of limited supply, these analyses could unfortunately not be done for the Croton charcoal.

2.5. *Analysis of effects on soil water retention*

To allow for analysis of biochar and charcoal effects on soil water retention characteristics, we fitted the Van Genuchten (1980) soil moisture retention model (Eqs. (1) and (2)) to the measured soil water retention data. First, unknown parameters of Eq. (1) were optimized, and results were used to calculate the relative degree of saturation (Eq. (2)) and relative hydraulic conductivity (K_r) or permeability coefficients (Eq. (3)). Available water content was calculated as the moisture retention difference between 30 and 1500 kPa.

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

$$S_e = \frac{\theta_{(\psi)} - \theta_r}{\theta_s - \theta_r} \tag{2}$$

$$K_r = S_e{}^l\left[1-\left(1-S_e{}^{\frac{1}{m}}\right)^m\right]^2 \tag{3}$$

where θ_r and θ_s are residual and saturated moisture contents, and $\theta(\psi)$ and ψ represent the moisture and corresponding tension respectively. α (kPa^{-1}), n, m, and l are dimensionless model fitting parameters, where α is proportional to the inverse of the air entry value n and m are related to soil pore size distribution. S_e and K_r represent relative saturation and hydraulic conductivity of soils, respectively. *l* was assigned a value of 0.5, and m was assigned a value of one minus the inverse of n (i.e., $m = 1 - 1/n$, provided $n > 1$) to reduce the number of unknown parameters as proposed by Van Genuchten (1980).

2.6. *Statistical analyses*

Statistical data analysis and optimization of soil water retention curves to obtain Van Genuchten parameters was performed using R (R Development Core Team 2010). Since water retention data obtained from pressure plates and column drainage experiments violated assumptions of normality and equal variance, separate two-way ANOVA tests were run for observations from similar tensions or days. Treatment was used as a main factor, while elevation range was a block factor. For factors with significant Analysis of Variance (ANOVA) results, Tukey HSD mean comparison tests were performed to identify significant differences between groups.

3. Results

The results of the soil properties and infiltration rate along the elevation gradient are presented first, followed by the effect of charcoal and biochar on soil physical properties.

3.1. Soil physical properties

Field and laboratory measurements summary results (Table 1) show that acidic to moderately acidic soils ($pH < 6$), with high mean clay and silt contents (42 and 32%, respectively), and low in organic carbon (mean of 1.1%) were dominant in the study area. Soils were quite similar across elevation ranges, with only pH showing a significant trend (increase) with elevation (Table 1). Dry bulk density and sand content showed no apparent trend, while clay content slightly increased with elevation (39.7 to 43.3%) (Table 1).

Correlations between soil parameters are presented in Table A1. As expected, clay content was strongly (negatively) correlated with the other two textural groups (sand and silt) with correlation coefficients (-0.62 and -0.60) respectively. Unexpectedly, bulk density (BD) was weakly positively correlated with steady state infiltration rate (f_s), while pH showed a negative (albeit weak) correlation with clay and organic carbon (OC), with correlation coefficients of -0.18 and -0.12, respectively (Table A1).

3.2. Storm characteristics and infiltration capacity

Analysis of five-year (1989–1993) rainfall records showed that rainfall had a considerable seasonal variation, with four months (June through September) accounting for 76% of annual precipitation on average (Fig. B1). Further analyses of 8651 storm records showed that short duration storms (<15 min, average intensity 6.3 mm/h) contributed for 68% of annual precipitation (Fig. C1).

As steady infiltration rates did not significantly vary with elevation, 25th, 50th and 75th percentile infiltration rates were calculated from the data aggregated over all three elevation ranges. The 25th percentile infiltration rate in the watershed was 4.6 mm/h, and the 50th and 75th percentile steady infiltration rates were 8.9 and 12.5 mm/h, respectively. Comparing five-year storm intensity records with these steady infiltration rates (Fig. 2) showed that the probabilities for any storm intensity to match or exceed the 25th, 50th, and 75th percentile infiltration rates were 37, 23, and 16%, respectively.

Though some of the highest average infiltration rates were found at the lower elevations (Table 1) and the risk of infiltration excess runoff may therefore be limited, overland flow may still occur at these locations. This is because these soils have gentle slopes and may saturate due to interflow from the steeper uplands, thereby producing saturation excess overland flow. At the higher elevations where infiltration rates were lowest, improvement of infiltration capacity can increase infiltration rates and thereby decrease the risk of infiltration excess overland flow during the most intense storms.

3.3. Effects of biochar and charcoal on soil water retention

Analysis of soil water retention data (Fig. 3) indicated that all biochar and charcoal amendments except corn biochar decreased soil water retention at most tensions considered. However, these effects were only significant at 10 and 30 kPa (Fig. 3). At 10 kPa, water retention of soils amended with the three charcoals (acacia, croton, and eucalyptus) was significantly lower than for biochar (corn and oak) amended and control soils. At 30 kPa, the lower water retention of charcoal amended soil was only significant for croton (Fig. 3). Surprisingly, available water content was affected by neither charcoal nor by biochar (Fig. 3). Available water content was also not affected by elevation (Fig. 4), though elevation did significantly affected soil water retention at lower (10 and 30 kPa) and higher (1500 kPa) tensions (Fig. 4). Tukey HSD mean comparison results indicated that at these tensions, soils at low elevations retained significantly more water than soils at high elevations.

Results from column weight measurements corresponded with the soil water retention data obtained from pressure plates (Fig. 5). Biochar from oak feedstock and all wood charcoals decreased water retention during most observation days; and treatment effects were significant for the first two days (Fig. 5). Tukey HSD mean comparison results indicated that amended soils retained significantly less water than the non-amended control after one day of free drainage (croton and eucalyptus charcoal; oak biochar), and after two days of free drainage (croton charcoal only). There was no significant effect of elevation on water retention in these free drainage column experiments, for any of the observation days.

Both the pressure plate data and the column weight experiments corroborate that wood charcoal amendments were effective in reducing soil moisture retention near saturation, without affecting available water content, while reduction from oak biochar was not significant.

3.4. Effects of biochar and charcoal on soil hydraulic properties

The Van Genuchten (1980) model fitted the observed data well, with R^2 between 0.89 and 0.94 and RMSE coefficients between 0.01 and 0.02 (Table 2). As expected, the model under-predicted residual moisture content (θ_r) for all treatments compared with observed values at 1500 kPa (Fig. 3). On average, fitted α-values (inverse of air entry pressure) ranged from 0.01 to 0.03 kPa^{-1} and n-values from 1.50 to 1.96. Interestingly, average n-values of all charcoal amendments (acacia, croton, and eucalyptus) exceeded those of the control treatment, while n-values of the biochars (corn and oak feedstocks) were smaller than the control (Table 2), indicating that the capillary rise was less for charcoal treatments and therefore consistent with the results in Fig. 3.

The values in Table 2 allow us to look at the effects of biochar and charcoal on relative hydraulic conductivity (K_r) of soils as a function of tension and soil moisture content, by calculating relative hydraulic conductivity rates using Eqs. (2) and (3). This is shown in Fig. 6, which illustrates the distinct differences between relative hydraulic conductivity rates at low tensions (<100 kPa, Fig. 6a) and high moisture contents

Table 1
Mean values of soil properties at three elevations ranges (based on 16 replicate measurements per elevation range), with standard deviations given between parentheses. Values not sharing the same letter within the same column are statistically different.

Elevation range	f_s	BD	pH	Clay	Silt	Sand	OC
	(mm/h)	(g/cm^3)	($-\log[H^+]$)	(%)			
Low	11.2^a (2.3)	1.27^a (0.03)	5.45^a (0.07)	39.7^a (2.0)	35.4^a (1.2)	24.9^a (1.4)	1.11^a (0.04)
Mid	11.0^a (1.4)	1.28^a (0.03)	5.67^{ab} (0.07)	41.7^a (1.9)	32.2^a (1.8)	26.1^a (1.5)	1.05^a (0.02)
High	8.5^a (2.8)	1.25^a (0.02)	5.95^b (0.09)	43.3^a (1.7)	35.4^a (1.48)	21.3^a (1.6)	1.10^a (0.02)

f_s: steady infiltration rate, BD: bulk density, and OC: organic carbon content.

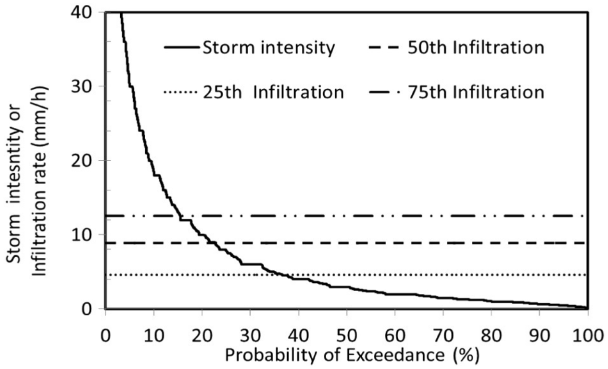

Fig. 2. Exceedance probability of rainfall intensity compared with 25th, 50th, and 75th percentile infiltration rates.

(approximately > 0.28 g/g, Fig. 6b). In these tension and moisture content ranges, all charcoals (acacia, croton, and eucalyptus) had relatively greater relative hydraulic conductivity (K_r) coefficients, while both biochars (corn and oak) had lower K_r coefficients compared with the control.

4. Discussion

4.1. Soil physical properties

Following USDA classification (USDA, 1999), the soils in the Anjeni watershed can be classified as clay loam (low elevations) to clay soils (mid to high elevations). Interestingly however, most studied parameters except pH were not significantly affected by elevation. These findings are in agreement with those of Adgo et al. (2013) and Assefa (2007) who found similar results for the Anjeni Watershed (Table 1). Likewise, these results (Table 1) concur with several authors who concluded that soils in the Ethiopian highlands are acidic (Chibsa and Ta, 2009; Demelash and Stahr, 2010; Feoli et al., 2002) and that its soil organic carbon pool is depleted (Hailu et al., 2012; Taddese, 2001; Zeleke et al., 2004). Soil acidity in the region is partly due to continuous weathering processes and leaching of base cations (Amare et al., 2013; Hodnett and Tomasella, 2002), while depletion of soil organic carbon is further acerbated by scarcity of farm inputs (including organic biomass) among other factors (Abegaz and Van Keulen, 2009; Feoli et al., 2002; Taddese, 2001). Organic carbon serves as a bridge (binding material) between primary soil particles (Bronick and Lal, 2005), and it is commonly accepted that both acidic pH (Dexter, 1988) and depletion of organic carbon (Bronick and Lal, 2005; Dexter et al., 2008; Hati et al., 2007; Lal, 2004; Reeves, 1997; Reynolds et al., 2007; Watts and Dexter, 1997) can enhance clay dispersion. A study by Dexter (1988) suggested that low pH results in net negative surface charges on clay particles that subsequently induce clay dispersion due to increased inter particle repulsion. Clay dispersion causes soil structural deterioration by blocking larger (hydraulically active) pores, causing a reduction in soil permeability (Chen et al., 1983; Daoud and Robert, 1992). Combined impacts of low organic carbon contents and low pH in these clayey soils therefore suggest high vulnerability to deteriorated soil physical condition (e.g., poor structural aggregation and stability), poor permeability (Watts and Dexter, 1997), and subsequent initiation of overland flow from open fields and waterlogged conditions on poorly drained fields (Temesgen et al., 2012) unless soil permeability is improved through appropriate management (Bayabil et al., 2010).

4.2. Infiltration capacity and storm intensity

The soils of Anjeni have developed from the basaltic Trapp series of Tertiary volcanic eruptions and is similar to most parts of central Ethiopia, with major soils: Alisols (41.5 ha) and Nitisols (23.8 ha) around 60% of the watershed area (SCRP, 2000; Zeleke, 2000), which could suggest good infiltration.

In contrast, however, construction of shallow ditches (10–15 cm deep) by local farmers (Fig. D1) supports the abovementioned view that prevalence of deteriorated physical conditions and poor permeability of soils in the Anjeni watershed. Moreover, compared with reports from similar watersheds, infiltration rates in Anjeni (Table 1, Fig. 2) were relatively lower: Engda (2009) and Demeku Derib (2005) for instance reported steady infiltration rates of 24–870 and 19–600 mm/h for the Andit Tid and Maybar watersheds, respectively. Like the Anjeni watershed, these watersheds are also located in the highlands, though Andit Tid and Maybar are situated at higher elevation (3040–3548 m and 2530–2858 m, respectively (Herweg and Ludi, 1999) vs. 2407–2507 for Anjeni) with steeper gradients.

Comparison of storm intensities and steady soil infiltration rates, as shown in Fig. 2, suggests that for the far majority of rainstorms, infiltration capacity considerably exceeds storm intensity. This indicates that saturation excess runoff, rather than infiltration excess runoff, is the root cause of observed overland flow in the Anjeni watershed. This is supported by a study by Tilahun et al. (2011) who analyzed long term rainfall and discharge data at the watershed outlet and reported that saturation excess runoff (mainly from saturated areas) was the dominant runoff mechanism.

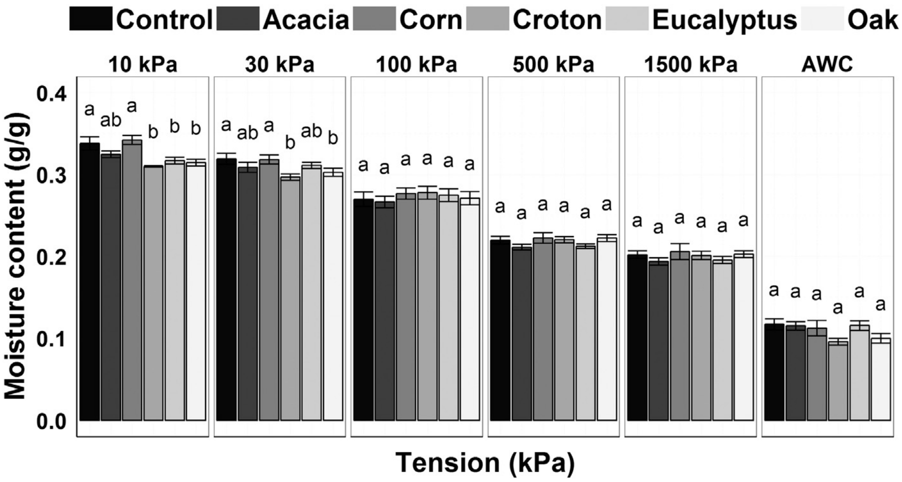

Fig. 3. Treatment effect on moisture retention at different tensions. Different letters at each tension indicate significant difference at $p < 0.05$. Acacia, croton, and eucalyptus are wood charcoals, and corn and oak are biochars.

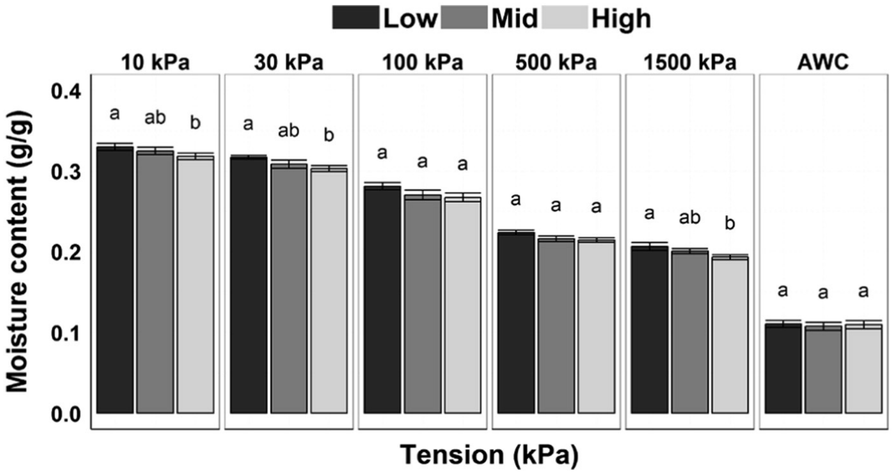

Fig. 4. Effect of elevation (low-mid-high) on moisture retention at different tensions. Different letters at similar tension indicate significant difference at $p < 0.05$.

4.3. Changes in soil hydraulic properties due to biochar and charcoal

The observed reduction in soil water retention at low tensions (near saturation) due to woody biochar and charcoal amendments (Fig. 3) is in agreement with previous study (Tryon, 1948), that observed significant reduction in water retention of clayey soils after incorporation of charcoal. These findings are also in line with the observed increase in both in relative hydraulic conductivity (K_r) at similar tensions (Fig. 6) and the Van Genuchten model parameter n for most soils amended with woody biochar and charcoal (Table 2). These n-values suggest steeper slopes of the soil water retention curve, which results in a significant reduction in soil moisture content for small changes in tension (Hodnett and Tomasella, 2002).

In contrast to charcoal, corn biochar (prepared from corn stover) did not decrease but rather increased soil water retention or had no effect (Fig. 3). In other studies mainly for sandy soils, organic amendments including biochar enhanced soil water retention (Abel et al., 2013; Bauer and Black, 1992; Feoli et al., 2002; Glaser et al., 2002; Hollis et al., 1977; Rawls et al., 2003) as well as available water content of medium textured soils (Emami and Astaraei, 2012; Karhu et al., 2011). Differences in impacts of biochar and charcoal on soil hydraulic properties could be due to variations in physico-chemical properties of feedstock sources (Enders et al., 2012; Verheijen et al., 2009). Physico-chemical properties of organic amendments may affect soil hydraulic properties in different ways. Direct substitution of clay particles by relatively larger biochar or charcoal particles might improve soil permeability by inducing tensile stresses around clay matrixes causing the formation of macropores or cracks as suggested by Dexter (1988) or just due to simple rearrangement of soil particles without altering total porosity of soil (Nimmo, 1997). For clayey soils, a small increase in macroporosity can significantly affect water flow near saturation (Eusufzai and Fujii, 2012; Sharma and Bhushan, 2001), whereas at higher tensions soil water retention is mainly affected by clay particles (texture), and thus organic amendments have diminished impacts (Saxton and Rawls, 2006). In line with this, Tryon (1948) reported coarse charcoal particles to be more effective in reducing moisture retention of clayey soils than fine charcoal particles. This would explain why the (coarser) charcoal significantly reduced water retention in the wet range of the water retention characteristic, while (finer) biochar only caused a slight reduction in this range (Fig. 3). Finally, biochar and charcoal amendments could also alter structural aggregation and stability of soils. Biochar and charcoal particles can bond with soil mineral surfaces through carboxylic and phenolic functional groups thereby contributing soil aggregate and structural stability (Soinne et al., 2014).

Another potential explanation for the fact that biochar and charcoal had different effects may lie in the interaction between biochar/charcoal

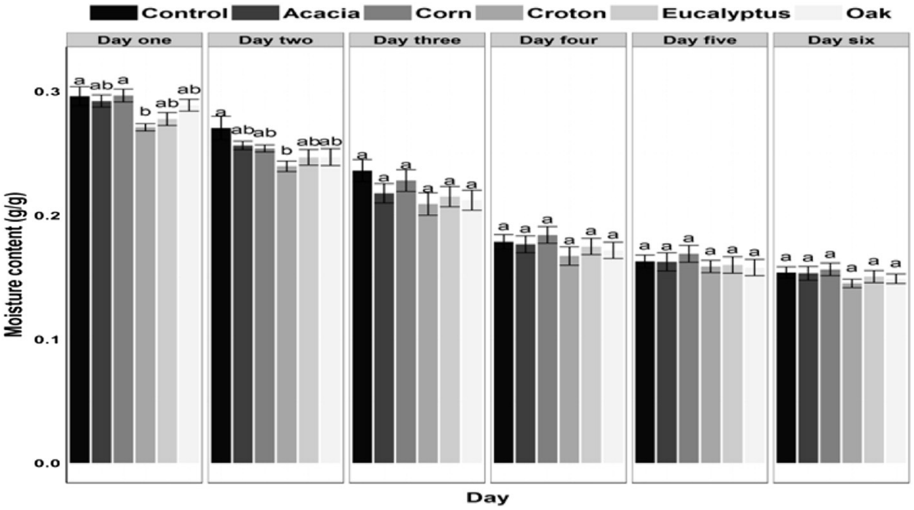

Fig. 5. Summary of treatment effects on soil moisture retention by day. Values are averages of replications ($n = 9$). Bars with different letters (with in the same day) indicate significant difference ($p < 0.05$). Acacia, croton, and eucalyptus are wood charcoals, and corn and oak are biochars.

Table 2
Summary of the Van Genuchten model fitting parameters and goodness of fit for charcoal and biochar treated and control soils. Results are based on combined data from all three elevation ranges together (n = 3).

Treatment	θ_r	θ_s	n (−)	α (kPa^{-1})	R^2	RMSE
	(g/g)					
Control	0.18^{a}	0.34^{a}	1.59^{a}	0.03^{ab}	0.90	0.02
Biochar						
Corn	0.17^{a}	0.35^{a}	1.50^{a}	0.03^{ac}	0.89	0.02
Oak	0.16^{a}	0.32^{bc}	1.50^{a}	0. 02^{bc}	0.91	0.01
Wood charcoal						
Acacia	0.17^{a}	0.33^{ab}	1.65^{a}	0.02^{ab}	0.94	0.01
Croton	0.17^{a}	0.31^{c}	1.65^{a}	0.01^{b}	0.91	0.01
Eucalyptus	0.18^{a}	0.32^{c}	1.96^{a}	0. 01^{b}	0.94	0.01

and clay, and the mechanisms by which biochar and charcoal could alter the chemistry of clay particles. Several studies reported that substituting monovalent cations (Na^+ and K^+) on exchange sites of clay particles by divalent cations with high charge density (such as Ca^{2+} and Mg^{2+}) enhanced clay flocculation, while the reverse processes induces clay dispersion (Dexter, 1988; Emami and Astaraei, 2012; Marchuk and Rengasamy, 2010). Clay dispersion often leads to clogging of macropores (Dexter, 1988; So and Aylmore, 1993), whereas flocculation of clay particles enhances macropores size and network (Rao and Mathew, 1995). Another study by Chen et al. (1983) reported the major mechanism for hydraulic conductivity reduction to be the dispersion of the 'fine soft fraction' (mostly clay aggregates) and its rearrangement in situ to form a dense network of particles and smaller pores, and not the extensive migration of clay and the subsequent formation of an impermeable layer.

Low hydraulic conductivity (K_r) coefficients for corn biochar, at low tensions, were in accordance with higher sodium adsorption ratios 2, 3,

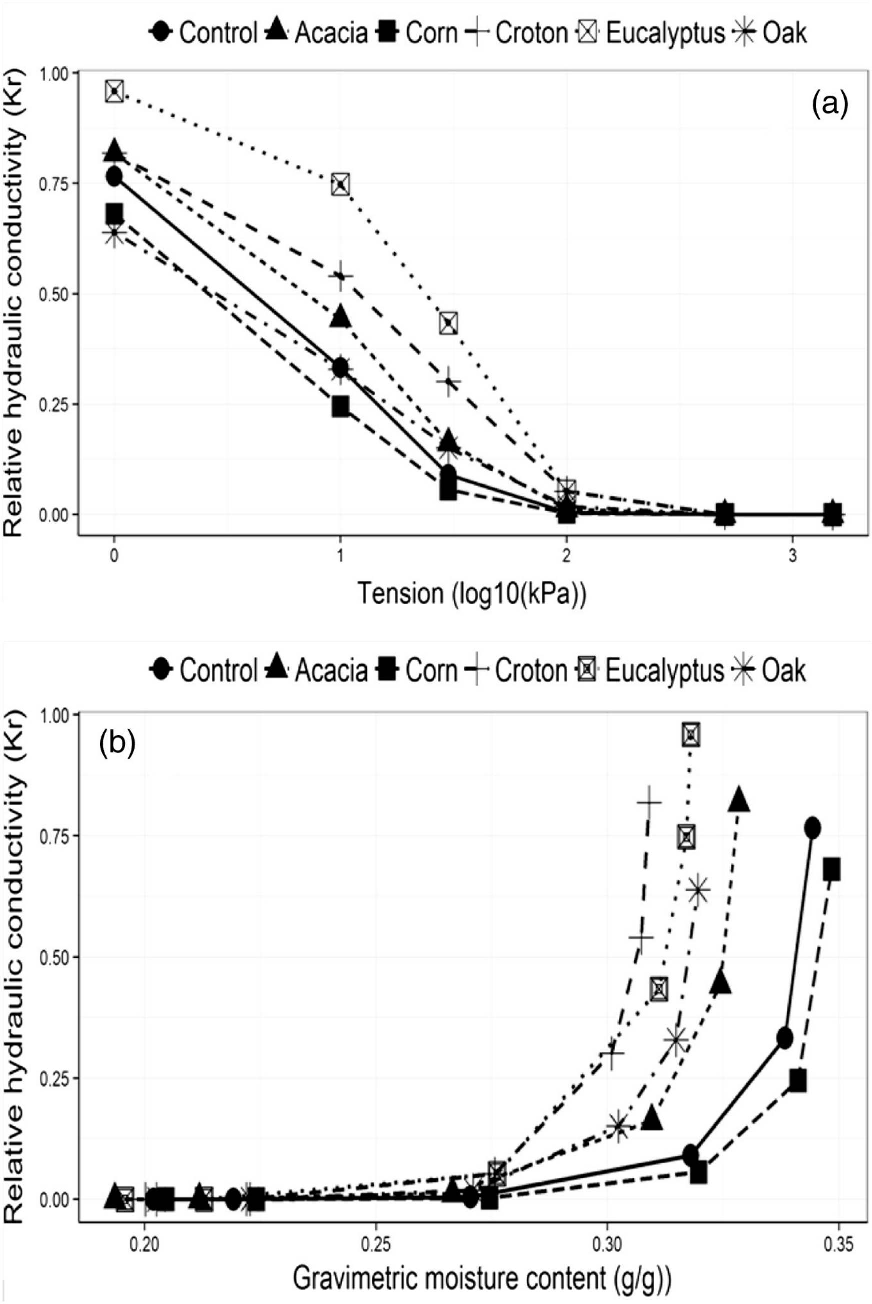

Fig. 6. Relative hydraulic conductivity curves as a function of tension (a) and moisture content (b). Acacia, croton, and eucalyptus are wood charcoals, and corn and oak are biochars.

and 8 times higher and potassium adsorption ratios 7, 49, and 62 times higher than oak biochar, and acacia and eucalyptus charcoal amendments, respectively (Table E1). High sodium adsorption ratio (SAR) (Dexter, 1988; Emami and Astaraei, 2012) and high potassium adsorption ratio (PAR) (Chen et al., 1983; Marchuk and Rengasamy, 2010) induced clay dispersion, but with varying magnitude depending on clay mineralogy (So and Aylmore, 1993). This suggests that, in addition to soil physical properties (texture), clay mineralogy, as well as elemental constituents of amendments could significantly affect impacts of pyrolized organic amendments.

5. Conclusion

In the Anjeni watershed, half of the catchment area generates infiltration excess runoff 23% of the time (Fig. 2). On these areas, management practices should focus on improving soil infiltration rates. Wood charcoal and biochar incorporation reduced soil moisture retention at lower tensions (<100 kPa) by increasing relative hydraulic conductivity (K_r) at these tensions. This was likely because of improved pore networks caused by binding clay particles that otherwise plug the major pathways for drainage. Therefore, we conclude that woody charcoal (acacia, croton, and eucalyptus) and biochar (oak) incorporation can improve soil physical properties (such as hydraulic conductivity) of degraded soils, which in turn could potentially reduce runoff, erosion, and field waterlogging. Results furthermore suggest that wood charcoal amendment may even be more effective than biochar, as biochar amendments (corn and oak) considered did not result in a significant improvement in these soil hydraulic parameters, for the soils considered here. Since none of the amendments significantly changed available water capacity, this study finally indicates that amendment with wood charcoals can improve soil drainage while having no effect on plant available water.

Overall findings of this study imply that decades of soil and water management planning approach needs to be adjusted. Future soil and water management practices need to target causes of runoff and erosion in relation to the dominant rainfall characteristics and the state of soil physical properties in a landscape. This study indicates that wood charcoal can be a viable low-cost alternative for improving soil physical properties, for instance in places like rural Africa where high-tech biochar is not available or too costly. However, a word of caution is needed here as all biomasses serve multiple purposes in daily livelihoods of smallholder farmers. Future studies therefore need to include socioeconomic factors to verify feasibility of biochar and charcoal use as soil amendments.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geoderma.2014.12.015.

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