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Sediment yield at southwest Ethiopia's forest frontier

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Abstract

Deforestation is one of the major factors affecting soil erosion in tropical regions but to what extent does the crop growth in deforested areas protect the land from erosion? We evaluated the effect of deforestation on suspended sediment yields on the scale of zero-order catchments by contrasting five paired small forest and cropland catchments at Ethiopia's southwestern forest frontier. Suspended sediment samples were collected from nine San Dimas flumes and one V-notch weir installed in catchments draining the natural forest and cropland, at different altitudes. The suspended sediment data were collected from June 8 to October 30, 2013 and 2014. The suspended sediment yields of both land-use types was strongly correlated with the corresponding runoff discharge. The results show that the average seasonal suspended sediment yields from cropland (17.0 ± 7.6 Mg ha^{-1}) is four times higher than from the paired forests (4.0 ± 1.9 Mg ha^{-1}). High sediment yields from forests are related to livestock grazing, but forests still have an important role in the protection of the surface soil from erosion at southwest Ethiopia's forest frontier. Land management in southwestern Ethiopia's highlands will need a strong change in paradigm, in which the overall belief in the recently imported *mahrasha* ard plough is abandoned, oxen and other cattle decreased in number and kept in homesteads, the forests being protected from human and livestock interferences and the open farmlands turned into agroforestry. Such an approach is still possible as all required elements are available in the landscape.

Keywords: Deforestation; Sediment yield; Soil loss; Afromontane forest, Tropics, Ethiopia.

1. Introduction

Deforestation is a global phenomenon, particularly severe in tropical regions (Song *et al.*, 2018). There, it considerably augments the rate of soil loss, mainly by increasing the soil's vulnerability to erosion (e.g. removal of protective vegetation, degradation of soil structure) and by higher magnitudes of splash, sheet, rill and gully erosion (Lal, 1987). Deforestation has been a major factor leading to land degradation in Ethiopia (Nyssen *et al.*, 2004). Currently, the closed Afromontane forest of southwestern Ethiopia (Fig. 1a) is facing deforestation. For example, the share of the closed natural forest declined by 24-28% in the Bonga Forest; 23% in the Sheko Forest; 15% of the Bench, Keffa and Sheka Forests, while agriculture land increased by 56% in Bonga, 14% in the Bench, Keffa and Sheka Forests between 1973 and 2005 (Kassa *et al.*, 2018).

This deforestation trend had several environmental and financial impacts on the region. Most notably, the Dembi hydro-electric power plant was decommissioned, due to the reduction of the reservoir's water storage capacity because of silting up (EEPCO, 2000). Furthermore, a water treatment plant has been forced to spend additional resources and time for water treatment, mainly due to the presence of high concentrations of suspended sediment in the water (MACWE, 2014). Thus, the environmental degradation emanating from deforestation is not only of concern to farmers in the catchment but also to the downstream communities benefiting from the water resources. Management of the affected areas requires understanding the extent and the impact of deforestation, for which our knowledge remains poor concerning tropical mountain regions worldwide.

Even though previous studies have pointed to the impact of deforestation on soil loss in the study area, the intensity of soil loss may vary depending on land use and land management practices, the duration of the cultivation period, climate, runoff volume and topography (Girmay *et al.*, 2009; Mekuria *et al.*, 2012; Kassa *et al.*, 2017a). However, no systematic studies have been done in order to quantify the impact of deforestation on sediment yields at the forest frontier in southern Ethiopia, also taking into account the variability in local catchment characteristics. Particular to tropical areas, crops grow rapidly in dense stands (Fig. 1b), an thus limit (at least temporally) the effect of destroyed forest root mats on erosion intensification (De Baets *et al.*, 2007; Ghidey & Alberts, 1997; Mamo & Bubenzer, 2001) . Furthermore, the soil loss in the Afromontane forest belt has hardly been studied and there are very few field measurements at the catchment scale, i.e. between the erosion plots and whole river basins in Africa (Vanmaercke *et al.*, 2014).

In order to increase our understanding of the impact of deforestation on the scale of small catchments in tropical mountains, we quantified suspended sediment yield in ten zero-order catchments at three altitudinal ranges in the Gacheb catchment of southwest Ethiopia. The objective of this study was to evaluate the effect of deforestation on suspended sediment yields between forest and cropland at a small catchment scale in the White Nile basin of Ethiopia and to get an insight to what extent the dense crop cover does (not) compensate for the lost tree cover and the corresponding soil strengthening by the root mat.

2. Materials and methods

2.1 Study area

The study area is the upper Gacheb catchment, located in the headwaters of the White Nile in southwestern Ethiopia. The altitude ranges between 1,000 and 2,600 m a.s.l. (Fig. 2). The underlying Precambrian basement formations comprise a variety of metamorphosed sedimentary and intrusive rocks. These Precambrian basement rocks are covered by Mesozoic marine strata and Tertiary basalt traps (Westphal, 1975; Mengesha *et al.*, 1996).

The annual rainfall pattern is unimodal with a rainy season from mid-March to mid-November. The average annual rainfall in Mizan Teferi (1,440 m a.s.l.) amounts to 1,780 ± 270 mm yr^{-1} and the annual reference evapotranspiration is 1,259 ± 12 mm yr^{-1} (FAO, 2006); the average air temperature ranges from 13 to 27°C (Tadesse *et al.*, 2006). The harmonized soil map of Africa (Dewitte *et al.*, 2013) indicates that Leptosols are dominant on crests, while Nitisols are dominant on the hill slopes (lower, middle and upper parts), to which Alisols and Cambisols are locally associated. Fluvisols are found in the flat valley bottoms where meandering rivers occur. The topsoils in the studied catchments typically contain 8.0-8.1% OC under forest and 5.3-5.5% OC in cropland (Kassa *et al.*, 2017b). The soil texture is again quite homogeneous per land-use type: clay-silt-sand proportions of 25-50-25% in the cropland and 35-50-15% in the forest (Kassa *et al.*, 2017b). Three main land-use types exist in this region: the Afromontane forest, the agroforestry zones particularly around the villages and the open field cropland (Kassa *et al.*, 2018).

The Afromontane forest vegetation of the Gacheb catchment is composed of *Aningeria adolfi-friederici* Engl., *Croton macrostachyus* Hochst. ex Delile, *Hagenia abyssinica* Willd., *Cordia africana Lam.*, *Prunus africana* Hook.f.Kalkman, *Millettia ferruginea* Hochst. Baker, *Polyscias fulva* Hiern.Harms, *Albizia gummifera* J.F.Gmel C.A.Sm., *Bridelia micrantha* Hochst.Baill. at the upper stratum of the vegetation structure, integrated with *Grewia ferruginea* Hochst. ex A.Rich, *Vernonia amygdalina* Delile. *Cyathe amanniana* and *Ricinus communis L.* at the lower stratum.

The agroforestry land of the Gacheb catchment is composed of *Coffea arabica* L., as a cash crop integrated with food crops such as false banana (*Ensete ventricosum* Welw. Cheesman), banana (*Musa sapientum* L.) and taro (*Colocasia esculenta* L. Schott) and spices like korarima (*Aframomum corrorima* Braun). Moreover, various fruit trees such as mango (*Mangifera indica* L.), avocado (*Persea americana* Mill.), papaya (*Carica papaya* L.) and orange (*Citrus sinensis* L. Osbeck) are also integrated in the farming system. Furthermore, native trees like *Albizia gummifera* J.F.Gmel. C.A.Sm., *Cordia africana* Lam. and *Millettia ferruginea* Hochst. Baker, are kept for shade, fodder, firewood, medicinal value and soil fertility maintenance.

In the croplands maize (*Zea mays*) is dominant, followed by taro (*Colocasia esculenta* L.). Beans grow as a mixed crop with maize and as a single crop in the uplands and sorghum may be added later on locations where maize cropping failed. Taking benefit of reliable rains at the onset of the rainy season, maize is sown in May, after 2-3 tillage operations with the oxen-drawn Ethiopian *maresha* ard plough and 1-2 by hand tools that generally take place in April (Table 1). Given the high and dense growth of maize, the cropped fields are not weeded after the crop is well established and a strong herb undergrowth develops on cropland, which -after crop harvesting- is used as livestock feed in the cropland (Fig. 1b).

2.2 Experimental set-up and data collection

Rainfall and runoff

Five rain gauges were installed in the study area, with one rain gauge in the proximity of two runoff monitoring stations (forest and cropland catchments) (Fig. 2, Table 2). Rainfall was manually recorded twice a day: in the morning at 8:00 AM and in the evening at 8:00 PM.

Runoff data were collected at the outlet of the forest and cropland catchments. Ten study sites were selected along the altitudinal transects and stratified according to the land-use type (forest and cropland) and three elevation zones (high, 1,900-2,300 m a.s.l.; middle, 1,500-1,900 m a.s.l.; and low, 1,200-1,500 m a.s.l.). No catchments were found that were entirely under agroforestry. All forest and cropland catchments were paired and had a runoff monitoring station equipped with a standardized flume at the outlet (Table 2).

Runoff data were collected during the main rainy season of 2013 and 2014 (June 8 to October 30). The runoff stations consisted of nine San Dimas flumes (Fig. 3) and one V-notch weir, installed at the outlet of the drainage basins. Compared to the rectangular cross-section of the San Dimas flumes, the V-shaped V-notch is more suitable for recording smaller flows. The flumes were equipped with a graduated strip to manually record the runoff depth. The flow depth was measured at a ten minutes' interval during every rainfall event. Because the maximum runoff depth is generally lower in forest catchments as compared to cropland catchments, the dimension of the rectangular flumes installed in the forest catchments (1.5×0.5×0.5 m; Length×Width×Height) is smaller than those installed in cropland catchments (2.1×0.7×0.7 m; L×W×H), Flow depth was converted to discharges using the Bermel (1950) rating curves, adapted for the 500 mm wide (small San Dimas flume) and a 700 mm wide (large San Dimas flume). Flow depth – discharge relationships were checked by defining the discharge in the San Dimas flumes independently by measuring flow velocity in the flumes from a current meter, and combine these measurements with the cross-sectional area of the flow. At the lowest forest, when observing the channel, a very small runoff discharge was expected and a V-notch weir was installed. The standardized rating curve for 90° V-notch weir was employed to calculate the discharge. However, as the V-notch weir was installed in a level area, large volumes of water ponded behind it; hence a stage-water volume rating curve was developed based on the pond's geometry. This volume was then added to the measured discharge in the V-notch weir. These rating curves were used to convert the manually recorded continuous flow depth series to storm discharge records. The resulting continuous runoff discharge series were integrated on an event and daily basis. Rainfall-runoff relations were established so that the missed events (particularly during nights) could be estimated.

Sediment yield measurements and export

During the runoff events, suspended sediment samples were collected at different flow depths. Grab samples were collected and transferred into 1 litre plastic bottles (Fig. 3). The samples were then filtered in a funnel using Whatman 42 filter paper (pore size of 2.5 μm). The filter paper with sediment was then oven-dried for 24 hours at 105 °C and weighed so as to determine the suspended sediment concentration.

The suspended sediment concentration (*SSC*, in g l^{-1} or kg m^{-3}) was calculated as:

$$SSC = (M - 1.6186)\, V^{-1} \tag{4}$$

where *M* is the gross mass of the dried filter with suspended sediments (g); 1.6186, the average mass (n = 10) of oven-dried empty filter paper (g); *V*, the volume of the water sample (l).

Based on a large set of *SSC* samples (999 in 2013 and 2015 in 2014, or ca. 300 per catchment), suspended sediment to discharge rating curves were developed for all forest and cropland sub- catchments (Asselman, 2000; Moliere *et al.*, 2004; Vanmaercke *et al.*, 2010).

Several studies show that the relation between *Q* and *SSC* is often subject to a lot of scatter and is variable on different temporal scales (Asselman, 2000; Moliere *et al.*, 2004; Alexandrov *et al.*, 2007). A preliminary check (Fig. 4) showed that in the studied catchments, relations were consistent throughout the rainy season. We have thus worked with seasonal rating curves per station. The daily sediment export was calculated for each forest and cropland station, using:

$$Qs,\mathrm{d} = \sum_{i=1}^{n} (Q\mathrm{i} * SSC\mathrm{i} * 600\ \mathrm{s}) \tag{5}$$

where *Q*s,d is the daily sediment export (t day^{-1}); *n* is the number of 10-min intervals per day; *Q*i is the runoff discharge for each 10-min interval ($m^3\ s^{-1}$) and SSC_i is the corresponding estimated *SSC* (kg m^{-3}), calculated with the discharge rating curves. The total sediment export for each forest and cropland sub- catchment was calculated as the sum of all *Q*s,d values. The suspended sediment yield (*SSY*) is the total exported sediment per month or season (June to October), calculated against the catchment area.

For about a quarter of the rainfall events, the runoff could not be monitored and no *SSC* samples were taken, particularly for storms that occurred in the middle of the night. We have estimated the sediment yield of those events by establishing -per station and based on the monitored events- a regression analysis between the event rainfall and the sediment yield. Using the rainfall data of the missed runoff event, we could then calculate the estimated sediment yield of that event (Table 3).

The catchment boundaries were digitized using topographic maps of the study area, complemented with the GPS recordings taken in the field. The area of all sub-catchments was then calculated using GIS software.

Plant density

The plant density, as a potential explanatory factor for differences in *SSY*, was recorded on plots within the forest and cropland catchments. The main plots were 20 × 20 m^2 replicated three times in each catchment. Trees above 1.5 m height were counted inside the 20 × 20 m^2 main plot and shrubs were counted in subplots of 5 × 5 m^2 on the four corners of the main plot. The plant density of the trees and shrubs was calculated based on the equation by Mueller-Dombois & Ellenberg (1974):

$$\text{Density of species i} = \frac{\text{Number of the plants of species i}}{\text{Area of quadrants}} \qquad (4)$$

Data analysis

The difference in the monthly average suspended sediment yield between the forest and cropland was analyzed with a one-way ANOVA using SPSS (software version 20). Means were compared by the least significant difference (LSD). The relation between the suspended sediment yield and the catchment area, seasonal rainfall and slope gradient was analyzed using a linear regression analysis.

3. Results

3.1 Suspended sediment concentration

The suspended sediment concentration (*SSC*) of the research sites reached values up to 16 g l^{-1}; all sites showed a pattern of linearly increasing *SSC* with discharge (Fig. 4). Data are relatively well grouped around the regression lines and for all catchments, the coefficients of determination between *SSC* and *Q* are strong (Table 3).

3.2 Sediment yield

The seasonal suspended sediment yield in cropland is higher than the forest on all sites. The seasonal average *SSY* in cropland ranges from 30 ± 5.5 Mg ha^{-1} in the FH site to 10 ± 2.7 Mg ha^{-1} in the FL site, whereas the forest seasonal average suspended sediment yields are between 6 ± 1.3 Mg ha^{-1} at FH site and 2 ± 0.7 Mg ha^{-1} at FL site (Table 4).

The average monthly *SSY* of the cropland is significantly different from the paired forest in all sites (Table 5). In general, the overall average monthly sediment yield of the cropland (3.5 ± 2.4 Mg ha^{-1}) is significantly higher than of the corresponding paired forest (0.9 ± 0.5 Mg ha^{-1}). The average monthly suspended sediment yield of the cropland and the forest (Table 5) shows very little hysteresis throughout the year (Fig. 5).

3.3 Explanatory factors for the suspended sediment yield

The measured values for the explanatory factors such as the catchment area, slope gradient, seasonal rain and tree density, were analyzed for the two sub-groups of catchments. It appears that the homogeneity in tree density (0.19-0.24 m^{-2} in forest, 0.003 m^{-2} in cropland) and shrubs (2.4-2.6 m^{-2} in forest, 0.71-0.72 m^{-2} in cropland) in the studied catchments (Table 2) does not allow analyzing their impact on the sediment yield, other than the overall contrast between the two land-use types. However, in cropland, the *SSY* is positively associated to the catchment area ($R^2 = 0.63$), to the average catchment slope gradient ($R^2 = 0.50$), and to the seasonal rainfall depth ($R^2 = 0.11$); and weaker positive associations were found under the forest: *SSY* with the catchment area ($R^2 = 0.19$), with an average catchment slope gradient ($R^2 = 0.68$) and with a seasonal rainfall depth ($R^2 = 0.93$) ($n = 5$) (Fig. 6).

4. Discussion

4.1 Impact of the land-use type on the seasonal suspended sediment yield

The average seasonal suspended sediment yield from catchments under cropland (17 Mg ha^{-1}) is four times larger than the yield from similar catchments under forests (4 Mg ha^{-1}). This can be explained by the high soil erosion rates under cropland. In southwestern Ethiopia, Hurni (1985) measured soil losses from cultivated fields of 68 Mg ha^{-1} yr^{-1}, while from bush and grasslands soil loss was only 1 Mg ha^{-1} yr^{-1} (Sidamo case study). The average suspended sediment yield in the forest (4 Mg ha^{-1}) is considerably lower than in cropland but larger than the 0.5 Mg ha^{-1} suspended sediment yield from a Caribbean forest (Cox *et al*., 2006) and much higher when compared with the worldwide estimates of soil loss of 0-0.58 Mg ha^{-1} yr^{-1} (Sands, 2013) and 0.004 to 0.05 Mg ha^{-1} yr^{-1} proposed for forests (Roose, 1988). The occurrence of the high suspended sediment yield in the studied forest catchments (and also a high suspended sediment concentration even at relatively low discharges) (Fig. 4, right) is probably partly due to the selective logging as evidenced by the presence of species, typical of secondary vegetation (such as *Albizia gummifera*, *Hagenia abyssinica*, *Polyscias fulva* or *Schefflera abyssinica*) and the pressure on the forest by grazing livestock, particularly in the crop growing period when stubble grazing is impossible. Livestock grazing basically results in a decreased soil porosity and infiltration, which in turn increases the surface runoff and the soil loss. Soil disturbance by the grazing livestock's hoofs and horns leads to a significant increase of the suspended sediment yield in the overland flow (McDowell *et al*., 2003).

When considering the monthly variation in *SSY*, we could not observe the expected higher sediment load for the same discharge in the early rainy season in contrast with the late rainy season (Fig. 5). The absence of such hysteresis could indicate that the production and transport conditions of sediment yield stay more or less the same throughout the rainy season (Bača, 2008). This is most probably related to the overall humid environment that favours a continuous vegetation growth, including off-season weeds and the soil humidity, hence little or no dust. Also the near-absence of the crop rotation favours the weed development (Liebman & Dyck, 1993).

The seasonal suspended sediment yield measured on the cropland catchments (17 Mg ha^{-1}) is somewhat larger than that of the earlier partial studies from agricultural lands with similar slope, rainfall and management practices in the neighbouring Keffa Zone. For example, the soil loss in the agriculture land was 15 Mg ha^{-1} yr^{-1} in the Keffa Zone (Mekuria *et al*., 2012), 8-15 Mg ha^{-1}yr^{-1} at different slope positions on settlers' farms near Bonga in the Keffa Zone (Berhanu, 2011). Just like in this paper, the measured results strongly contrast with the model results of 184 Mg ha^{-1}yr^{-1} in the Bench Maji Zone (Getachew, 2010). The findings on cropland are also higher than the median of the measured values in Africa for catchments of 2 ha (7.8 Mg ha^{-1} yr^{-1}) or 8 ha

(6.3 Mg ha^{-1} yr^{-1}) (Vanmaercke *et al*., 2014). In Ethiopia, all measured *SSY* for catchments up to 1,000 km² are situated in the range of 5-40 Mg ha^{-1} yr^{-1} (Vanmaercke *et al*., 2010: Lemma *et al*., 2018). Despite the higher rainfall than on all other measurement sites, the two-year measurement results on cropland lie well within this range. Most plausible explanations are that the rains are starting slowly, giving all chance to crops (and weeds) to get well established by the time the June-September rains will occur.

4.2 Impacts of rainfall depth and topography on the sediment yield

Besides the overwhelming effect of the land-use type, the suspended sediment yield also depends on other catchment characteristics (Fig. 6). The increasing trends of *SSY* to catchment area, both in forest and in cropland, could be related to the fact that soils are relatively saturated in the rainy season. In absence of soil and water conservation structures, alluvial plains or topographical flats, this leads to a longer runoff length in the larger catchments, hence accelerated soil erosion, with little opportunity for deposition. Another reason for this positive relation is that - in larger catchments (on this scale range) - topographic thresholds are exceeded; e.g. gully erosion and shallow landslides, which were visually observed in the catchments. Such processes become often more important when the catchment size is increasing, as shown for instance by Verbist *et al*. (2010) in a tropical volcanic agroforestry landscape in Indonesia.

A steeper slope gradient leads to an increase in *SSY*, despite the coarsening of the soil particles on steeper slopes and higher rock fragment covers, as seen elsewhere in Ethiopia (Miserez, 2013; Lanckriet *et al*., 2012). Finally, we could also notice a higher *SSY* in catchments with a more seasonal rainfall (Fig. 6, right); as, per land-use type, the land cover is quite similar, more rain is expected to lead to more splash erosion, more runoff and hence a greater *SSY*. When comparing forest and cropland (Fig. 6), the correlations are equally strong but the gradient is less, translating an overall buffering forest effect.

5. Conclusions

This study is one of few that quantifies sediment yield at tropical forest frontiers. It shows that changing southwestern Ethiopia’s Afromontane forest into an open field cropland significantly affects the sediment concentration and the seasonal suspended sediment yield, which is around four times higher in cropland catchments compared to the paired forest catchments. The suspended sediment concentration is strongly correlated with the runoff in both forest and cropland. Even under grazing pressure, the forest plays an important role in the protection of the soil from erosion. Yet, the soil loss from cropland (17 Mg ha^{-1} per rainy season) is lower than what could be expected following tropical deforestation, which we particularly relate to a dense cover by crops and weeds, particularly at the time of the strongest rains. An unexpectedly high sediment yield from forests (4 Mg ha^{-1} per rainy season) is probably due to the degradation of (and particularly livestock pressure on) the forests. Under both land-use types, the soil loss increases with the catchment area, average catchment slope gradient and seasonal rainfall. We also showed that a reduction in tree cover leads to strong increases in suspended sediment yield. In sum, the land management in the southwestern Ethiopian highlands will need a strong change in paradigm in order to avoid a strong increase in sediment yield following deforestation.

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Figure captions:

Figure 1. Forest and cropland sub-catchments. (a) view of the Faketen (FHF) forest in the upper Gacheb basin, at approx. 2,250 m a.s.l., on October 21, 2013. (b) View of the cropped Oka (OMC) catchment during harvesting time on October 7, 2013. In front, sorghum was planted where maize failed.

Figure 2. Location of the Gacheb catchment and studied catchments. In the codes, the first letter stands for location (see Table 2), the second for elevation (**L**ow, **M**iddle, **H**igh) and the third for **C**ropland, **F**orest or **R**ainfall.

Figure 3. Measurement station and suspended sediment filtering. (a) San Dimas flume installed at the outlet of the Dakin Forest catchment (8 September 2013). (b) The wooden boards have been perforated so as to fix funnels, in which the Whatman filter paper was inserted.

Figure 4. Suspended sediment concentration (*SSC*) as a function of discharge (Q*)* in two paired catchments in the mid-elevation belt: (left) OMC Oka cropland, n= 116, 5.2 ha, outlet at 1,606 m a.s.l.; (right) DMF Dakin Forest, n=93, 7.9 ha, outlet at 1,632 m a.s.l.

Figure 5 Average monthly (June to October) suspended sediment yield (From Table 5) relation to runoff in five paired catchments. (a) FH site: (a1) forest, (a2) cropland; (b) DM site: (b1) forest, (b2) cropland; (c) ZH site: (c1) forest, (c2) cropland; (d) ZM site: (d1) forest, (d2) cropland; (f) FL site: (f1) forest, (f2) cropland.

Figure 6. Seasonal sediment yield (*SSY*) in forested (n = 5) and cropland catchments (n = 5) astride the forest frontier in southwest Ethiopia, as a function of the catchment area (left), the average catchment slope gradient (centre) and the seasonal rainfall (right).

Tables

Table 1. Agricultural calendar in the Gacheb catchment for major crops in the main growing season: maize (*), taro (¤) and beans (#).

Major activities[1]	J	F	M	A	M	J	J	A	S	O	N	D
Land preparation[2]				¤	*#							
Sowing or planting				¤	*#							
Weeding and cultivation[3]						*#¤	*#¤					
Harvesting									*#	*#	¤	¤

[1] In the study catchments, farmers do not use fertilizers and maize monocropping is dominant (without crop rotation, without fallowing). Only in the upper FHC catchment, there is crop rotation with beans and barley.

[2] The land is tilled three times in all catchments with an oxen-span and a plough of the ard- type (2 times in DMC).

[3] Cultivation is done once with hand tools (twice at FHC).

Table 2. Characteristics of sub-catchments monitored in the main rainy seasons of 2013 and 2014 (June 8-October 30).

Description	FHF	FHC	DMF	OMC	ZHF	ZHC	ZMF	ZMC	FLF	FLC
Location of stations	6°59' N 35°39' E	7° 0' N 35°39' E	7° 2' N 35°38' E	7° 1' N 35°39' E	6°55' N 35°34' E	6°55' N 35°34' E	6°55' N 35°33' E	6°55' N 35°33' E	6°58' N 35°30' E	6°57' N 35°30' E
Area (ha)	11.5	7.0	7.9	5.2	5.9	6.2	3.7	5.5	4.1	5.1
Average elevation (m a.s.l.)	2135	1990	1632	1606	2022	1879	1544	1717	1261	1324
Rainfall (mm)	1405 ±92	1405 ±92	1218 ±88	1218 ±88	1535 ±31	1535 ±31	1360 ±23	1360 ±23	1126 ±14	1126 ±14
Slope gradient (%)	42	29	23	33	35	18	20	23	19	15
Perimeter (m)	1399	1064	1050	990	952	954	730	1034	888	1032
Compactness	0.74	0.78	0.90	0.67	0.83	0.86	0.87	0.65	0.65	0.60
Tree density (m^{-2})	0.24 ±0.004	0.003 ±0.001	0.21 ±0.01	0.003 ±0.001	0.23 ±0.01	0.003 ±0.001	0.21 ±0.004	0.003 ±0.001	0.19 ±0.01	0.003 ±0.001
Shrub density (m^{-2})	2.6 ±0.08	0.72 ±0.1	2.5 ±0.06	0.7 ±0.04	2.5 ±0.1	0.7 ±0.1	2.5 ±0.1	0.71 ±0.1	2.4 ±0.1	0.7 ±0.04
Location of rain gauge stations	6°59' N 35°39' E		7° 2' N 35°39' E		6°55' N 35°34' E		6°55' N 35°33' E		6°58' N 35°30' E	

FHF: Faketen high forest; FHC: Faketen high cropland; DMF: Dakin middle forest; OMC: Oka middle cropland; ZHF: Zemika high forest; ZHC: Zemika high cropland; ZMF: Zemika middle forest; ZMC: Zemika middle cropland; FLF: Fanika low forest; FLC: Fanika low cropland.

Table 3. Regression equations for the relation between the measured discharge (Q, in $m^3\ s^{-1}$) and the suspended sediment concentration (SSC, g L^{-1}) and the event rainfall (P, mm) and the suspended sediment yield (SSY, g) in the Gacheb catchment.

Station	Catch-ment	Year	Regression equation of *SSC* and *Q*	Regression equation of event P and *SSY*
FHF	Forest	2013	$SSC = 67.398Q + 1.706$ (R^2 =0.52; n=117)	$SSY = 97362P - 54032$ (R^2 = 0.900)
		2014	$SSC = 13.967Q + 2.534$ (R^2 =0.54; n=113)	$SSY = 83312P - 36986$ (R^2 = 0.814)
DMF	Forest	2013	$SSC = 17.675Q + 3.327$ (R^2 =0.53; n=93)	$SSY = 24294P - 11229$ (R^2 = 0.842)
		2014	$SSC = 20.274Q + 3.582$ (R^2 =0.56; n=89)	$SSY = 37773P - 27201$ (R^2 = 0.857)
ZHF	Forest	2013	$SSC= 12.640Q + 3.239$ (R^2 =0.51; n=91)	$SSY = 40645P - 18456$ (R^2 = 0.906)
		2014	$SSC= 12.046Q+ 3.210$ (R^2 =0.50; n=95)	$SSY = 35056P - 16243$ (R^2 = 0.909)
ZMF	Forest	2013	$SSC = 17.049Q + 3.399$ (R^2 =0.53; n=89)	$SSY = 23242P - 11326$ (R^2 = 0.874)
		2014	$SSC = 16.421Q + 2.766$ (R^2 =0.58; n=94)	$SSY = 19028P - 10296$ (R^2 = 0.844)
FLF	Forest	2013	$SSC= 36.209Q+ 0.624$ (R^2 =0.51; n=91)	$SSY = 21095P - 84346$ (R^2 = 0.828)
		2014	$SSC = 34.432Q + 1.589$ (R^2 =0.52; n=99)	$SSY = 12320P - 54359$ (R^2 = 0.891)
FHC	Cropland	2013	$SSC= 76.047Q + 4.542$ (R^2 =0.67; n=114)	$SSY = 32182P - 2E+06$ (R^2 = 0.909)
		2014	$SSC = 77.485Q + 6.510$ (R^2 =0.68; n=118)	
OMC	Cropland	2013	$SSC = 91.743Q + 5.799$ (R^2 =0.64; n=116)	$SSY = 15333P - 72667$ (R^2 = 0.858)
		2014	$SSC = 70.491Q + 6.229$ (R^2 =0.61; n=108	
ZHC	Cropland	2013	$SSC = 77.278Q + 5.057$ (R^2 =0.60; n=106)	$SSY = 12974P - 56175$ (R^2 = 0.927)
		2014	$SSC = 70.180Q + 4.816$ (R^2 =0.60; n=110)	
ZMC	Cropland	2013	$SSC = 98.102Q + 4.209$ (R^2 =0.65; n=92)	$SSY = 11263x - 57532$ (R^2 = 0.873)
		2014	$SSC = 71.207Q + 4.849$ (R^2 =0.64; n=97	
FLC	Cropland	2013	$SSC = 95.235Q + 2.513$ (R^2 =0.62; n=90)	

		2014	$SSC = 79.818Q + 3.920$ ($R^2 = 0.65$; n=92)	$SSY = 71590x - 37402$ ($R^2 = 0.862$)

Catchment names as in Table 2.

Table 4. Total seasonal rainfall and suspended sediment yield (period of June to October) from paired catchments at southwest Ethiopia's forest frontier

Station	Land use	Year	Rf (mm)	*SSY* (Mg ha^{-1})
FHF	Forest	2013	1470	6.6
FHF		2014	1340	4.8
Average			1405±92	6±1.3
FHC	Cropland	2013	1470	33
FHC		2014	1340	26
Average			1405±92	30±5.5
DMF	Forest	2013	1280	2.3
DMF		2014	1155	2.9
Average			1218±88	3±0.4
OMC	Cropland	2013	1280	19.1
OMC		2014	1155	18.7
Average			1218±88	19±0.2
ZHF	Forest	2013	1312	5.1
ZHF		2014	1757	6.7
Average			1535±315	6±1.1
ZHC	Cropland	2013	1312	14.3
ZHC		2014	1757	15.0
Average			1535±315	15±0.5
ZMF	Forest	2013	1195	3.9
ZMF		2014	1524	4.6
Average			1360±233	4±0.5
ZMC	Cropland	2013	1195	10.9
ZMC		2014	1524	15.0
Average			1360±233	13±2.9
FLF	Forest	2013	1023	1.1
FLF		2014	1230	2.1
Average			1127±146	2±0.7
FLC	Cropland	2013	1230	8.2
FLC		2014	1230	12.1
Average				10±2.7
Overall averages	Forest		1127±146	4±1.9

	Cropland	1127±146	17±7.6

Rf: Rainfall; *SSY*: Area-specific seasonal suspended sediment yield. Catchment names as in Table 2.

Table 5. Monthly area-specific suspended sediment yield (*SSY*, Mg ha^{-1}) in the monitored catchments (2013 and 2014)

Station	Catchment	Year	June	July	August	September	October	Monthly average
FHF	Forest	2013	0.7	1.9	1.0	2.3	0.7	1.1±0.6^{b}
		2014	0.5	1.6	1.2	1.0	0.5	
		Average	0.6±0.2	1.7±0.2	1.1±0.1	1.6±0.9	0.6±0.1	
FHC	Cropland	2013	3.2	10.5	5.9	11.6	2.3	5.9±3.5^{a}
		2014	3.0	9.4	5.6	5.9	1.8	
		Average	3.1±0.1	9.9±0.8	5.8±0.2	8.8±4.0	2.1±0.4	
DMF	Forest	2013	0.3	0.8	0.7	0.2	0.3	0.5±0.3^{b}
		2014	0.3	0.9	0.8	0.5	0.4	
		Average	0.3±0.0	0.9±0.1	0.8±0.1	0.4±0.1	0.3±0.1	
OMC	Cropland	2013	2.1	6.8	5.6	2.3	2.3	3.8±1.9^{a}
		2014	1.7	6.3	4.4	3.5	2.8	
		Average	1.9±0.3	6.5±0.3	5.0±0.8	2.9±0.9	2.5±0.3	
ZHF	Forest	2013	0.4	1.9	1.1	1.1	0.6	1.2±0.5^{b}
		2014	0.5	1.9	1.5	1.2	1.5	
		Average	0.4±0.1	1.9±0.0	1.3±0.3	1.2±0.0	1.1±0.7	
ZHC	Cropland	2013	0.7	6.0	2.8	3.1	1.8	2.9±1.6^{a}
		2014	1.0	4.9	3.1	3.0	3.0	
		Average	0.8±0.2	5.5±0.7	2.9±0.3	3.1±0.1	2.4±0.9	
ZMF	Forest	2013	0.3	1.7	0.8	0.6	0.5	0.9±1.7^{b}
		2014	0.4	1.5	0.7	1.1	0.9	
		Average	0.3±0.1	1.6±0.2	0.8±0.0	0.9±0.3	0.7±0.3	
ZMC	Cropland	2013	0.6	4.2	2.2	2.1	1.9	2.6±1.2^{a}
		2014	1.5	4.3	2.2	3.5	3.5	
		Average	1±0.7	4.2±0.0	2.2±0.0	2.8±1.0	2.7±1.2	
FLF	Forest	2013	0.3	1.2	0.3	0.8	0.6	0.5±0.3^{b}
		2014	0.3	0.8	0.4	0.3	0.3	
		Average	0.3±0	1.0±0.3	0.4±0.1	0.6±0.4	0.5±0.2	
FLC	Cropland	2013	0.6	2.7	1.0	2.6	1.3	2.0±1.1 ^{a}
		2014	1.3	4.3	2.3	2.0	2.2	
Average		Average	0.9±0.5	3.5±1.1	1.7±0.9	2.3±0.5	1.7±0.6	
Summary		Forest						0.9±0.5^{b}
		Cropland						3.5±2.4^{a}

Mean values with different letters among the land-use types on the same site are significantly different from each other ($P<0.05$). Catchments names as in Table 2.

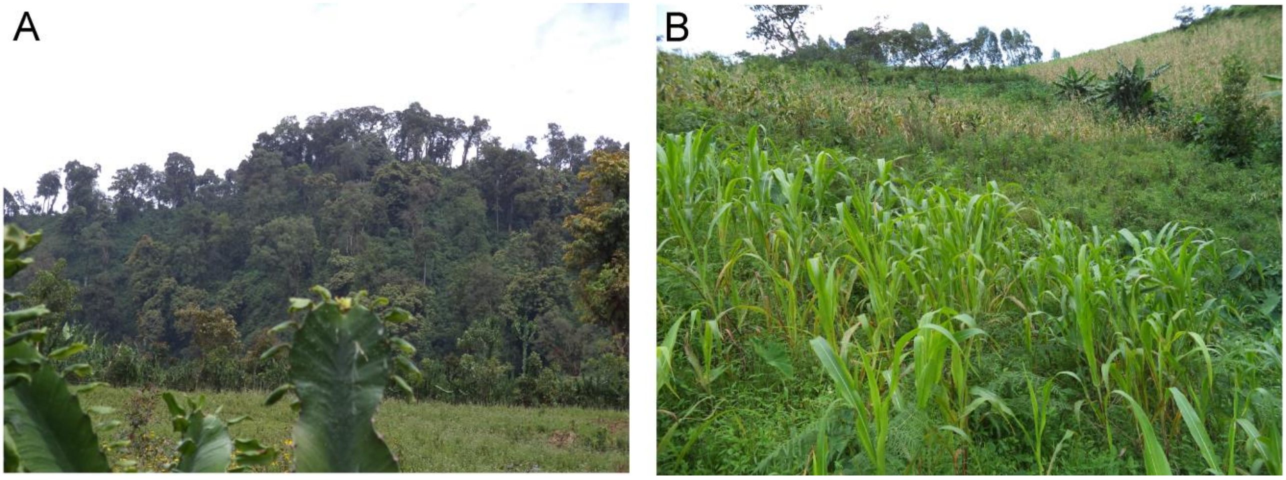
A
B

FIG 1

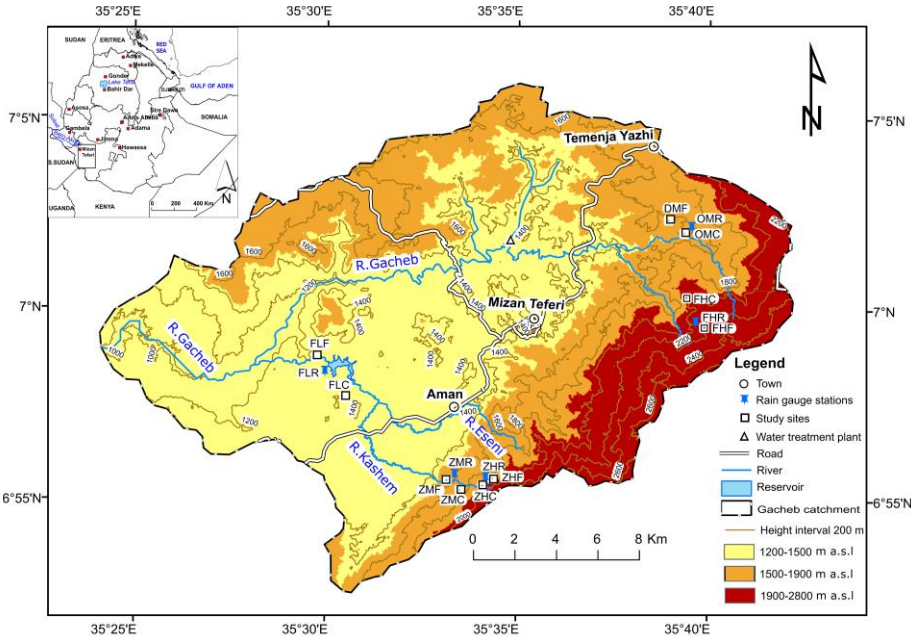
35°25'E
35°30'E
35°35'E
35°40'E
7°5'N
7°N
6°55'N
SUDAN
ERITREA
RED SEA
Adwa
Mekelle
Gonder
Lake Tana
Bahir Dar
DJIBOUTI
GULF OF ADEN
Asosa
Dire Dawa
Addis Ababa
SOMALIA
Gambela
Adama
Jimma
Hawassa
S.SUDAN
Mizan Teferi
UGANDA
KENYA
0 200 400 Km
N
Temenja Yazhi
DMF
OMR
OMC
R.Gacheb
Mizan Teferi
FHC
FHR
FHF
R.Gacheb
FLF
FLR
FLC
Aman
R.Eseni
R.Kashem
ZMR
ZHR
ZHF
ZMF
ZMC
ZHC
1000
1200
1400
1600
1800
2000
2200
2400
2600
0 2 4 6 8 Km
Legend
Town
Rain gauge stations
Study sites
Water treatment plant
Road
River
Reservoir
Gacheb catchment
Height interval 200 m
1200-1500 m a.s.l
1500-1900 m a.s.l
1900-2800 m a.s.l

FIG 2


A
B

FIG 3

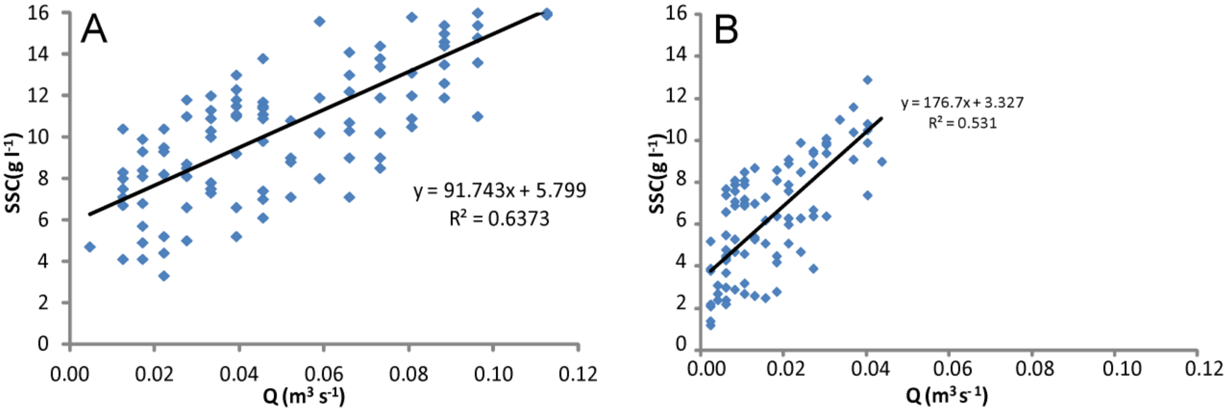
A
16
14
12
10
8
6
4
2
0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
SSC(g l-1)
Q (m3 s-1)
y = 91.743x + 5.799
R² = 0.6373
B
16
14
12
10
8
6
4
2
0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
SSC(g l-1)
Q (m3 s-1)
y = 176.7x + 3.327
R² = 0.531

FIG 4

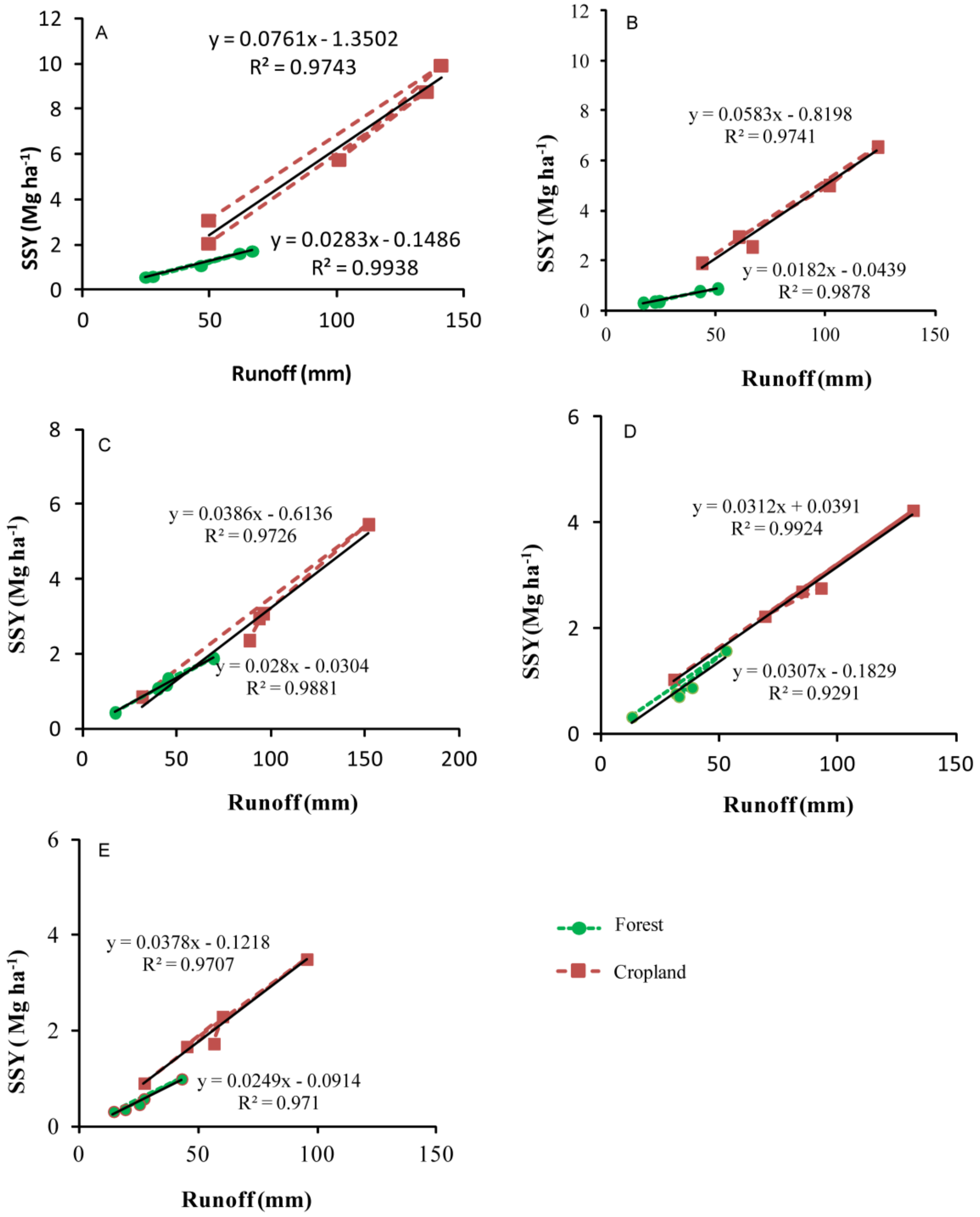
A
SSY (Mg ha^{-1})
0
2
4
6
8
10
12
Runoff (mm)
0
50
100
150
y = 0.0761x - 1.3502
R² = 0.9743
y = 0.0283x - 0.1486
R² = 0.9938
B
SSY (Mg ha^{-1})
0
2
4
6
8
10
12
Runoff (mm)
0
50
100
150
y = 0.0583x - 0.8198
R² = 0.9741
y = 0.0182x - 0.0439
R² = 0.9878
C
SSY (Mg ha^{-1})
0
2
4
6
8
Runoff (mm)
0
50
100
150
200
y = 0.0386x - 0.6136
R² = 0.9726
y = 0.028x - 0.0304
R² = 0.9881
D
SSY(Mg ha^{-1})
0
2
4
6
Runoff (mm)
0
50
100
150
y = 0.0312x + 0.0391
R² = 0.9924
y = 0.0307x - 0.1829
R² = 0.9291
E
SSY (Mg ha^{-1})
0
2
4
6
Runoff (mm)
0
50
100
150
y = 0.0378x - 0.1218
R² = 0.9707
y = 0.0249x - 0.0914
R² = 0.971
Forest
Cropland

FIG 5

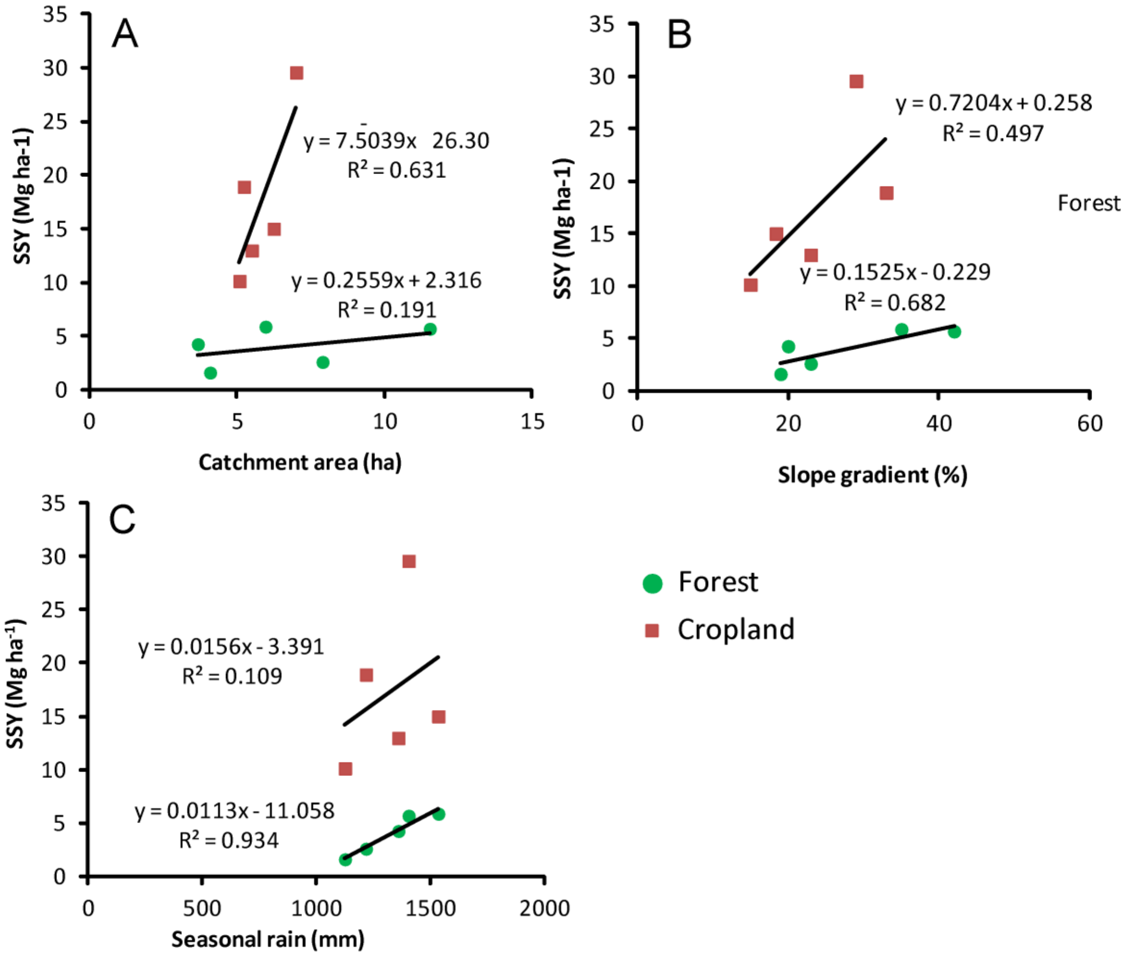
A
SSY (Mg ha-1)
Catchment area (ha)
0
5
10
15
20
25
30
35
y = 7.5039x - 26.30
R² = 0.631
y = 0.2559x + 2.316
R² = 0.191
B
SSY (Mg ha-1)
Slope gradient (%)
0
20
40
60
y = 0.7204x + 0.258
R² = 0.497
Forest
y = 0.1525x - 0.229
R² = 0.682
C
SSY (Mg ha-1)
Seasonal rain (mm)
0
500
1000
1500
2000
y = 0.0156x - 3.391
R² = 0.109
y = 0.0113x - 11.058
R² = 0.934
● Forest
■ Cropland

FIG 6