

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

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10
11 **Abstract**

12 Placement and hence performance of many soil and water conservation structures in
13 tropical highlands has proven to be challenging due to uncertainty of the actual location of
14 runoff-generating areas in the landscape. This is the case especially in the (sub) humid areas
15 of the Ethiopian highlands, ~~therefore~~ resulting in limited success of such conservation
16 measures. To improve understanding of the effect of land use on spatial and temporal runoff
17 patterns in the Ethiopian highlands, we monitored runoff volumes from 24 runoff plots
18 constructed in the 113 ha Anjeni watershed, where historic data of rainfall and stream
19 discharge were available. In addition, we assessed the effectiveness of charcoal amendment
20 and crop rooting depth in reducing runoff, ~~in which we~~ compared the effect of lupine (a
21 deep-rooted crop) to that of barley. Daily rainfall, surface runoff, and root zone moisture
22 contents were measured during the monsoon seasons of 2012 and 2013 (with all plots being
23 tilled in 2012, but only barley plots tilled in 2013). In addition, long-term surface runoff from
24 four plots and outlet discharge data from the research site (1989-1993) ~~was~~ analyzed and
25 compared with our observations. Results showed that the degree of soil degradation and soil
26 disturbance (tillage) were significant factors affecting plot-scale runoff responses. As
27 expected, runoff was greater from more degraded soils. Overall, under the commonly

1 applied lupine cropping practice, runoff was higher than under the commonly applied barley
2 cropping practice. ~~Especially~~, considerable difference was observed during smaller rainfall
3 events (approximately < 20 mm) in 2013, when lupine plots (non-tilled) had greater runoff
4 than barley plots (tilled). Charcoal tended to decrease runoff but results were not significant.

5

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

7

8 **1 Introduction**

9 Performance of many soil and water conservation structures in the tropical highlands has
10 proven to be challenging due to uncertainty of their placement. Ideally, the location of
11 conservation structures should be directly related to where runoff is generated in the
12 landscape. Evaluating the effectiveness of landscape modifications is especially timely in the
13 Ethiopian highlands where the Ethiopian government is implementing land management
14 practices to both increase rainwater productivity in the degrading landscape, and increase
15 the life of hydroelectric power plants such a as the Grand Ethiopian Renaissance Dam on the
16 Blue Nile near Sudan (Humphreys et al., 2008; MOFED, 2010; MOA, 2013; Dagnew et al.,
17 2015; Chen and Swain, 2014). The ultimate goal of these actions is to increase prosperity and
18 assure food security for the rapidly increasing population (Hurni, 1988a, 1999; Nyssen et al.,
19 2009b). Most areas in the Ethiopian highlands receive high amounts of annual precipitation,
20 aiding soil leaching and promoting land degradation, however, water scarcity is common for
21 8-9 months every year (Amsalu and Graaff, 2006; Bewket and Sterk, 2005; Biazin et al., 2011;
22 Hugo et al., 2002). Rainfall distribution is variable not only spatially but also temporally
23 (Biazin et al., 2011; Bitew et al., 2009; McHugh et al., 2007). To counteract this problem of
24 periodic water scarcity, soil and water conservation practices are ubiquitous in the Ethiopian
25 highlands. However, surprisingly, most non-traditional soil and water conservation practices
26 are ineffective because their placement neither addresses drivers of runoff nor considers
27 spatial and temporal variation of runoff in a landscape.

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

~~17 In contrast, (Bewket and Sterk, 2005; Taddese, 2001)~~ reported that infiltration excess runoff
18 mechanism was dominant mainly based on analysis of the hydrograph at the outlet focusing
19 on land use change. Land use is important because it affects soil infiltration capacity. For
20 example, several studies reported that land use change from natural vegetation to
21 agricultural lands increased overland flow during the rainy monsoon phase, and reduced
22 base flows during the dry phase in this region (Bewket and Sterk, 2005; Feoli et al., 2002;
23 Taddese, 2001; Zeleke, 2000). In other countries as well, clearing of forests resulted in
24 decreased infiltration rates especially in the sub soils (Hanson et al., 2004; Mendoza and
25 Steenhuis, 2002; Nyberg et al., 2012; Shougrakpam et al., 2010). Identification of the
26 dominant runoff mechanism in relation to not only topography but also land use in the
27 Ethiopian Highlands is therefore essential for development of effective soil and water
28 conservation methods in this region.

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

9 Another solution for improving soil physical and hydraulic properties is by increasing the
10 organic carbon pool through the addition of biochar or charcoal (Abel et al., 2013; Asai et al.,
11 2009; Bayabil et al., 2015; Glaser et al., 2002; Kameyama et al., 2010; Karhu et al., 2011;
12 Laird et al., 2010; Spokas, 2010). Biochar and charcoal incorporation have been reported to
13 improve soil bulk density (Abel et al., 2013; Laird et al., 2010), porosity (Abel et al., 2013;
14 Atkinson et al., 2010), and hydraulic conductivity (Asai et al., 2009). Although both biochar
15 and ~~charcoal amendments~~ can be effective in improving soil hydraulic properties, Bayabil et
16 al. (2015) argued charcoal to be a more viable solution for rural Africa because it is widely
17 produced in most rural areas of Africa (Lehman et al., 2006) and therefore more accessible
18 to smallholder farmers than biochar. The analysis above shows that deep-rooted crops and
19 additions of charcoal could ameliorate soil and water losses in a degrading landscape.
20 However, field research on the effectiveness of these two management practices in a
21 tropical highland setting with monsoon rainfalls ~~do not exist to our knowledge.~~

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

26 The research was carried out in the Anjeni watershed in the Ethiopian highlands in 2012 and
27 2013. Twenty-four runoff plots were established along three transects going upslope in sets

1 of three at each landscape position. Each set of three plots had one plot in which lupine was
2 planted and two plots with barley - of which one was amended with charcoal.

3

4 **2 Materials and Methods**

5 **2.1 Study site**

6 The Anjeni watershed is situated in the northwestern part of Ethiopia (Fig. 1), and was
7 selected because of the availability of historic discharge records at the outlet and from
8 runoff plots inside the watershed. The watershed has a drainage area of 113 ha and is one of
9 the experimental watersheds established under the Soil Conservation and Research Program
10 (SCRP) of the Ministry of Agriculture of Ethiopia in collaboration with the Swiss Agency for
11 Development and Cooperation (SDC; Hurni et al., 2005). Its gauging station is located at
12 10°40' N, 37°31'E.

13 The watershed has a unimodal rainy season that lasts from mid-May to mid-October, with a
14 mean annual rainfall of 1690 mm yr⁻¹. The topography of Anjeni is typical of Tertiary volcanic
15 landscapes: it has been deeply incised by streams, resulting in the current diversity of
16 landforms (SCRP, 2000) with elevation between 2407 and 2507 m (Herweg and Ludi, 1999).
17 The soils of Anjeni have been developed from the basaltic Trapp series of Tertiary volcanic
18 eruptions and is similar to most parts of central Ethiopia with dominant soils being Alisols
19 (41.5 ha), Nitisols (23.8 ha), Cambisols (18.9 ha) and Regosols (10 ha) covering more than
20 80% of the watershed (Fig. A1 in Supplementary material A; SCRCP, 2000; Zeleke, 2000). The
21 deep Alisols cover the bottom part of the watershed; moderately deep Nitisols cover the
22 mid-transitional, gently sloping parts of the watershed, while the shallow Regosols and
23 Leptosols cover the high, steepest part of the watershed (Zeleke, 2000). Fields are
24 intensively cultivated for crop production and a large proportion of the watershed is
25 degraded (SCRP, 2000). In 1986, graded fanya-juu structures were installed for soil and
26 water conservation, resulting in terraces across the landscape (SCRP, 2000).

1 2.2 Experimental setup

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

16 At the start of the 2012 growing season (June), all plots were plowed and two plots were
17 seeded with barley. Effects of charcoal amendment were assessed by amending one of the
18 barley plots with charcoal during plowing, the non-amended barley plot serving as a control
19 treatment. Effects of crop rooting depth were assessed by seeding the third plot at each
20 transect location with the deep-rooted lupine (*Lupinus albus* L.) crop, with again the non-
21 amended barley plot serving as a control treatment. Barley and lupine crops were assigned
22 randomly to plots; and the same crop was maintained on each plot for two years (2012 and
23 2013). These crops were chosen as they are widely grown throughout the Ethiopian
24 highlands. Farmers grow lupine as intercrop with cereals (e.g. barley and wheat) or as the
25 sole crop on marginal lands without additional farm inputs. Barley has a fibrous root system,
26 while lupine has deep-rooted system and is widely grown on marginal lands for its
27 leguminous nature. Because of their contrasting root architecture, lupine and barley are
28 expected to have contrasting effects on soil hydraulic properties.

1 **2.3 Agronomic practices on plots**

2 Barley, one of the predominantly grown crops in the watershed (SCRIP, 2000), was grown
3 following local farmers' cultural practices and thus barley plots were tilled in both 2012 and
4 2013. While lupine seedbeds are typically not tilled, tillage was done in 2012 because the
5 plots were originally designated to be sown with alfalfa, another deep rooted crop **though**
6 **one that is always tilled**. When the alfalfa **did not establish successfully**, lupine was sown on
7 the tilled soil **shortly after**. The **next growing season**, in 2013, only barley plots were tilled
8 and seeded, while lupine seeds were **seeded** on untilled plots (**the** more common practice in
9 the area). Also in line with farmer practices, all barley plots were fertilized with 100 kg/ha Di-
10 Ammonium Phosphate (DAP; 46% Nitrogen, 23% Phosphorous, and 21% Potassium) during
11 seeding, and 100 kg/ha of Urea (100% Nitrogen) one month after sowing. **Lupine** plots were
12 not fertilized. **Both fertilization and tillage are different for lupine and barley treatments**
13 **during the two-year study period (2012 and 2013)**. **To distinguish crop effect (barley and**
14 **lupine crops grown under common practices) from tillage effects, data from the two-year**
15 **study was therefore analyzed for each year separately.**

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

21 **2.4 Plot installation and data collection**

22 While crop and charcoal treatments were applied to 9 m² (3 m wide, 3 m long) areas, runoff
23 was only measured on 4.5 m² plots (1.5 m wide, 3 m long) **inside these areas, to allow for**
24 auxiliary measurements (e.g. soil moisture **content) to be taken adjacent to instead of inside**
25 **the runoff plots and thereby avoid trampling and soil disturbance inside the plots**. For this,
26 runoff plot boundaries were installed 0.75 m inside the seeded area from both sides. As
27 illustrated in Fig. 2, all runoff plots were constructed at the level bottom ends of terraces.

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

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

17 2.5 Long-term plot runoff and river discharge data

18 In addition to runoff data from the 24 newly installed plots, we obtained long-term data
19 from the Amhara Regional Agricultural Research Institute (ARARI). The data consists of
20 runoff from four long-term 3 m²-plots (3 m length, 1 m width; Fig. 1b, 'Permanent plots'),
21 and discharge at the outlet of the watershed (Fig. 1b, 'Gauging station'). To place our newly
22 installed plot-scale runoff observations into a broader and longer-term context, we
23 compared our data with historic plot-scale runoff data available in the watershed for the
24 years 1989 through to 1993. These data were measured on the four 3 m² plots that had
25 slopes of 12, 16, 22, and 28%. The 16% sloped plot was on grassland, while the other three
26 plots were cultivated with food crops (e.g. barley and wheat; SCRP, 2000). Discharge was
27 measured continuously since 1984 (two years before the installation of the '*fanya juu*'
28 conservation structures) as part of the ongoing hydrological and erosion monitoring

1 activities (SCRIP, 2000), and we used discharge data for the 2012 and 2013 monsoon seasons
2 to compare our plot-scale observations with watershed-scale patterns. Rainfall data
3 obtained from the watershed (Fig. 1b, 'Weather station') was available for the same period.

4 **2.6 Data quality control and aggregation**

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

$$7 \quad R_{coef} = \frac{runoff}{rainfall} \quad (1)$$

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

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

24 To reduce the impact of delayed peak runoff, we therefore decided to aggregate rainfall and
25 runoff data over a 3-day period, resolving most of the high runoff coefficients. Yet 47 events
26 (2.6% of total) observed on the 24 plots and recorded on 11 observation days spread over

1 the two-year study period were left with $R_{coef} > 1$ (Fig. C1 in Supplementary material C).
2 Further data aggregation, even on a weekly interval, did not solve these high runoff events.
3 One of the options to deal with such outlier data points would be excluding observations
4 from data analysis. However, to avoid bias between treatments and spatial locations, all
5 observations from those 11 days would need to be discarded for all (24) plots, which would
6 result in discarding 264 observations. Losing this many observations (14.9% from 1777 total
7 3-day observations) would considerably reduce the power of our analysis. Thus, to achieve a
8 balance between the number of runoff events remaining for analysis and the objective to
9 analyze large runoff events, the remaining high runoff events ($R_{coef} > 1$) after data
10 aggregation on 3-day intervals, were therefore assigned a maximum value that equals the 3-
11 day rainfall amount – resulting in a runoff coefficient of 1. As such, adjusted 3-day aggregate
12 runoff data were used for all statistical data analyses in this paper.

13 In addition to this analysis of runoff coefficients, to assess the differences in soil water
14 storage between plots, the SCS curve number was fitted to three-day rainfall and three
15 day adjusted runoff data for each treatment type and cropping year using Eq. 2. The SCS
16 equation was effectively used in predicting rainfall-runoff relationships in the Ethiopian
17 highlands (Tilahun, 2012) and for different regions in the USA and Australia (Steenhuis et al.,
18 1995).

$$19 \quad Q = \frac{(P_e - 0.2S)^2}{(P_e - 0.8S)} \quad (2)$$

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

22 **2.7 Statistical analysis**

23 Data analysis aimed at detecting differences in runoff response between land uses and
24 spatial locations (transects and elevation ranges) during the two-year study period.
25 Statistical data analysis was performed using R (R Development Core Team 2010). To
26 determine the effect of charcoal amendment and deep-rooted lupine as well as spatial

1 location with different soil degradation levels (transects) and slope position, a linear mixed
2 effect model was fitted using the 'nlme' package in R. In this model, crop type, slope
3 position, and transect were used as fixed factors, and individual plots as random factors. For
4 fixed factors with significant effects, post hoc mean comparison tests were performed using
5 the 'lsmeans' package in R to identify group pairs with significant difference.

6 **3 Results and Discussion**

7 **3.1 Plot-scale rainfall-runoff response and effect of charcoal amendment and deep-** 8 **rooted lupine**

9 The adjusted runoff depths during the monsoon seasons of 2012 and 2013 are shown in Fig.
10 3 for all eight groups of plots along the three transects. In 2013, runoff response from lupine
11 plots was considerably greater than barley plots, while in 2012, runoff tended to be more or
12 less similar for all treatments. In addition, a summary of observed rainfall and original (non-
13 adjusted) runoff data recorded from all 24 plots is presented in Table 2. Average monthly
14 rainfall in 2012 was similar to the 5-year average (based on 1989-1993 observations; Fig. D1
15 in Supplementary material D), while in 2013 it exceeded the 5-year average.

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

1 that in areas with complex topography (like the Anjeni watershed), extrapolation of point
2 rainfall observations to larger scales **could be less accurate.**

3 **3.2 Plot runoff and outlet discharge**

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

15 Comparison of plot-scale cumulative runoff (**colored lines, Fig. 6**) and cumulative river
16 discharge observed at the watershed outlet (**black line, Fig. 6**) with cumulative rainfall
17 indicated that approximately 100 mm of cumulative rainfall was needed before runoff was
18 initiated from all plots. In general, during the start of the monsoon season (until 500 mm
19 cumulative rainfall in Fig. 6), plot-scale runoff response generally exceeded watershed-scale
20 discharge response. Nevertheless, as the rainy season progressed, starting from the middle
21 of August and at approximately 500 mm cumulative rainfall, watershed-scale discharge
22 started to exceed plot-scale runoff depths (**with the exception of the lupine plots in 2013,**
23 **see below**). The difference between plot-scale runoff and outlet discharge **during the onset**
24 **of the monsoon season** indicates that detention storage at a watershed scale occurs; while
25 the difference **between the plot and watershed scale** later in monsoon season **is caused by**
26 **base flow** at the watershed outlet. This is consistent with previous observations by Tilahun
27 et al. (2013 a, b) and Bayabil et al. (2010) **who observed that** initially, the runoff from the

1 hillsides infiltrates on lower slope position while later in the season these bottom lands start
2 to contribute both subsurface flow and surface runoff.

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

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

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

7 **4 Conclusions**

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

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

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

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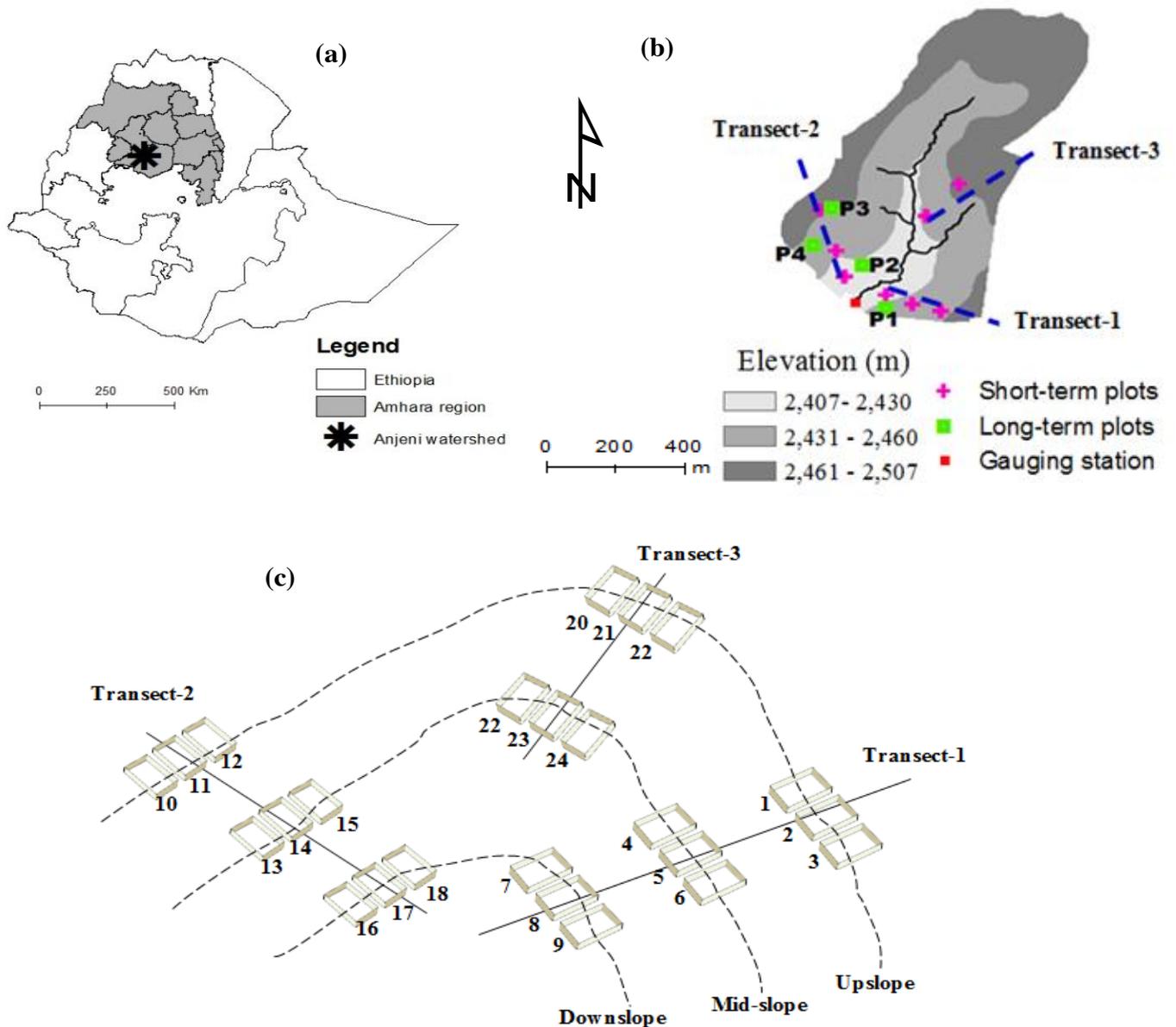
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26

1 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

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



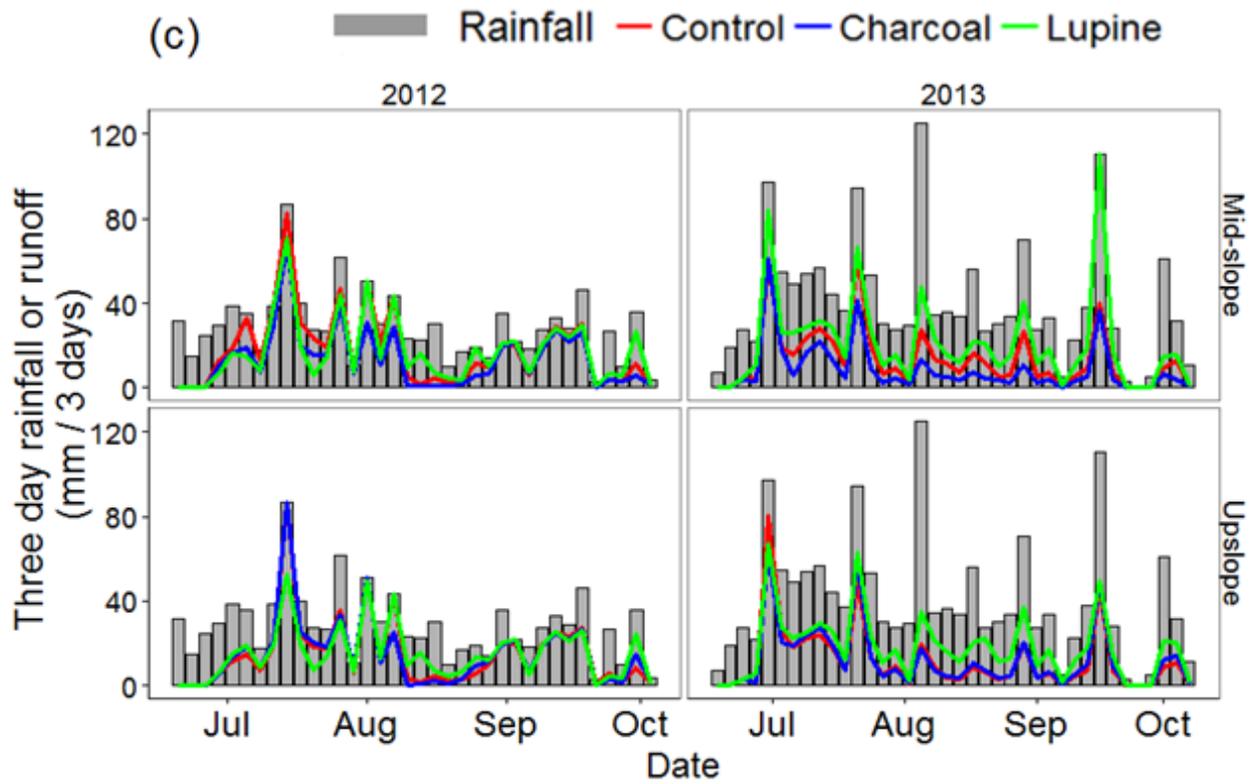
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 2 **Figure 1.** Location of the Anjeni watershed in the Amhara region in Ethiopia (a), with the
 3 location of downslope transects and runoff plots indicated in (b) and (c – not to scale).
 4 Dashed lines in (c) are elevation contours. Three treatments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



1

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

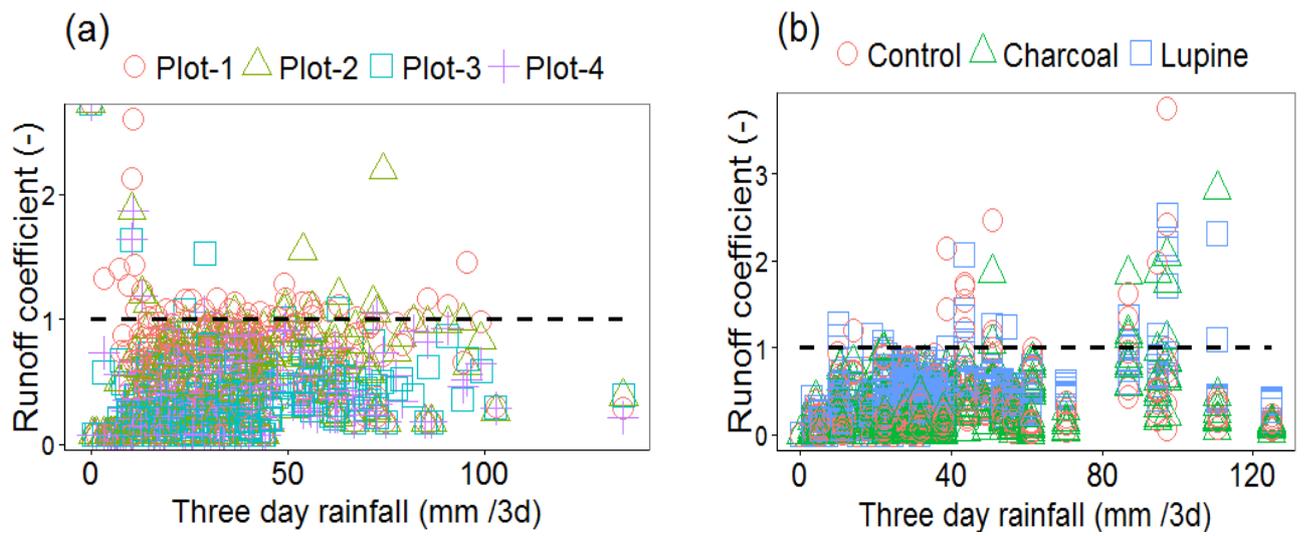
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 2 Figure 3. Three day rainfall and adjusted 3-day runoff depths (aggregated over 3 days) from
 3 individual plots at different slope positions along Transect 1 (a), Transect 2 (b), and Transect
 4 3 (c)

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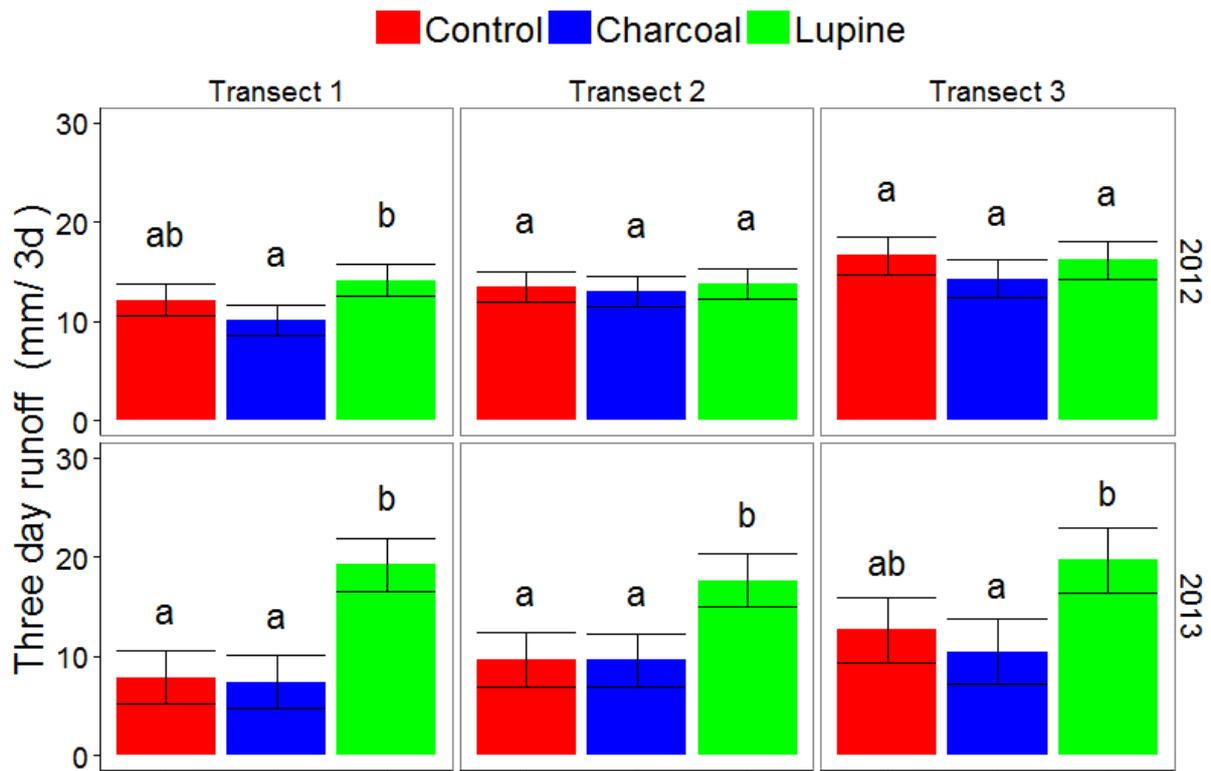
3 Figure 4. Runoff coefficients computed from observations from long-term monitoring plots
4 (3 m length, 1 m width) (a) and plots in 2012 and 2013 (b). The black dashed horizontal line
5 represents $R_{coef} = 1$

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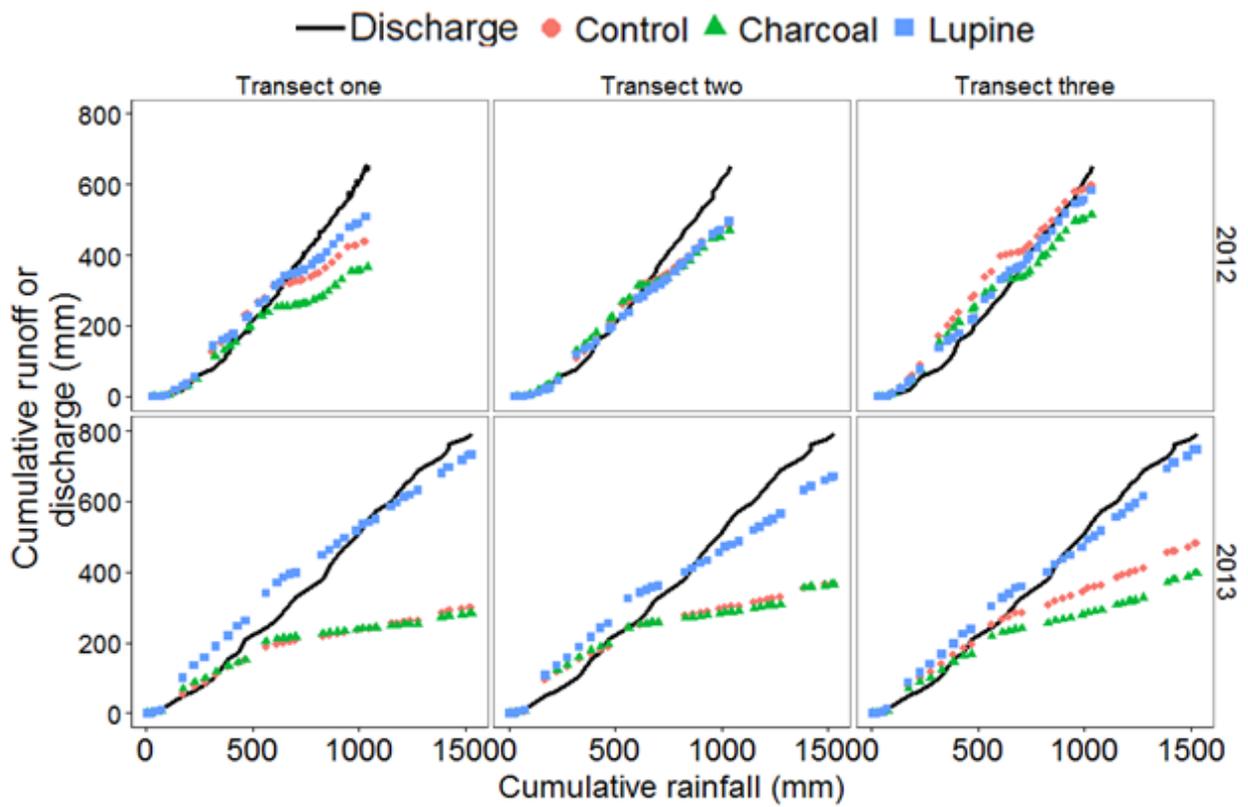
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 2 Figure 5. Effect of charcoal amendment and deep-rooted lupine crop on plot-scale runoff (3-
 3 day total) for each transect and year. Treatments not sharing the same letter within an
 4 individual transects for a given year are significantly different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

5

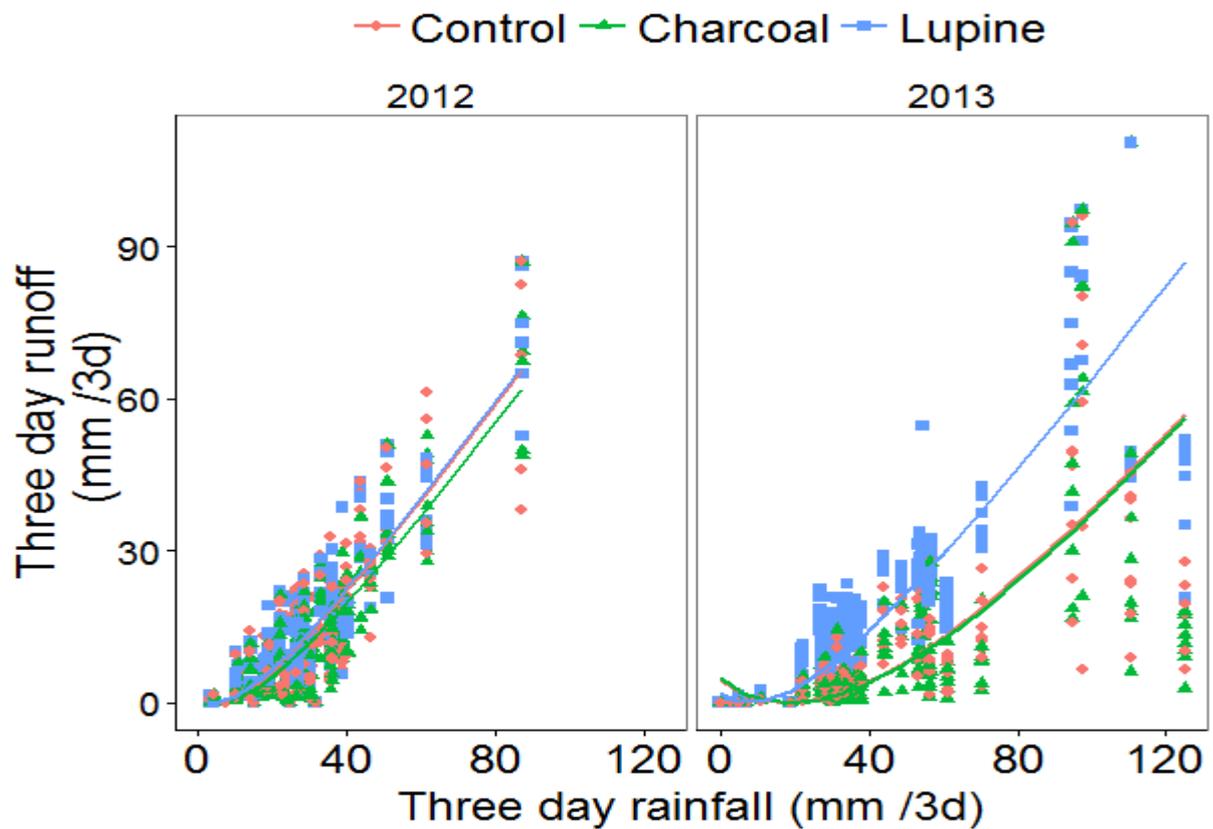
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2 Figure 6. Cumulative rainfall vs. cumulative runoff (from control, charcoal, and lupine plots
 3 along three transects) and discharge at the watershed outlet, for 2012 and 2013.

4



1
 2 Figure 7. Effect of charcoal amendment and deep-rooted lupine on 3-day soil water storage:
 3 three day rainfall vs. three day runoff with SCS-CN fitted lines fitted using Steenhuis et al.
 4 (1995) SCS-CN equation. Fitted 3-day storages values in 2012 were: 22, 26, 21 mm for
 5 control, charcoal, and lupine, respectively; and in 2013: 93, 94, and 40 mm for control,
 6 charcoal, and lupine, respectively.

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