Effects of charcoal amendment and a deep rooted crop on spatial and temporal runoff patterns in a degrading tropical highland watershed

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Abstract

Placement and hence performance of many soil and water conservation structures in tropical highlands has proven to be challenging due to uncertainty of the actual location of runoff-generating areas in the landscape. This is the case especially in the (sub) humid areas of the Ethiopian highlands, therefore resulting in limited success of such conservation measures. To improve understanding of the effect of land use on spatial and temporal runoff patterns in the Ethiopian highlands, we monitored runoff volumes from 24 runoff plots constructed in the 113 ha Anjeni watershed, where historic data of rainfall and stream discharge were available. In addition, we assessed the effectiveness of charcoal amendment and crop rooting depth in reducing runoff, in which we compared the effect of lupine (a deep-rooted crop) to that of barley. Daily rainfall, surface runoff, and root zone moisture contents were measured during the monsoon seasons of 2012 and 2013 (with all plots being tilled in 2012, but only barley plots tilled in 2013). In addition, long-term surface runoff from four plots and outlet discharge data from the research site (1989-1993) was analyzed and compared with our observations. Results showed that the degree of soil degradation and soil disturbance (tillage) were significant factors affecting plot-scale runoff responses. As expected, runoff was greater from more degraded soils. Overall, under the commonly applied lupine cropping practice, runoff was higher than under the commonly applied barley cropping practice. Especially, considerable difference was observed during smaller rainfall events (approximately < 20 mm) in 2013, when lupine plots (non-tilled) had greater runoff than barley plots (tilled). Charcoal tended to decrease runoff but results were not significant.

Keywords: rainfall, runoff, topography, crop cover, soil and water management

1 Introduction

Performance of many soil and water conservation structures in the tropical highlands has proven to be challenging due to uncertainty of their placement. Ideally, the location of conservation structures should be directly related to where runoff is generated in the landscape. Evaluating the effectiveness of landscape modifications is especially timely in the Ethiopian highlands where the Ethiopian government is implementing land management practices to both increase rainwater productivity in the degrading landscape, and increase the life of hydroelectric power plants such a as the Grand Ethiopian Renaissance Dam on the Blue Nile near Sudan (Humphreys et al., 2008; MOFED, 2010; MOA, 2013; Dagnew et al., 2015; Chen and Swain, 2014). The ultimate goal of these actions is to increase prosperity and assure food security for the rapidly increasing population (Hurni, 1988a, 1999; Nyssen et al., 2009b). Most areas in the Ethiopian highlands receive high amounts of annual precipitation, aiding soil leaching and promoting land degradation, however, water scarcity is common for 8-9 months every year (Amsalu and Graaff, 2006; Bewket and Sterk, 2005; Biazin et al., 2011; Hugo et al., 2002). Rainfall distribution is variable not only spatially but also temporally (Biazin et al., 2011; Bitew et al., 2009; McHugh et al., 2007). To counteract this problem of periodic water scarcity, soil and water conservation practices are ubiquitous in the Ethiopian highlands. However, surprisingly, most non-traditional soil and water conservation practices are ineffective because their placement neither addresses drivers of runoff nor considers spatial and temporal variation of runoff in a landscape.

Planning of effective soil and water management measures requires knowledge of dominant runoff generating mechanisms and its controlling factors (e.g., land use, topography). There are two mechanisms of surface runoff generation: (1) Hortonian overland flow or infiltration excess surface runoff that occurs when rainfall intensity exceeds infiltration capacity of the soil, and (2) saturation excess surface runoff that occurs when the (perched) water table rises, saturating the whole soil profile. However, there is still lack of agreement regarding the nature of the runoff initiation mechanisms and its controlling factors in the Ethiopian highlands. Previous studies highlighted saturation excess as the dominant runoff mechanism (Bayabil et al., 2010; Steenhuis et al., 2009; Tilahun et al., 2014, 2013). A field study by Bayabil et al. (2010) found that in the Maybar watershed, with highly conductive soils, saturation excess runoff was mainly driven by topography, with water channeling through the hillsides as interflow, saturating the lower-lying fields. This is in line with findings from the Debra Mawi watershed in the northern Ethiopian highlands where saturated lower-lying fields contributed most of the surface runoff (Tilahun et al., 2013). This strong evidence for saturation excess runoff being the driver of overland flow in the Ethiopian Highlands is in contrast with findings from (Bewket and Sterk, 2005; Taddese, 2001).

In contrast, (Bewket and Sterk, 2005; Taddese, 2001) reported that infiltration excess runoff mechanism was dominant mainly based on analysis of the hydrograph at the outlet focusing on land use change. Land use is important because it affects soil infiltration capacity. For example, several studies reported that land use change from natural vegetation to agricultural lands increased overland flow during the rainy monsoon phase, and reduced base flows during the dry phase in this region (Bewket and Sterk, 2005; Feoli et al., 2002; Taddese, 2001; Zeleke, 2000). In other countries as well, clearing of forests resulted in decreased infiltration rates especially in the sub soils (Hanson et al., 2004; Mendoza and Steenhuis, 2002; Nyberg et al., 2012; Shougrakpam et al., 2010). Identification of the dominant runoff mechanism in relation to not only topography but also land use in the Ethiopian Highlands is therefore essential for development of effective soil and water conservation methods in this region.

On degraded fields with poor soil infiltration capacity, management practices should aim at improving infiltration rates. This can be done by restoring the soil macropore network by improving soil organic carbon pools, or by disturbing the soil profile either physically (tillage) or biologically (using deep-rooted crops). Deep rooted crops can penetrate through the soil profile and thereby increase soil conductivity (Angers and Caron, 1998; Cresswell and Kirkegaard, 1995; Lesturgez et al., 2004; Meek et al., 1992). Moreover, upon decomposition of these roots, channels and biopores are created that could provide a network of macropores with considerable vertical and lateral conductivity (Yunusa and Newton, 2003).

Another solution for improving soil physical and hydraulic properties is by increasing the organic carbon pool through the addition of biochar or charcoal (Abel et al., 2013; Asai et al., 2009; Bayabil et al., 2015; Glaser et al., 2002; Kameyama et al., 2010; Karhu et al., 2011; Laird et al., 2010; Spokas, 2010). Biochar and charcoal incorporation have been reported to improve soil bulk density (Abel et al., 2013; Laird et al., 2010), porosity (Abel et al., 2013; Atkinson et al., 2010), and hydraulic conductivity (Asai et al., 2009). Although both biochar and charcoal amendments can be effective in improving soil hydraulic properties, Bayabil et al. (2015) argued charcoal to be a more viable solution for rural Africa because it is widely produced in most rural areas of Africa (Lehman et al., 2006) and therefore more accessible to smallholder farmers than biochar. The analysis above shows that deep-rooted crops and additions of charcoal could ameliorate soil and water losses in a degrading landscape. However, field research on the effectiveness of these two management practices in a tropical highland setting with monsoon rainfalls do not exist to our knowledge.

The objective of this study was, therefore, to investigate spatial and temporal rainfall-runoff relationships in the Ethiopian highlands by investigating the effects of soil degradation status and landscape position. For this, soil degradation status was experimentally changed by adding biochar and growing a deep-rooted lupine crop.

The research was carried out in the Anjeni watershed in the Ethiopian highlands in 2012 and 2013. Twenty-four runoff plots were established along three transects going upslope in sets of three at each landscape position. Each set of three plots had one plot in which lupine was planted and two plots with barley - of which one was amended with charcoal.

2 Materials and Methods

2.1 Study site

The Anjeni watershed is situated in the northwestern part of Ethiopia (Fig. 1), and was selected because of the availability of historic discharge records at the outlet and from runoff plots inside the watershed. The watershed has a drainage area of 113 ha and is one of the experimental watersheds established under the Soil Conservation and Research Program (SCRP) of the Ministry of Agriculture of Ethiopia in collaboration with the Swiss Agency for Development and Cooperation (SDC; Hurni et al., 2005). Its gauging station is located at 10°40' N, 37°31'E.

The watershed has a unimodal rainy season that lasts from mid -May to mid-October, with a mean annual rainfall of 1690 mm yr^{-1}. The topography of Anjeni is typical of Tertiary volcanic landscapes: it has been deeply incised by streams, resulting in the current diversity of landforms (SCRP, 2000) with elevation between 2407 and 2507 m (Herweg and Ludi, 1999). The soils of Anjeni have been developed from the basaltic Trapp series of Tertiary volcanic eruptions and is similar to most parts of central Ethiopia with dominant soils being Alisols (41.5 ha), Nitisols (23.8 ha), Cambisols (18.9 ha) and Regosols (10 ha) covering more than 80% of the watershed (Fig. A1 in Supplementary material A; SCRP, 2000; Zeleke, 2000). The deep Alisols cover the bottom part of the watershed; moderately deep Nitisols cover the mid-transitional, gently sloping parts of the watershed, while the shallow Regosols and Leptosols cover the high, steepest part of the watershed (Zeleke, 2000). Fields are intensively cultivated for crop production and a large proportion of the watershed is degraded (SCRP, 2000). In 1986, graded fanya-juu structures were installed for soil and water conservation, resulting in terraces across the landscape (SCRP, 2000).

2.2 Experimental setup

Effect of land use and soil management on runoff patterns were studied using 24 runoff plots installed across the watershed, accounting for spatial variability in soil degradation status and slope position (Fig. 1). Effects of charcoal amendment and crop rooting depth were assessed along three transect locations. The 24 plots were positioned in groups of three along three transects perpendicular to the slope (Fig. 2). Soil degradation varied between transects: Transects 1 and 2 are located in the southeast and southwest part of the watershed (Fig. 1b, Table 1), and have deep soils while Transect 3, located between Transects 1 and 2, is characterized by shallow and degraded soils. Transects 1 and 3 are steep (with slopes approximately 14.5 and 15.6 %, respectively), while Transect 2 has moderate slope (11.8%). Effects of landscape position were assessed by placing plots at different slope positions: at downslope, mid-slope, and upslope positions along Transects 1 and 2; and at the two upper positions along Transect 3 (Fig. 1c). A factorial experimental design was used during installation of plots, with the effect of charcoal and a deep-rooting crop assessed at every landscape position.

At the start of the 2012 growing season (June), all plots were plowed and two plots were seeded with barley. Effects of charcoal amendment were assessed by amending one of the barley plots with charcoal during plowing, the non-amended barley plot serving as a control treatment. Effects of crop rooting depth were assessed by seeding the third plot at each transect location with the deep-rooted lupine (*Lupineus* albus L.) crop, with again the non-amended barley plot serving as a control treatment. Barley and lupine crops were assigned randomly to plots; and the same crop was maintained on each plot for two years (2012 and 2013). These crops were chosen as they are widely grown throughout the Ethiopian highlands. Farmers grow lupine as intercrop with cereals (e.g. barley and wheat) or as the sole crop on marginal lands without additional farm inputs. Barley has a fibrous root system, while lupine has deep-rooted system and is widely grown on marginal lands for its leguminous nature. Because of their contrasting root architecture, lupine and barley are expected to have contrasting effects on soil hydraulic properties.

2.3 Agronomic practices on plots

Barley, one of the predominantly grown crops in the watershed (SCRP, 2000), was grown following local farmers' cultural practices and thus barley plots were tilled in both 2012 and 2013. While lupine seedbeds are typically not tilled, tillage was done in 2012 because the plots were originally designated to be sown with alfalfa, another deep rooted crop though one that is always tilled. When the alfalfa did not establish successfully, lupine was sown on the tilled soil shortly after. The next growing season, in 2013, only barley plots were tilled and seeded, while lupine seeds were seeded on untilled plots (the more common practice in the area). Also in line with farmer practices, all barley plots were fertilized with 100 kg/ha Di-Ammonium Phosphate (DAP; 46% Nitrogen, 23% Phosphorous, and 21% Potassium) during seeding, and 100 kg/ha of Urea (100% Nitrogen) one month after sowing. Lupine plots were not fertilized. Both fertilization and tillage are different for lupine and barley treatments during the two-year study period (2012 and 2013). To distinguish crop effect (barley and lupine crops grown under common practices) from tillage effects, data from the two-year study was therefore analyzed for each year separately.

On charcoal-amended barley plots, charcoal was applied at a fixed rate of 12 ton/ha during tillage in 2012 and 2013. Charcoal (prepared from *Eucalyptus camaladulensis* biomass in a way similar to that described by Bayabil et al. (2015) was manually crushed to obtain relatively uniform particle size (2 mm diameter) and then manually incorporated on the top 20 cm of the soil.

2.4 Plot installation and data collection

While crop and charcoal treatments were applied to 9 m^2 (3 m wide, 3 m long) areas, runoff was only measured on 4.5 m^2 plots (1.5 m wide, 3 m long) inside these areas, to allow for auxiliary measurements (e.g. soil moisture content) to be taken adjacent to instead of inside the runoff plots and thereby avoid trampling and soil disturbance inside the plots. For this, runoff plot boundaries were installed 0.75 m inside the seeded area from both sides. As illustrated in Fig. 2, all runoff plots were constructed at the level bottom ends of terraces.

The plot boundaries consisted of 50 cm high metal sheets of which 25 cm was belowground and 25 cm was aboveground, and the lower plot boundaries were reinforced with concrete. A 5-cm diameter PVC pipe carried surface runoff into a primary collection tanks (76 L volume). When the primary tanks were full, excess water flowed through divisor slots directing one-tenth (10%) of the excess flow into secondary tanks (76 L volume). The tanks were made from barrels cut in half and were covered on the top to minimize evaporation and prevent rainfall entry.

All runoff plots were monitored manually for runoff volumes on a daily basis during the monsoon season (from June 29 to October 4 in 2012 and from June 25 to October 8 in 2013). When runoff occurred, the depth of water in the two tanks was measured and then the water was drained out through valves fitted at the bottom of the tanks. Daily rainfall totals were measured using a manual rain gauge installed at the weather station in the watershed (see Fig. 1b 'Weather station'). In addition, during the 2013 growing period, soil moisture content, θ (g g^{-1}), was measured gravimetrically by taking bulk soil samples from the top 20 cm depth at 10-day intervals. To prevent disturbance, samples were taken inside the seeded area but just outside each runoff plot.

2.5 Long-term plot runoff and river discharge data

In addition to runoff data from the 24 newly installed plots, we obtained long-term data from the Amhara Regional Agricultural Research Institute (ARARI). The data consists of runoff from four long-term 3 m^2-plots (3 m length, 1 m width; Fig. 1b, 'Permanent plots'), and discharge at the outlet of the watershed (Fig. 1b, 'Gauging station'). To place our newly installed plot-scale runoff observations into a broader and longer-term context, we compared our data with historic plot-scale runoff data available in the watershed for the years 1989 through to 1993. These data were measured on the four 3 m^2 plots that had slopes of 12, 16, 22, and 28%. The 16% sloped plot was on grassland, while the other three plots were cultivated with food crops (e.g. barley and wheat; SCRP, 2000). Discharge was measured continuously since 1984 (two years before the installation of the '*fanya juu*' conservation structures) as part of the ongoing hydrological and erosion monitoring activities (SCRP, 2000), and we used discharge data for the 2012 and 2013 monsoon seasons to compare our plot-scale observations with watershed-scale patterns. Rainfall data obtained from the watershed (Fig. 1b, 'Weather station') was available for the same period.

2.6 Data quality control and aggregation

To make sure that peaks of daily rainfall and runoff coincided, we checked all daily data visually and by calculating the daily runoff coefficients (R_{coef}) using Eq. 1:

$$R_{coef} = \frac{runoff}{rainfall} \tag{1}$$

where *runoff* is daily runoff (mm/day), and *rainfall* is daily rainfall amount (mm).

Plot-scale rainfall-runoff data (Fig. B1-B3 in Supplementary material B) showed that there were 214 events (spread over 11 days in 2012 and 32 days in 2013) out of 5232 events total (i.e. 4.1% of total) where daily runoff was greater than the rainfall amount recorded on the same day (i.e. $R_{coef} > 1$). In some cases, large rainfall events were visible that did not produce runoff on the same day, but for which peak runoff appeared on the following day. In other cases, there was more runoff than rainfall without delays (see spikes of blue, green, and red lines in Fig. B1-B3 in Supplementary material B). Runoff in excess of rainfall can be caused by rainfall and runoff measurement periods that do not coincide. Here, rainfall was measured at 8 am every day. The first of the 24 runoff plots was also measured at 8 am but emptying the barrels and scooping out the sediment is time consuming, causing the last plot to be emptied around noon. Rainfall and runoff periods therefore did not exactly coincide, which likely raised problems on days that rainfall occurred between 8 am and 12 pm. Other potential causes for runoff exceeding rainfall are high spatial variation in rainfall that is not picked up by our single rain gauge, and interflow from outside the plot entering the plot during large rainstorms.

To reduce the impact of delayed peak runoff, we therefore decided to aggregate rainfall and runoff data over a 3-day period, resolving most of the high runoff coefficients. Yet 47 events (2.6% of total) observed on the 24 plots and recorded on 11 observation days spread over the two-year study period were left with $R_{coef} > 1$ (Fig. C1 in Supplementary material C). Further data aggregation, even on a weekly interval, did not solve these high runoff events. One of the options to deal with such outlier data points would be excluding observations from data analysis. However, to avoid bias between treatments and spatial locations, all observations from those 11 days would need to be discarded for all (24) plots, which would result in discarding 264 observations. Losing this many observations (14.9% from 1777 total 3-day observations) would considerably reduce the power of our analysis. Thus, to achieve a balance between the number of runoff events remaining for analysis and the objective to analyze large runoff events, the remaining high runoff events ($R_{coef} > 1$) after data aggregation on 3-day intervals, were therefore assigned a maximum value that equals the 3-day rainfall amount – resulting in a runoff coefficient of 1. As such, adjusted 3-day aggregate runoff data were used for all statistical data analyses in this paper.

In addition to this analysis of runoff coefficients, to assess the differences in soil water storage between plots, the SCS curve number was fitted to three-day rainfall and and three day adjusted runoff data for each treatment type and cropping year using Eq. 2. The SCS equation was effectively used in predicting rainfall-runoff relationships in the Ethiopian highlands (Tilahun, 2012) and for different regions in the USA and Australia (Steenhuis et al., 1995).

$$Q = \frac{(P_e - 0.2S)^2}{(P_e - 0.8S)} \quad (2)$$

where Q is 3-day runoff (mm) P_e is 3-day rainfall (mm) and S (mm) is potential maximum soil storage (Steenhuis et al., 1995).

2.7 Statistical analysis

Data analysis aimed at detecting differences in runoff response between land uses and spatial locations (transects and elevation ranges) during the two-year study period. Statistical data analysis was performed using R (R Development Core Team 2010). To determine the effect of charcoal amendment and deep-rooted lupine as well as spatial location with different soil degradation levels (transects) and slope position, a linear mixed effect model was fitted using the 'nlme' package in R. In this model, crop type, slope position, and transect were used as fixed factors, and individual plots as random factors. For fixed factors with significant effects, post hoc mean comparison tests were performed using the 'lsmeans' package in R to identify group pairs with significant difference.

3 Results and Discussion

3.1 Plot-scale rainfall-runoff response and effect of charcoal amendment and deep-rooted lupine

The adjusted runoff depths during the monsoon seasons of 2012 and 2013 are shown in Fig. 3 for all eight groups of plots along the three transects. In 2013, runoff response from lupine plots was considerably greater than barley plots, while in 2012, runoff tended to be more or less similar for all treatments. In addition, a summary of observed rainfall and original (non-adjusted) runoff data recorded from all 24 plots is presented in Table 2. Average monthly rainfall in 2012 was similar to the 5-year average (based on 1989-1993 observations; Fig. D1 in Supplementary material D), while in 2013 it exceeded the 5-year average.

As discussed in the Methods section, runoff exceeding rainfall (i.e. $R_{coef} > 1$), as shown in Fig. B1-B3 in Supplementary material B and Fig. C1 in Supplementary material C, is not expected and worrisome. We therefore checked historic long-term data (1989-1993) from four permanent plots (3 m length, 1 m width) measured by the well-trained technicians at the experimental station, and found the same "problem" that in many cases there was more runoff than rainfall (Fig. 4a). This indicates that our daily observations with $R_{coef} > 1$ (Fig. 4b) are real and not caused by measurement errors. This phenomenon of runoff exceeding rainfall has not been reported often for temperate climates, and it is therefore likely that rainfall in monsoon climates is more variable over short distances than rains in temperate climates. Studies found that rainfall in the Ethiopian highlands significantly varies in space (Bewket and Conway, 2007; Bitew et al., 2009). Bitew et al. (2009) observed up to 424% coefficient of variation of daily rainfall between rain gauges. These authors further noted that in areas with complex topography (like the Anjeni watershed), extrapolation of point rainfall observations to larger scales could be less accurate.

3.2 Plot runoff and outlet discharge

All plots on degraded soils along Transect 3 produced significantly greater runoff than plots along the other two transects with relatively deeper soils (Fig. E1 in supplementary material E). While we expected slope position to affect runoff, results from the linear mixed effects model showed that plot-scale runoff responses between slope positions were not significant. Because of this, 2012 and 2013 runoff responses of barley (both control and charcoal amended) and deep-rooted lupine were grouped by transect and then compared. Statistical test results showed that, for all transects, lupine plots produced significantly more runoff than both the control and charcoal-amended barley plots. Charcoal amendment, on the other hand, caused no significant effects (Fig. 5). The cumulative runoff for the lupine plots followed the cumulative runoff for the outlet more than the barley plots, particularly in 2013 (Fig. 6).

Comparison of plot-scale cumulative runoff (colored lines, Fig. 6) and cumulative river discharge observed at the watershed outlet (black line, Fig. 6) with cumulative rainfall indicated that approximately 100 mm of cumulative rainfall was needed before runoff was initiated from all plots. In general, during the start of the monsoon season (until 500 mm cumulative rainfall in Fig. 6), plot-scale runoff response generally exceeded watershed-scale discharge response. Nevertheless, as the rainy season progressed, starting from the middle of August and at approximately 500 mm cumulative rainfall, watershed-scale discharge started to exceed plot-scale runoff depths (with the exception of the lupine plots in 2013, see below). The difference between plot-scale runoff and outlet discharge during the onset of the monsoon season indicates that detention storage at a watershed scale occurs; while the difference between the plot and watershed scale later in monsoon season is caused by base flow at the watershed outlet. This is consistent with previous observations by Tilahun et al. (2013 a, b) and Bayabil et al. (2010) who observed that initially, the runoff from the hillsides infiltrates on lower slope position while later in the season these bottom lands start to contribute both subsurface flow and surface runoff.

A considerable difference in the runoff response of barley and lupine plots was observed between the monsoon seasons of 2012 and 2013. In 2012, runoff tended to be more or less similar for all treatments, whereas in 2013 runoff from barley and lupine plots began to deviate after approximately 250 mm cumulative rainfall (Fig. 6). In agreement with this, a closer look at the plots (Fig. 3) clearly shows that for most of the high rainfall amounts, there is little difference in runoff response between the barley and lupine plots. Only for smaller rain events (approximately < 20 mm) and during the start of the 2013 rainy season (around July 1), runoff from lupine plots exceeded that of barley plots. It is interesting that this is the case for all three transects in 2013, but does not occur in 2012. The only management difference between these two years is that lupine was tilled in 2012 but not in 2013. This implies that tillage resulted in relatively greater soil water storage for lupine plots, and that the difference in rainfall-runoff response between these crop treatments in 2013 may be ascribed to the fact that barley plots were tilled and lupine plots were not. Soil water storage estimated by fitting the SCS-CN equation (Steenhuis et al., 1995) confirmed smaller storage for lupine than for barley (Fig. 7). This would mean that there is very little infiltration in the lupine plots other than to refill the water abstracted by the lupine for evapotranspiration.

These findings indicate that both soil degradation status (soil depth) and disturbance (tillage) are important factors affecting rainfall-runoff relationships in the landscape. In addition to tillage activities, inherent differences in plant root morphology (e.g. length and density) between the barley and lupine could likely be another factor. Most of the root masses of barley are located at shallow depths in the upper part of the soil profile (Lugg et al. (1988) and thereby take water from the top soil, whereas lupine roots grow deeper (Figure F1 in supplementary material F) than barley and extracts water from deeper depths (French and Buirchell, 2005). These differences in root water uptake are somewhat visible in slightly greater, albeit not significant, root zone moisture readings (measured from the top 20 cm) observed for lupine plots beginning in August in 2013 (not shown).

It is important to note that the fact that lupine did not decrease runoff during this study period does not imply it would not reduce runoff in the long-term. When the roots of lupine decompose, it is likely that biopores and channels would be created (as reported by Meek et al. (1992) and Lesturgez et al. (2004) and that the resulting high vertical and lateral continuity improves the network of macropores (Yunusa and Newton, 2003), which would result in reduced surface runoff and associated erosion.

4 Conclusions

We set out to investigate the factors that control runoff initiation by investigating the effects of soil degradation status, landscape position, and different land uses (barley with and without charcoal, and deep-rooted lupine crop) on spatial and temporal rainfall-runoff relationships. We observed and analyzed the discharge of 24 runoff plots installed in groups of three in three transects over a 2-year period. Each group consisted of plots grown with lupine with no amendment, barley with no amendment, and barley with a charcoal amendment. Monsoonal rains are highly variable even over short distances, and in several cases there was more runoff from the plot than rainfall at the rain gauge. In general, we found that: First, watershed detention storage increased during the first half of the rainy phase and plot-scale runoff depths exceeded those at watershed-scale. The opposite was true later on in the rainy phase due to the occurrence of base flow at the watershed outlet. Second, under the commonly applied cropping practices (tillage for barley, no tillage for lupine), runoff was greater for lupine than barley. Especially, during small rainfall events (approximately < 20 mm) in 2013, runoff from non-tilled lupine plots exceeded that of tilled barley plots. Charcoal amendment tended to decrease runoff but results were not significant. Third, plot-scale rainfall-runoff relationships are greatly affected by root-zone soil water storage capacity, which is directly affected by a range of factors including soil degradation and the amount of water than can percolate to deeper soil layers, tillage practices and fertilization (that were different for lupine and barley treatments), and root morphology of crops (e.g. root length and density).

In the near term, the decreased soil water storage for lupine than for barley crops in this region implies that lupine has a smaller rainfall threshold for runoff initiation. In the long term however, lupine may have the potential to actually reduce runoff by improving infiltration rates through the creation of bio-pores once its large taproot decomposes (Figure F1 in supplementary material F). The long-term impact of lupine cropping on runoff processes therefore requires further investigation. Understanding the drivers of hardpan formation and permeability is essential for the development of management approaches that can effectively tackle hardpan occurrence and its hydrologic impacts, in order to ultimately reverse the land degradation trend and reduce erosion.

Our findings are in agreement with other studies that show that rainfall runoff relationships at a small plot scale are different than at the outlet (e.g. Han et al., 2012; Stoof et al., 2012), and that better use of green water (rainfall) for smallholder agriculture systems in the Ethiopian highlands could be achieved by decreasing runoff by increasing the storage of water in the root zone. However, more research has to be done how best to achieve the latter.

Acknowledgements

This study was funded by the N. Borlaug Leadership Enhancement in Agriculture Program (LEAP) in cooperation with IWMI's East Africa office, and by a grant from USAID in cooperation with the Higher Education for Development (HED) office by the Cornell's Bradfield Award Committee. The authors would like thank Prof. Hans Hurni for his foresight and efforts in establishing the SCRP watershed sites in the 1980s. We also thank Dr. Molla Addisu, Debre Markos University, for his help in obtaining some of the materials used in the field. Birhanu Mehiretu (field technician in the Anjeni watershed) was very helpful during the research and field data collection.

References

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., Wessolek, G., 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma 202-203, 183–191. doi:10.1016/j.geoderma.2013.03.003

Amsalu, A., Graaff, J., 2006. Farmers' Views of Soil Erosion Problems and their Conservation Knowledge at Beressa Watershed, Central Highlands of Ethiopia. Agric. Hum. Values 23, 99–108. doi:10.1007/s10460-005-5872-4

Angers, D.A., Caron, J., 1998. Plant-induced changes in soil structure: Processes and feedbacks. Biogeochemistry 42, 55–72.

Asai, H., Samson, B.K., Stephan, H.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., Horie, T., 2009. Biochar amendment techniques for upland rice production in Northern Laos: Soil physical properties, leaf SPAD and grain yield. Field Crops Res. 111, 81–84.

Atkinson, C.J., Fitzgerald, J.D., Hipps, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337, 1–18.

Bayabil, H.K., Stoof, C.R., Lehmann, J.C., Yitaferu, B., Steenhuis, T.S., 2015. Assessing the potential of biochar and charcoal to improve soil hydraulic properties in the humid Ethiopian Highlands: The Anjeni watershed. Geoderma 243-244, 115–123. doi:10.1016/j.geoderma.2014.12.015

Bayabil, H.K., Tilahun, S.A., Collick, A.S., Yitaferu, B., Steenhuis, T.S., 2010. Are Runoff Processes Ecologically or Topographically Driven in the (Sub) Humid Ethiopian Highlands? The Case of the Maybar Watershed. Ecohydrology 3, 457–466.

Bewket, W., Conway, D., 2007. A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. Int. J. Climatol. 27, 1467–1477. doi:10.1002/joc.1481

Bewket, W., Sterk, G., 2005. Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia. Hydrol. Process. 19, 445–458. doi:10.1002/hyp.5542

Biazin, B., Stroosnijder, L., Temesgen, M., AbdulKedir, A., Sterk, G., 2011. The effect of long-term Maresha ploughing on soil physical properties in the Central Rift Valley of Ethiopia. Soil Tillage Res. 111, 115–122. doi:10.1016/j.still.2010.09.006

Bitew, M.M., Gebremichael, M., Hirpa, F.A., Gebrewubet, Y.M., Seleshi, Y., Girma, Y., 2009. On the local-scale spatial variability of daily summer rainfall in the humid and complex terrain of the Blue Nile: observational evidence. Hydrol. Process. n/a–n/a. doi:10.1002/hyp.7468

Cresswell, H.., Kirkegaard, J.., 1995. Soil Amelioration by Plant Roots - the Process adn the Evidence. Aust J Soil Res 33, 221–239.

Feoli, E., Gallizia, L.., Woldu, Z., 2002. Processes of Environmental Degradation and Opportunities for Rehabilitation in Adwa, Northern Ethiopia. Landsc. Ecol. 17, 315–325.

French, R.J., Buirchell, B.J., 2005. Lupin: the largest grain legume crop in Western Australia, its adaptation and improvement through plant breeding. Aust. J. Agric. Res. 56, 1169. doi:10.1071/AR05088

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Biol. Fertil. Soils 35, 219–230. doi:10.1007/s00374-002-0466-4

Hanson, D.L., Steenhuis, T.S., Walter, M.F., Boll, J., 2004. Effects of soil degradation and management practices on the surface water dynamics in the Talgua River Watershed in Honduras. Land Degrad. Dev. 15, 367–381. doi:10.1002/ldr.603

Han, S., Xu, D., Wang, S., 2012. Runoff formation from experimental plot, field, to small catchment scales in agricultural North Huaihe River Plain, China. Hydrol. Earth Syst. Sci. 16, 3115–3125. doi:10.5194/hess-16-3115-2012

Herweg, K., Ludi, E., 1999. The performance of selected soil and water conservation measures—case studies from Ethiopia and Eritrea. Catena 36, 99–114.

Hugo, L.., Johann, B., Juergen, G., Hiremagalur, G., Mohammad, J., Victor, M., John, M., Martin, O., Mohamed, S., 2002. Linking Natural Resources, Agriculture and Human Health: Case Studies from East Africa. LEISA Mag. supplement, 17–20.

Hurni, H., Tato, K., Zeleke, G., 2005. The Implications of Changes in Population, Land Use, and Land Management for Surface Runoff in the Upper Nile Basin Area of Ethiopia. Mt. Res. Dev. 25, 147–154.

Kameyama, K., Miyamoto, T., Shinogi, Y., 2010. Increases in available water content of soils by applying bagasse-charcoals, in: Proceedings of the 19th World Congress of Soil Science: Soil Solutions for a Changing World, Brisbane, Australia, 1-6 August 2010.. pp. 105–108.

Karhu, K., Mattila, T., Bergström, I., Regina, K., 2011. Biochar addition to agricultural soil increased CH4 uptake and water holding capacity – Results from a short-term pilot field study. Agric. Ecosyst. Environ. 140, 309–313. doi:10.1016/j.agee.2010.12.005

Laird, D.A., Fleming, P., Davis, D.D., Horton, R., Wang, B., Karlen, D.L., 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158, 443–449. doi:10.1016/j.geoderma.2010.05.013

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-charhar sequestration in terrestrial ecosystems – a review. Mitig. Adapt. Strateg. Glob. Change 11, 403–427. doi:10.1007/s11027-005-9006-5

Lesturgez, G., Poss, R., Hartmann, C., Bourdon, E., Noble, A., Ratana-Anupap, S., 2004. Roots of Stylosanthes hamata create macropores in the compact layer of a sandy soil. Plant Soil 260, 101–109.

Lugg, D.G., Tubaileh, A.S., Kallsen, C.E., Sammis, T.W., 1988. Irrigation effects on rooting patterns of spring barley. Irrig. Sci. 9, 27–43.

McHugh, O.V., Steenhuis, T.S., Berihun Abebe, Fernandes, E.C.M., 2007. Performance of in situ rainwater conservation tillage techniques on dry spell mitigation and erosion control in the drought-prone North Wello zone of the Ethiopian highlands. Soil Tillage Res. 97, 19–36. doi:10.1016/j.still.2007.08.002

Meek, B.D., Rechel, E.R., Carter, L.M., DeTar, W.R., Urie, A.L., 1992. Infiltration rate of a sandy loam soil: effects of traffic, tillage, and plant roots. Soil Sci. Soc. Am. J. 56, 908–913.

Mendoza, G., Steenhuis, T.S., 2002. Determination of Hydraulic Behavior of Hillsides with a Hillslope Infiltrometer. Soil Sci. Soc. Am. J. 66, 1501–1504.

Nyberg, G., Bargués Tobella, A., Kinyangi, J., Ilstedt, U., 2012. Soil property changes over a 120-yr chronosequence from forest to agriculture in western Kenya. Hydrol. Earth Syst. Sci. 16, 2085–2094. doi:10.5194/hess-16-2085-2012

SCRP, 2000. Area of Anjeni, Gojam, Ethiopia: Long-term Monitoring of the Agricultural Environment 1984 - 1994. Centre for Development and Environment, University of Berne, Switzerland, in Association with The Ministry of Agriculture, Ethiopia.

Shougrakpam, S., Sarkar, R., Dutta, S., 2010. An experimental investigation to characterise soil macroporosity under different land use and land covers of northeast India. J. Earth Syst. Sci. 119, 655–674.

Spokas, K., 2010. Impacts of biochar additions on soil microbial processes and nitrogen cycling, in: Abstracts of Papers of The American Chemical Society.

Steenhuis, T.S., Collick, A.S., Easton, Z.M., Leggesse, E.S., Bayabil, H.K., White, E.D., Awulachew, S.B., Adgo, E., Ahmed, A.A., 2009. Predicting discharge and sediment for the Abay (Blue Nile) with a simple model. Hydrol. Process. n/a–n/a. doi:10.1002/hyp.7513

Steenhuis, T.S., Winchell, M., Rossing, J., Zollweg, J., Walter, M., 1995. SCS Runoff Equation Revisited For Variable-Source Runoff Areas. J. Irrig. Drain. Eng. 121, 234–238.

Stoof, C.R., Vervoort, R.W., Iwema, J., van den Elsen, E., Ferreira, A.J.D., Ritsema, C.J., 2012. Hydrological response of a small catchment burned by experimental fire. Hydrol. Earth Syst. Sci. 16, 267–285. doi:10.5194/hess-16-267-2012

Taddese, G., 2001. Land Degradation: A Challenge to Ethiopia. Environ. Manage. 27, 815–824. doi:10.1007/s002670010190

Tilahun, S.A., 2012. Observations and modeling of erosion from spatially and temporally distributed sources in the (semi) humid Ethiopian highlands. Cornell University.

Tilahun, S.A., Guzman, C.D., Zegeye, A.D., Dagnew, D.C., Collick, A.S., Yitaferu, B., Steenhuis, T.S., 2014. Distributed discharge and sediment concentration predictions in the sub-humid Ethiopian highlands: the Debre Mawi watershed: DISTRIBUTED DISCHARGE AND EROSION PREDICTIONS IN ETHIOPIA. Hydrol. Process. n/a–n/a. doi:10.1002/hyp.10298

Tilahun, S.A., Guzman, C.D., Zegeye, A.D., Engda, T.A., Collick, A.S., Rimmer, A., Steenhuis, T.S., 2013. An efficient semi-distributed hillslope erosion model for the subhumid Ethiopian Highlands. Hydrol. Earth Syst. Sci. 17, 1051–1063. doi:10.5194/hess-17-1051-2013

Yunusa, I.A.., Newton, P., 2003. Plants for amelioration of subsoil constraints and hydrological control: the primer-plant concept. Plant Soil 257, 261–281.

Zeleke, G., 2000. Landscape Dynamics and Soil Erosion Process Modelling in the North-western Ethiopian Highlands, African Studies Series A 16. Berne, Switzerland: Geographica Bernensia.

Table 1. Spatial attributes and soil properties of plots

Transect	Position	Plots	Elevation (m.a.s.l.)	Slope (%)	Sand	Silt (%)	Clay	[1]OM	[2]BD (g cm^{-3})	[3]D (m)
One	Upslope	1,2,3	2438	3.0	24.8	35.4	39.8	2.2	1.1	1.15
	Mid slope	4,5,6	2431	2.5	31.7	28.0	40.3	2.1	1.1	1.22
	Downslope	7,8,9	2411	1.5	23.6	36.7	39.6	2.2	1.1	> 1.3
Two	Upslope	10,11,12	2461	2.5	23.8	32.2	44.0	2.1	1.1	0.84
	Mid slope	13,14,15	2426	2.0	17.8	39.0	43.2	2.4	1.2	1.09
	Downslope	16,17,18	2415	1.0	24.7	36.3	39.0	2.4	1.3	> 1.3
Three	Upslope	19,20,21	2455	3.0	21.0	37.7	41.4	1.3	1.4	0.33
	Mid slope	22,23,24	2438	2.0	30.6	37.4	32.0	1.4	1.3	0.72

[1]OM: Organic Matter; [2]BD: bulk density; and [3]D: soil depth

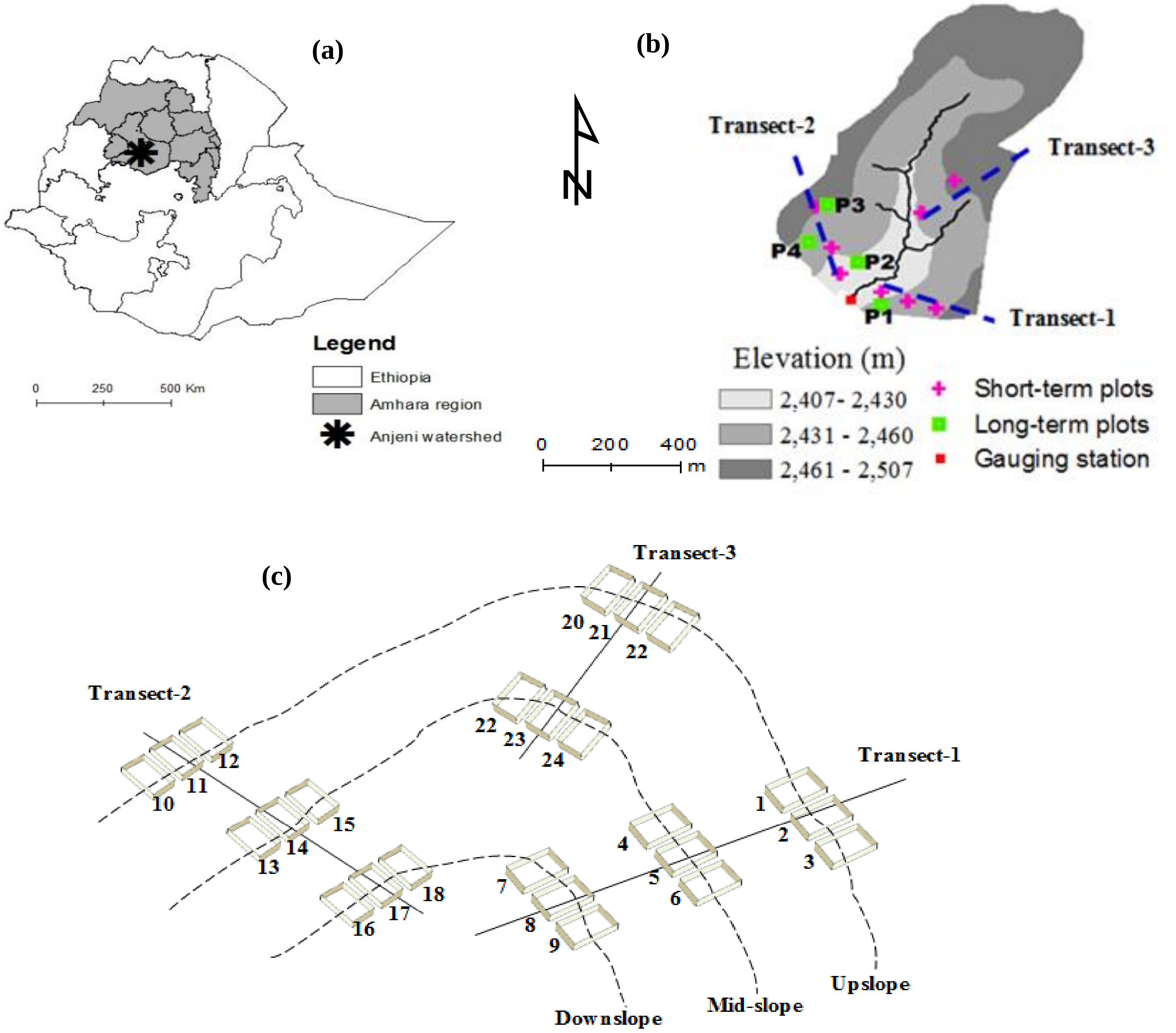
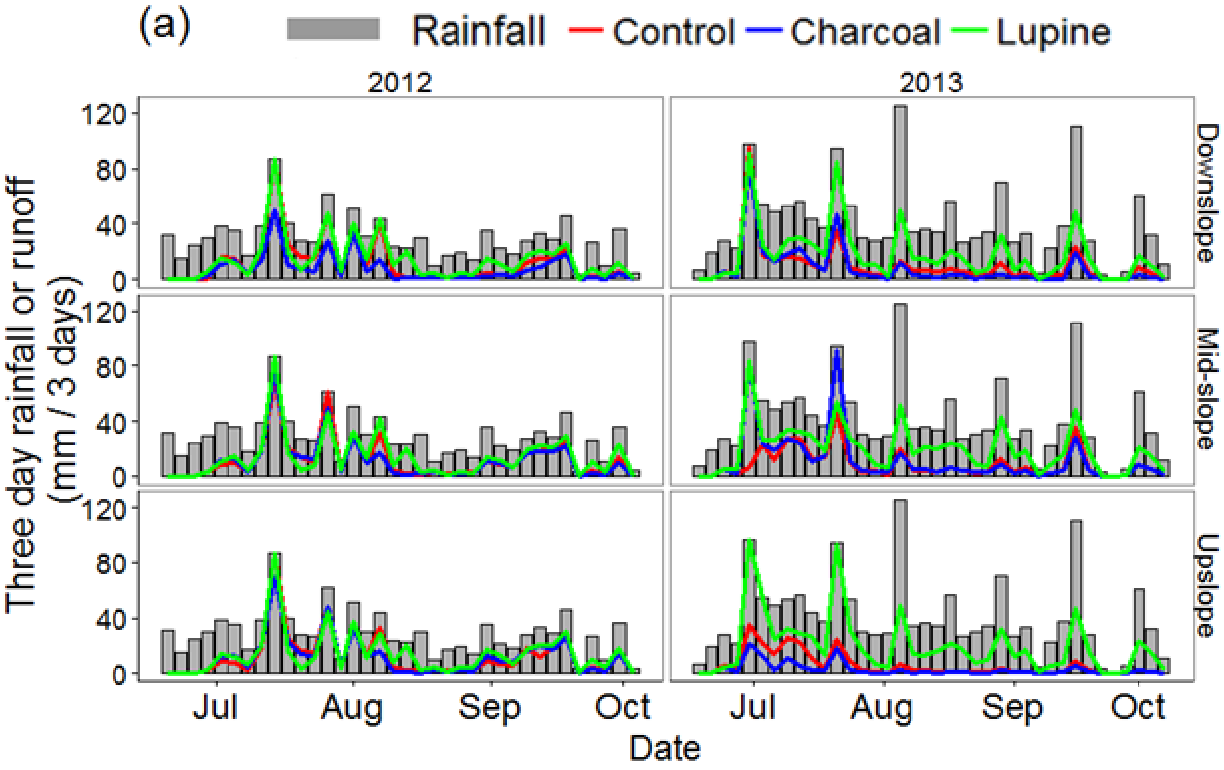
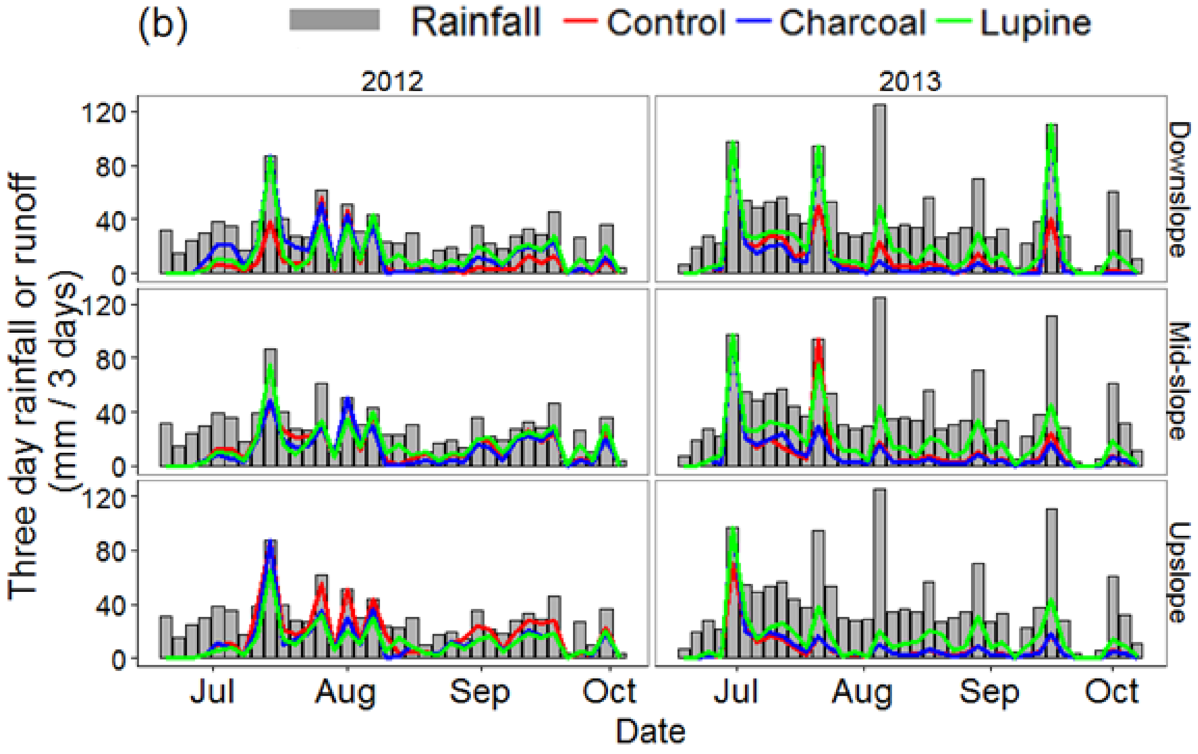


Figure 1. Location of the Anjeni watershed in the Amhara region in Ethiopia (a), with the location of downslope transects and runoff plots indicated in (b) and (c – not to scale). Dashed lines in (c) are elevation contours. Three treatments were applied: barley without soil amendment (control) was grown on plots 2,4,7,12,15,18,21,23; barley with charcoal amendment was grown on plots 1,6,8,11,13,17,20,22; lupine without soil amendment was grown on plots 3,5,9,10,14,16,19,24. Soil and spatial attributes of plots are presented in Table 1.

Figure 2. Groups of three runoff plots setup at downslope position along Transect 2. Water storage tanks are positioned below the plots, on the downslope side of the terrace edge. Dark brown lines above runoff plots are traditional conservation practices (drainage ditches) constructed by farmers to channel out excess water from fields.


(a)
Rainfall
Control
Charcoal
Lupine
2012
2013
Downslope
Mid-slope
Upslope
Three day rainfall or runoff (mm / 3 days)
0
40
80
120
Jul
Aug
Sep
Oct
Date


(b)
Rainfall
Control
Charcoal
Lupine
2012
2013
Downslope
Mid-slope
Upslope
Three day rainfall or runoff (mm / 3 days)
0
40
80
120
Jul
Aug
Sep
Oct
Date

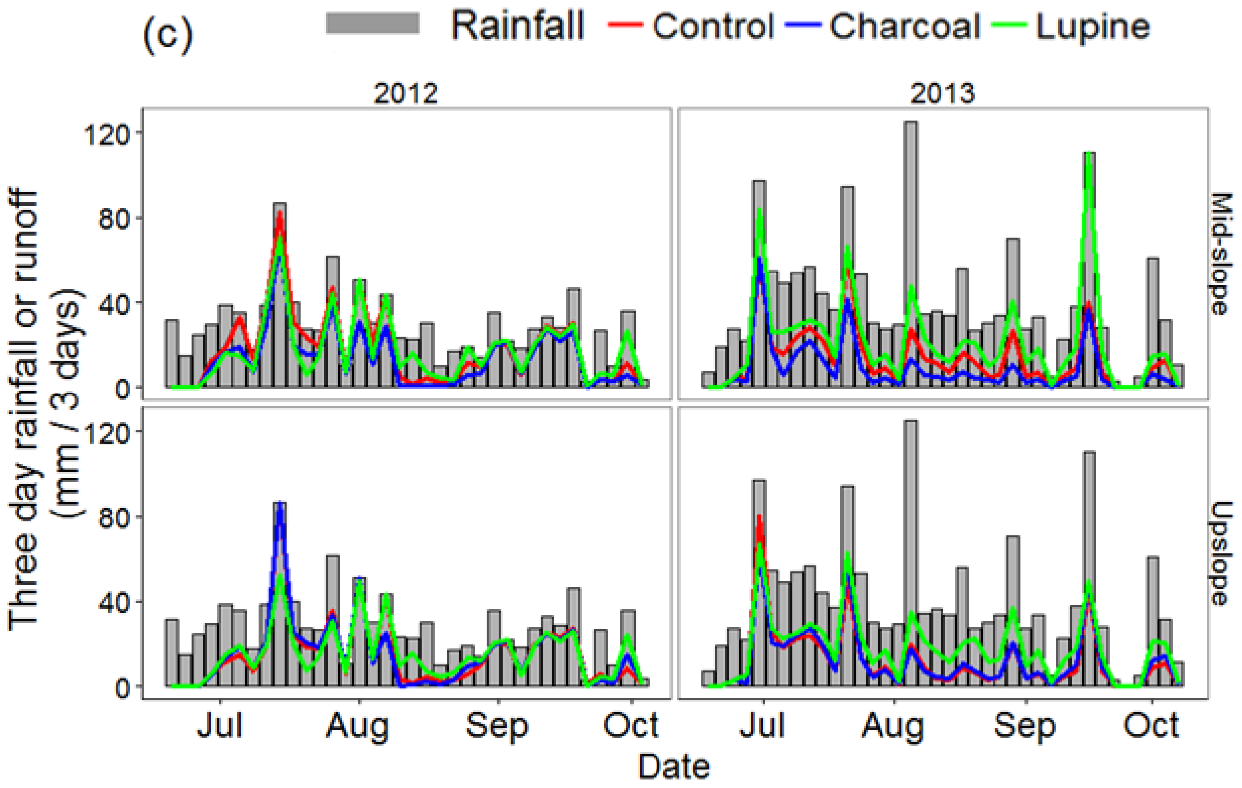


Figure 3. Three day rainfall and adjusted 3-day runoff depths (aggregated over 3 days) from individual plots at different slope positions along Transect 1 (a), Transect 2 (b), and Transect 3 (c)

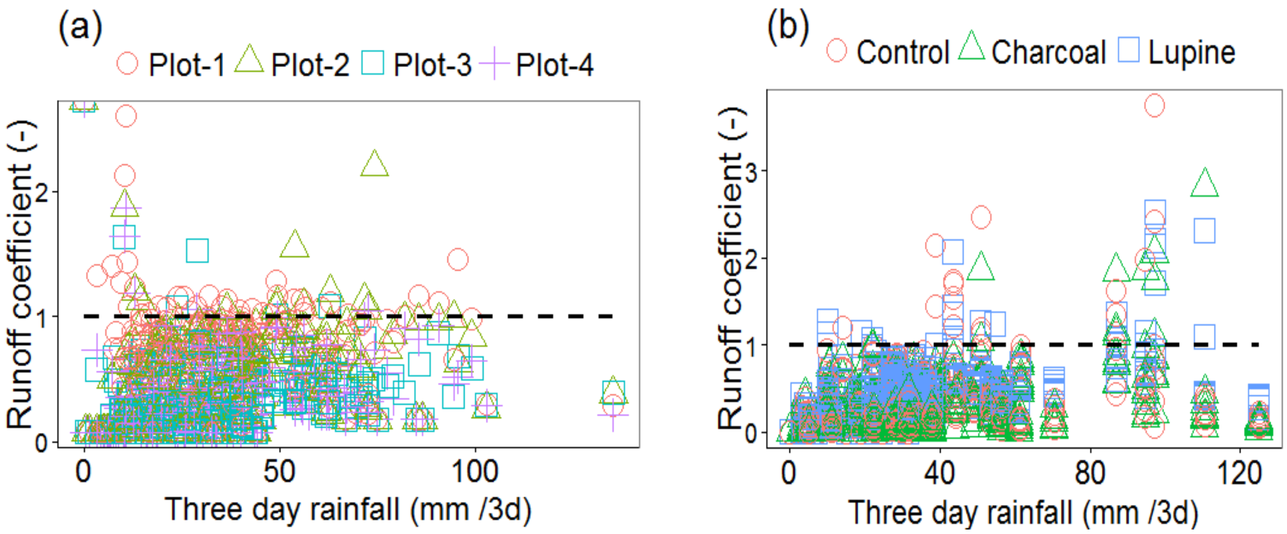


Figure 4. Runoff coefficients computed from observations from long-term monitoring plots (3 m length, 1 m width) (a) and plots in 2012 and 2013 (b). The black dashed horizontal line represents $R_{coef} = 1$

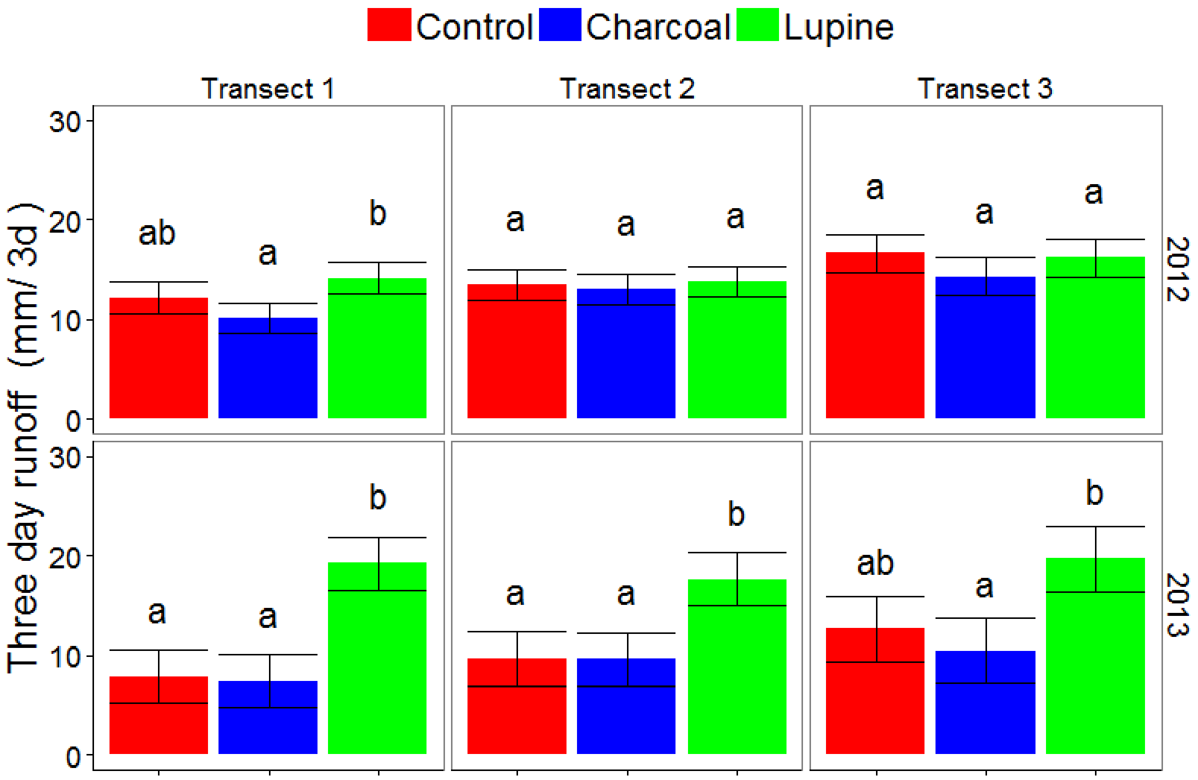


Figure 5. Effect of charcoal amendment and deep-rooted lupine crop on plot-scale runoff (3-day total) for each transect and year. Treatments not sharing the same letter within an individual transects for a given year are significantly different at $p < 0.05$.

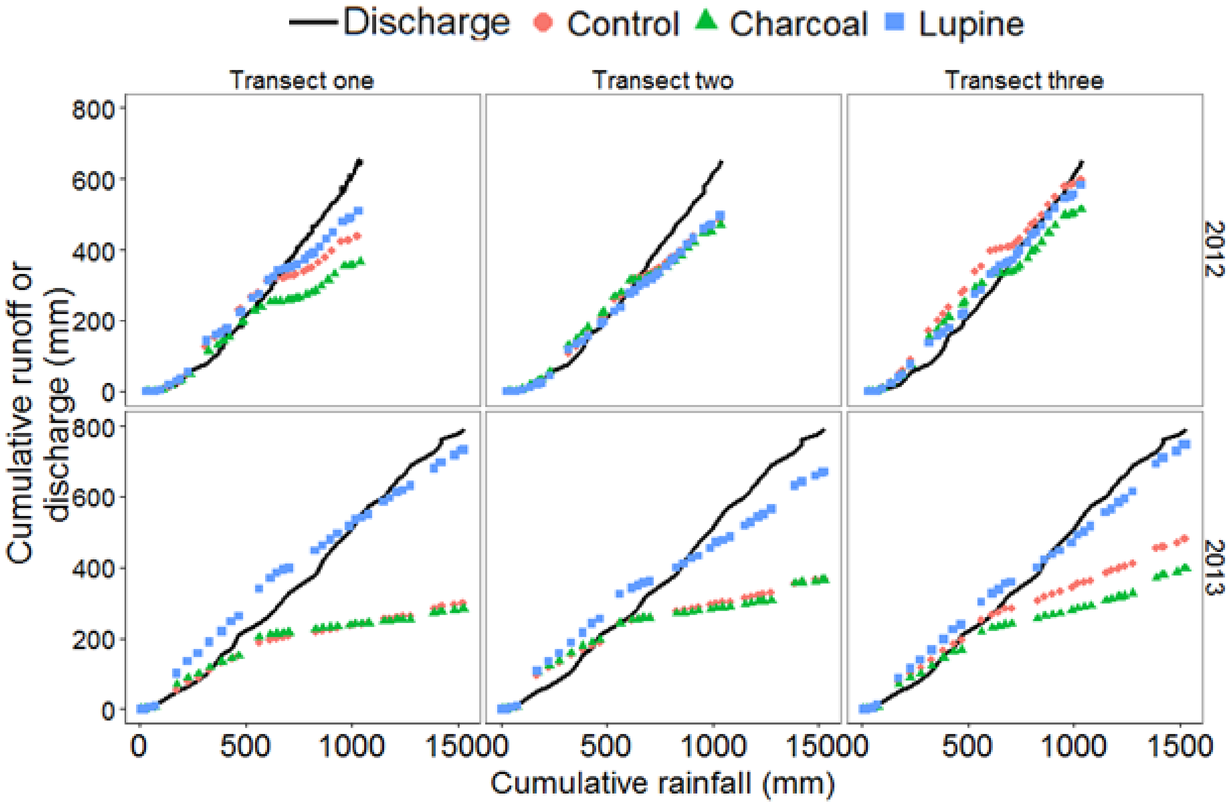


Figure 6. Cumulative rainfall vs. cumulative runoff (from control, charcoal, and lupine plots along three transects) and discharge at the watershed outlet, for 2012 and 2013.

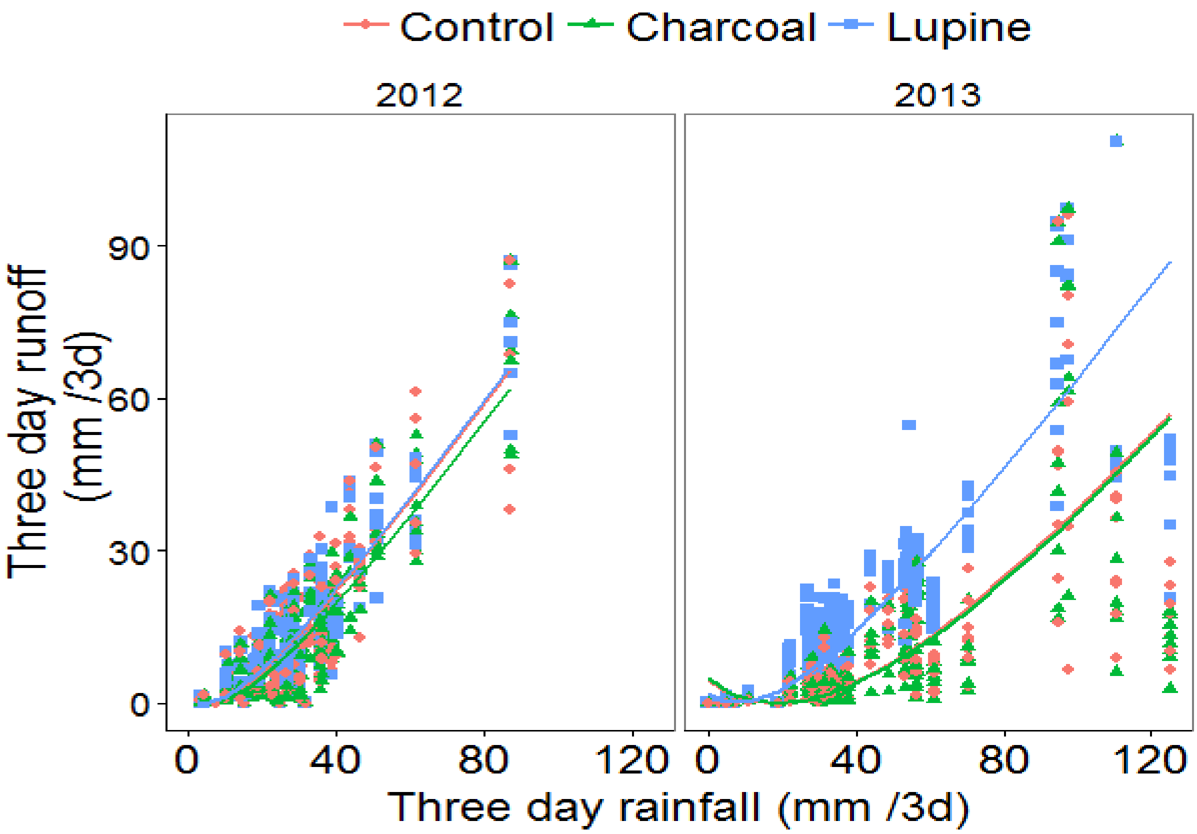


Figure 7. Effect of charcoal amendment and deep-rooted lupine on 3-day soil water storage: three day rainfall vs. three day runoff with SCS-CN fitted lines fitted using Steenhuis et al. (1995) SCS-CN equation. Fitted 3-day storages values in 2012 were: 22, 26, 21 mm for control, charcoal, and lupine, respectively; and in 2013: 93, 94, and 40 mm for control, charcoal, and lupine, respectively.