ORIGINAL ARTICLE

Runoff, soil loss and their relationships under different land uses in the central highland of Ethiopia

Zenebe Adimassu[1,2*] and Nigusse Haile[1]
[1] Holeta Agricultural Research Center, Ethiopian Institute of Agricultural Research, P. O. Box 2003, Addis Ababa, Ethiopia
[2] Land Degradation and Development Group, Wageningen University, The Netherlands
***Corresponding author:** Tel.: +251-920325920; E-mail: Zenebeteferi@yahoo.com

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ABSTRACT

The study was conducted at Holeta Agricultural Research Center to assess runoff and soil losses and establish rainfall-runoff-soil loss relationships. Nine hydrologically isolated experimental runoff plots of 22 m length and 6 m width were installed on 10% slope and three dominant land uses (crops types) viz. faba bean (*Vicia faba* L. var. *Degaga*), field pea (*Pisum sativum* L. var. T*egegnech*) and wheat (*Triticum aestivum* L. var. *Kubsa*). Daily values of rainfall, runoff and soil loss for three successive years (2005 to 2007) were recorded. The results showed that the average surface runoff generated from field pea, faba bean and wheat plots were 144.7 mm, 181.4 mm and 169.5 mm, respectively and the corresponding soil losses in the land use of the same order were 16.9, 29.9 and 20.29 Mg ha^{-1}, respectively. Thus field pea was found to be effective in reducing runoff and soil loss. However, the actual runoff and soil losses recorded were still high in all cases which warrant the requirement of more effective soil and water conservation measures in the area. The runoff coefficient revealed that an average of 19 to 42% of the annual rainfall became runoff in the study areas under these land uses. The result of linear regression of rainfall-runoff-soil losses shows positive and strong relationships.

Keywords: Highland, Land use, Rainfall, Runoff, Soil loss

INTRODUCTION

Livelihood of peoples in Ethiopia is dependent on land resource for food and other necessities , and more than 80% of the total population is engaged in agricultural activities (CSA, 2008). However, the Ethiopian agricultural economy is under continuous threat from various forms of land degradation. Among the different forms of land degradation processes in Ethiopia, soil erosion by water is the most important environmental problem that poses an ominous threat to the food security of the population and future development prospects of the country (Hurni, 1989). Soil erosion is not a new phenomenon in Ethiopia; it is a process as old as the history of agriculture in the country (Hurni, 1989). Ethiopia has also been described as one of the most serious soil erosion areas in the world (Blaikie, 1985). Several studies indicated the severity of soil loss in different parts of the country. For instance, 42 t ha^{-1} yr^{-1} (Hurni, 1993), 57 t ha^{-1} yr^{-1} (Girmay *et al.*, 2009), 20 t ha^{-1} yr^{-1} (Gebreegziabher *et al.*, 2008) and 179 t ha $^{-1}$ yr $^{-1}$ (Shiferaw and

Holden, 1999). The high variation in soil loss might be due to variations in slope, rainfall, soil type, land use, plot size and method of estimations.

Repeated problems of famine and starvation have been attributed at least partly to this phenomenon of soil erosion (Blaikie, 1985; Hurni, 1989). Soil erosion is particularly a widespread phenomenon in the highlands, which accounts for about 45% of the Ethiopia's total land area (Yeraswork, 1997; Hurni, 1989). Beside soil losses, rainwater loss in the form of runoff is an important production constraint. Loss of rainwater as runoff not only limits the water available for crop production but also forms an erosion hazard (Rao *et al.*, 1998; Nyssen *et al*., 2005). Knowledge of rainfall, runoff, and soil loss, and their relationships as well as variation in time and space are very important for soil and water management such as designing soil and water conservation and water harvesting structures (Sharman *et al.*, 2001). Runoff studies can also produce useful information on the water-yield capabilities of different land uses and help to determine the proportion of rainfall that reaches the rivers as runoff and sediment contributed to water bodies.

Keeping other factors constant, runoff and soil loss from a given catchment vary depending on the type of land uses (Singh, 1999; Gebresamuel *et al*., 2010). This is because different land uses have different ground cover and root system which affects runoff generated under such land uses. Very limited studies have been conducted on runoff and soil loss as well as rainfall-runoff-soil loss relationships under different land uses in Ethiopian highlands. Therefore, an extensive study was initiated in 2005 in Nitisols of Holeta to assess runoff and soil loss and establish rainfall-runoff-soil loss relationships under different land uses.

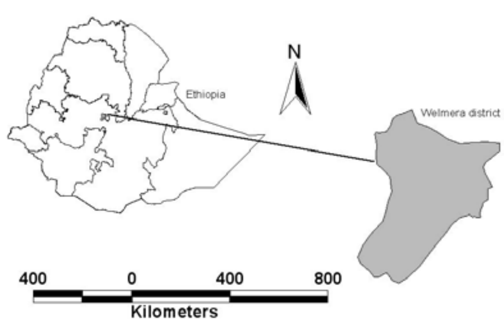

Figure 1. Map showing the study area.

MATERIALS AND METHODS

Description of the study area

The study was conducted in the central highlands of Ethiopia particularly at Holetta Agricultural Research Center which is located at $09^0$04'N and $38^0$29'E. The area lays in the Awash basin, located in Welmera district of West Shewa zone and about 33 Km to West of Addis Ababa (Fig. 1). The area is 2400 m above sea level in the Nitisols soil type. Rainfall of the area is represented by Class A weather station at Holeta Agricultural Research Center. The area receives high rainfall with historical mean annual (1969 to 2007) of 1045 mm. The annual rainfall of 2005 (914 mm) and 2006 (921 mm) were less than the historical mean annual rainfall which was associated with a lower than average rainfall during August. The annual rainfall of 2007 (1057 mm) exceeds the average rainfall associated with a higher than normal rainfall during July and August. In general, 75% of the rainfall occurred in the main rain season (*Kiremt*) (Figure 2). Previous studies on rainfall distribution showed similar result in which greater than 70% of the rainfall occurred in the main rainy season (Nyssen *et al*., 2005; Cheung *et al*., 2008).

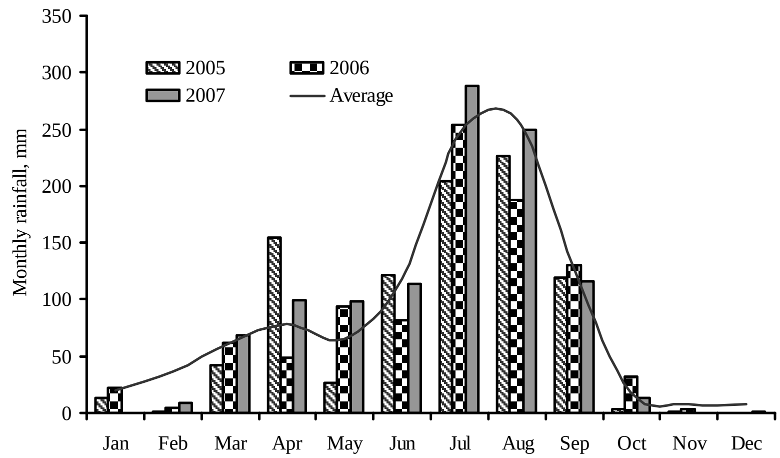

Figure 2. Distribution of rainfall during study period (2005 to 2007) and average rainfall (1969 to 2007).

Experimental setup, data collection and analysis

Nine hydrologically isolated runoff plots of 22 m long and 5 m wide were delineated on uniform land slope of 10%, and bounded by galvanized sheet metal of 60 cm of which 15 cm was inserted into the ground to prevent lateral flow of runoff. Faba bean (*Vicia faba* L. var. *Degaga*), field pea (*Pisum sativum* L. var. *Tegegnech*) and wheat (*Triticum aestivum* L. var. *Kubsa*) were grown (Table 1) during the main rain season (June to September) for three successive years (2005 to 2007). The experiment was laid down in randomized complete block design with three replications. Daily rainfall was recorded with the help of non-automatic rain gauge installed near the experimental plots. The runoff sample was taken using multi-slot divisors (Fig. 3). Accordingly, the surface runoff was collected in first tank, which also overflows into a second tank via a multi-slot (nine-slot) devisor that allowed the overflow into the second tank (five-slot) that also allows to the last tank (Kothyari *et al.*, 2004). The volume of runoff in each tank was measured every day at 9:00 AM and the total runoff volume per plot was calculated. All tanks were emptied and cleaned after samples were collected.

Table 1. Land use (crop) type, variety, seeding rate and fertilizer rate used

Land use (crop) type	Variety	Seeding rate (Kg/ha)	Fertilizer rate (Kg/ha)	
			P_2O_5	N
Vicia faba	*Degaga*	150	46	18
Pisum sativum	*Tegegnech*	150	46	18
Triticum aestivum	*Kubsa*	175	69	60

All sown by bradcasting

Figure 3. Typical runoff plot cultivated with wheat crop.

The total amount of eroded soil was estimated by filtration of a composite sample collected from both tanks after thoroughly mixing the runoff and sediment collected in them (Heron, 1990; Hudson, 1993). The sediment retained after filtration (Whatman No. 1, pore size 1.2 µm) was dried at 105^0C for 24 hours weighed and compared with weight of another filter paper of the same size, after filtration of an equal volume of pure water as a control (Kothyari *et al*., 2004). Daily soil loss was calculated by multiplying the runoff volume and the sediment concentration.

Statistical Analysis

Runoff and soil loss data from different experimental plots were analyzed separately in order to understand the effect of different land use on runoff and soil loss. One-way analysis of variance (ANOVA) was performed to test whether the annual runoff and soil losses induced by land uses were statistically significant. Significant means were compared using the least significant difference (LSD) test. Decadal values (ten days total) of rainfall, runoff and soil loss were related amongst themselves to establish rainfall–runoff-soil loss relationships. Microsoft Office Excel 2003 and Statistical Package for Social Sciences (SPSS v.17) were used to analyze the data.

RESULTS AND DISCUSSION

Runoff and soil loss

The total values of rainfall, runoff and soil loss during the study period in different years for different land uses are shown in Table 2. Annual runoff varies from 103.5mm from field pea plots in 2007 to 223.94 mm from faba bean plots in 2005. The average annual runoff volume in field pea plots (144.72 mm) was found significantly lower than faba bean and wheat plots (($p < 0.05$; Table 2). The reason for these lower values might be due to the maximum interception of rainwater that occurred in field pea plots because of its high ground cover and creeping nature which in turn reduce the detachment and transport capacity of rainfall and runoff. The annual soil loss varied from 7.49 t ha^{-1} yr^{-1} in field pea plot in 2007, to 60.44 t ha^{-1} yr^{-1} in faba bean plot in 2006. Average soil loss in field pea plots was found significantly ($p < 0.05$) lower than faba bean. Although it is statistically non-significant, the average soil loss from field pea plots is also lower than from wheat plots by 17%.

Table 2. Annual rainfall (P), runoff (Ro), average runoff coefficient (RoC) and soil loss (SL) under different land uses in 2005 to 2007

Year	Land use	P (mm)	Ro (mm)	RoC (%)	SL (t/ha)
2005	Field pea	531	172.65 [a]	32.5	15.18 [a]
	Wheat	531	204.04 [b]	38.4	18.45 [a]
	Faba bean	531	223.64 [c]	42.1	15.80 [a]
2006	Field pea	503.1	153.76 [a]	30.6	28.21 [a]
	Wheat	503.1	172.29 [b]	34.2	33.10 [a]
	Faba bean	503.1	176.63 [b]	35.1	60.44 [b]
2007	Field pea	541.2	103.56 [a]	19.1	7.49 [a]
	Wheat	541.2	127.11 [b]	23.5	9.61 [a]
	Faba bean	541.2	137.43 [b]	25.4	15.58 [b]
Average	Field pea	525.1	144.72 [a]	27.6	16.88 [a]
	Wheat	525.1	169.53 [b]	32.3	20.31 [a]
	Faba bean	525.1	181.44 [b]	34.6	29.95 [b]

Columns with different letters are significantly different at 0.05 level, least significant difference (LSD) test

Rainfall–runoff relationships

During the 3-year study a total of 220 rainy days that generated runoff was recorded. It was 70 days in 2005 and 2006, and 80 days in 2007. In all three years, runoff occurred when the daily rainfall exceeded 7 mm regardless of land uses which is in line with previous study in the Rift Valley of Ethiopia (Welderufael *et al*., 2009). However, a study in Tigray (northern Ethiopia) showed 3mm rainfall was sufficient to generate runoff from cultivated lands (Girmay *et al*., 2009). The relationships between decadal values of rainfall and runoff volumes were established under different land uses (Fig. 4(a-c)). Positive and significant correlations were observed between rainfall and runoff for the different land uses in all study years. Statistically significant relationships revealed by high value of coefficient of determination (R^2) and correlation coefficient (r) which are derived through regression between rainfall and runoff (Fig. 4(a-c)).

The coefficients of determination (R^2), for faba bean were 0.59 (r=0.77, $p < 0.05$), 0.67 (r=0.82, $p < 0.05$), and 0.66 (r=0.81, p<0.05) for the years 2005, 2006 and 2007, respectively. R^2 for field pea were 0.22 (r=0.47, $p > 0.05$), 0.67 (r=0.82, $p < 0.05$) and 0.49 (r=70, $p < 0.05$) for the years 2005, 2006 and 2007, respectively. Similarly, R^2 for wheat were also 0.64 (r=0.8, $p < 0.05$), 0.60 (r=0.78, $p < 0.01$) and 0.81 (r=0.90, $p < 0.01$) for the years 2005, 2006 and 2007, respectively. The relationship between runoff and rainfall is relatively lower in field pea plots due to the fact that large proportion of rainfall is absorbed by the field pea plots regardless of rainfall volume. However, the correlation coefficients still show strong relationship between rainfall and runoff in field pea plots. The correlation coefficient (r) provides a good estimate of the overall fit of the regression model. Its large value indicates a strong relationship. Different ranges have assigned for the magnitude of r. Recent publication by Field (2006) rated values as low ($r \le +0.3$), medium ($+0.3 < r > +0.5$) and high ($r \ge +0.5$). However, the higher magnitudes of r values are not enough and sometimes misleading unless supported by its test of significance. The *p*-value less than 0.05 conclude that there is strong evidence that the two variables are strongly associated.

Runoff amount in a given area is highly variable over time (Peugeot *et al*., 1997). In order to characterize this variability, the cumulative runoff (sum of runoff depth for all the previous decades) was plotted against cumulative rainfall (sum of rainfall depth for all the previous decades) (Fig. 5(a-c)). The figure shows steady trend with lower slope in the first and last two decades in year 1. But the slopes in years 2 and 3 are steep in the first three decades. These variations over years might be due to variations in rainfall intensities. The lower slope at the end of the rain season is due to the dense ground cover.

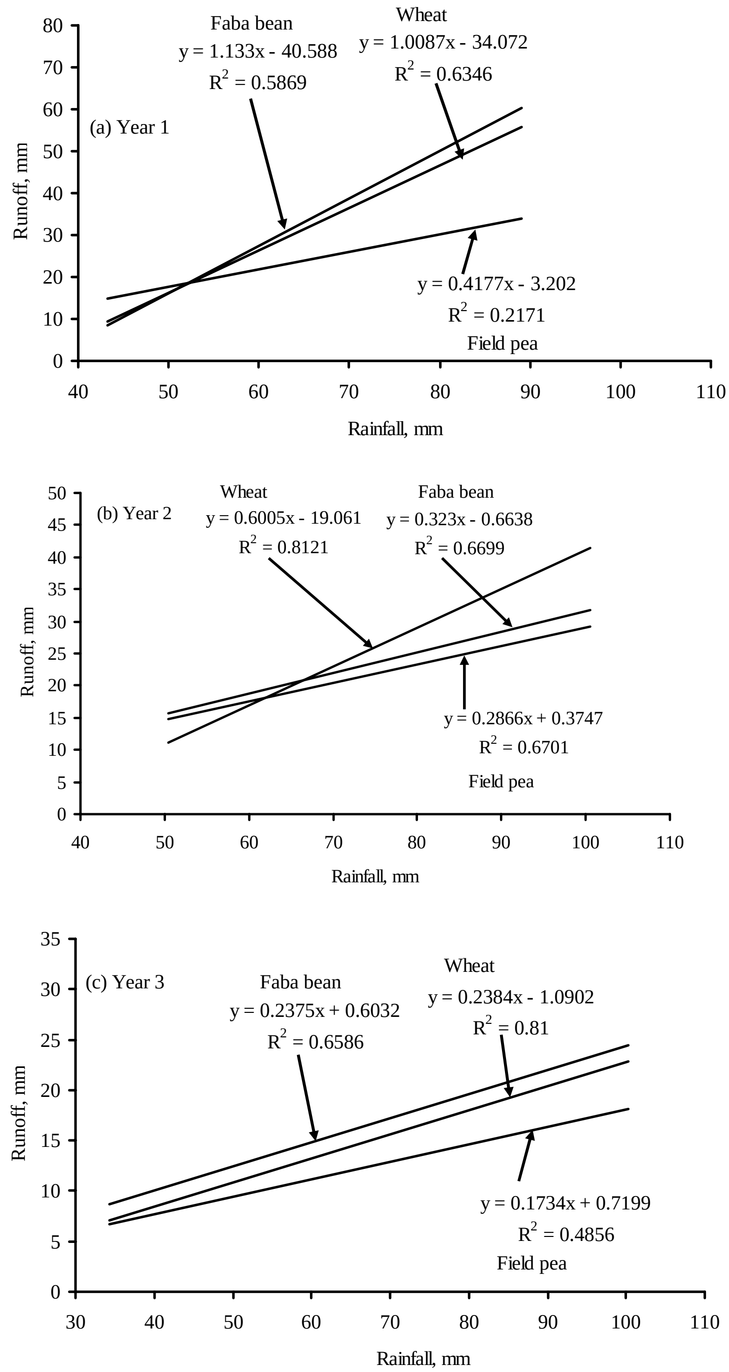

Figure 4. Runoff-rainfall relationships of plots under different crops in different years.

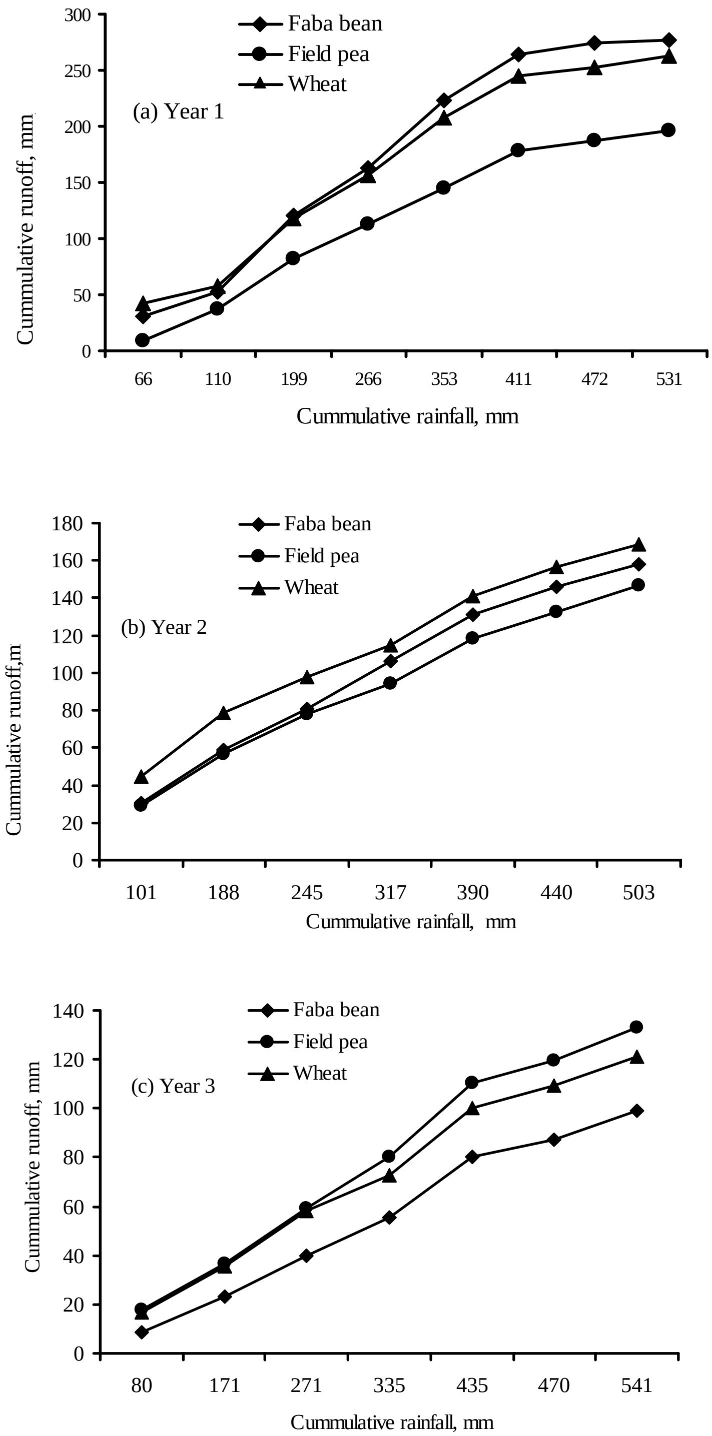

Figure 5. Distribution of cumulated rainfall and runoff in different land uses.

Runoff coefficients

A runoff coefficient, which is the ratio of runoff to the corresponding rainfall both expressed as depth (mm) over the runoff plots, shows the relationships between rainfall and runoff. The values of runoff coefficient also indicate what proportion of the rainfall becomes runoff. This means the smaller the runoff coefficient of a given land use, the more effective to reduce runoff. The knowledge of runoff coefficient of different land uses are essential to estimate the amount of runoff collected from a given catchment under given land use. This is also valuable to design water harvesting structures, drainage canals, waterways, reservoirs and to predict flood hazards. The average runoff coefficients for field pea, wheat and faba bean were 27.6%, 32.3% and 34.6%, respectively. The result of the runoff coefficients shows that field pea is more effective in reducing runoff as compared to faba bean and wheat. The values varied among land uses and years ranged from 19% in field pea to 42% in faba bean (Table 2).

Runoff-soil loss relationships

The decade values of soil losses (t ha^{-1}) were plotted against corresponding runoff values to establish runoff-soil loss relationships (Fig. 6(a-c)). R^2 of faba bean ranged from 0.63 (r=0.82, $p < 0.05$) in 2006 to 0.86 (r=0.93, $p < 0.05$) in 2007. R^2 for field pea varied from 0.65 (r=0.81, $p < 0.05$) in 2005 to 0.85 (r=0.92, $p < 0.01$) in 2006. Similarly R^2 for wheat ranged from 0.83 (r=0.91, $p < 0.01$) in 2007 to 0.98 (r=0.99, $p < 0.01$) in 2005. Although there were variations in the runoff volume and soil losses among land uses, the correlation between runoff volume and soil loss for all land uses were positive and significant over years. This relationship is highly strong relative to rainfall-runoff relationships. Generally, the distribution of soil loss over time follows roughly similar trend to the distribution of runoff over years for different land uses. This was shown by plotting the cumulative runoff versus cumulative soil losses (Fig. 7(a-c)). As shown in these figure, the cumulative soil loss increases with cumulative runoff in the first five decades and remain constant in the last two decades. The higher rate of soil loss in the first 2 to 3 decades is due to high detachability of the soil resulted from low aggregate stability and lack of ground cover.

CONCLUSIONS

Concurrent data on rainfall, runoff and soil loss have been observed from nine experimental plots having different land uses (field pea, faba bean and wheat) in the Nitisols of central highlands of Ethiopia. The result highlights and demonstrates the capacity of land use to reduce runoff and soil loss. The results suggest that crop selection can reduce runoff and soil loss significantly. However, the actual runoff and soil loss from all land use types are still high. This reflects the need for soil and water conservation measures in the area. Moreover, result of runoff coefficient indicates that large proportion of rainfall is lost as runoff under all land uses and it can be used to estimate the amount of water that can be collected from a given catchment under similar environment. The result of this study also shows that there are strong and linear relationships of rainfall-runoff-soil losses under different land uses over years. Nevertheless, the study is constrained by the use of limited soil type, slope, land uses, and rainfall regime. Therefore, further site specific studies are necessary to accommodate these factors.

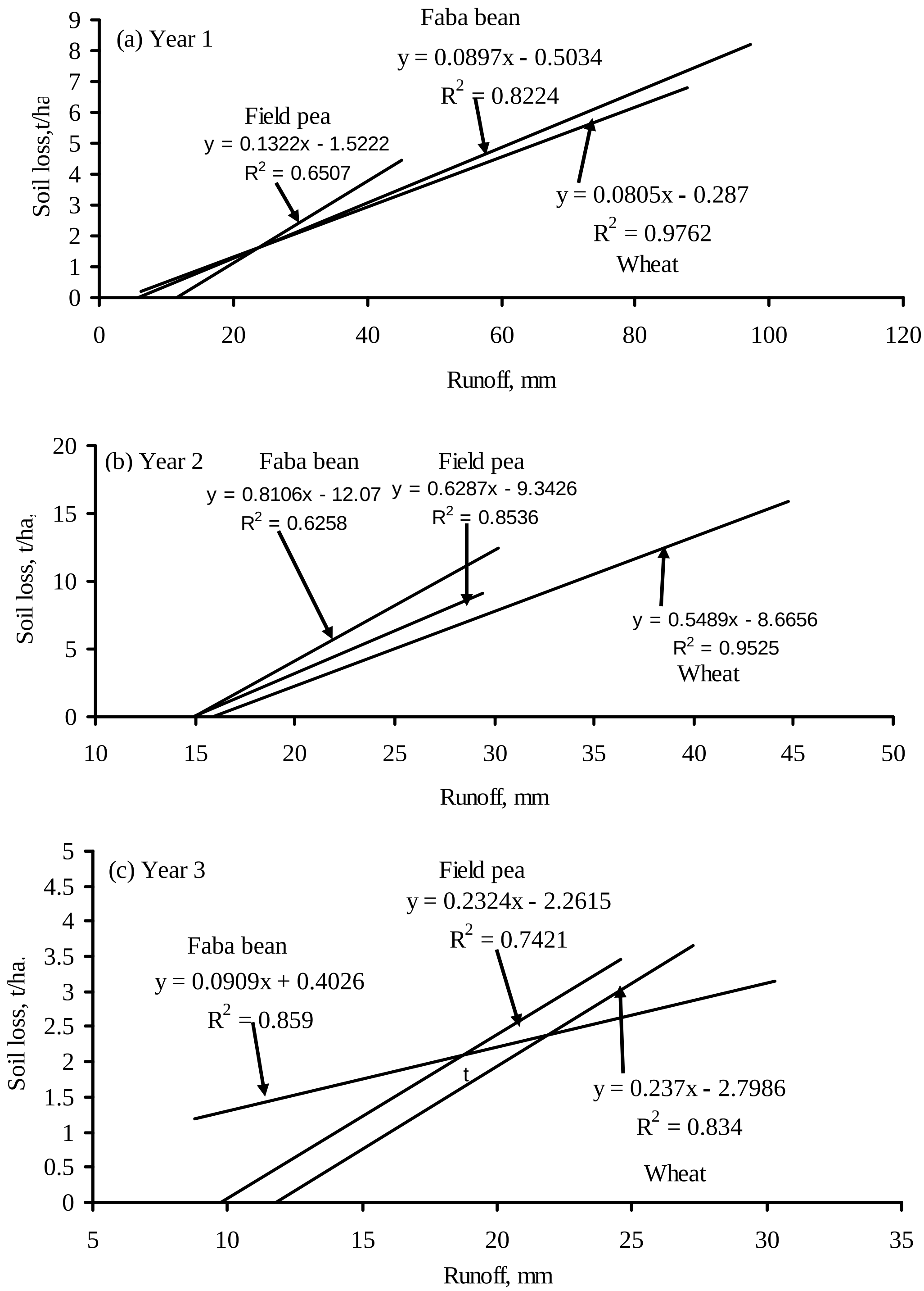

Figure 6. Soil loss-runoff relationships of plots under different crops in different years.

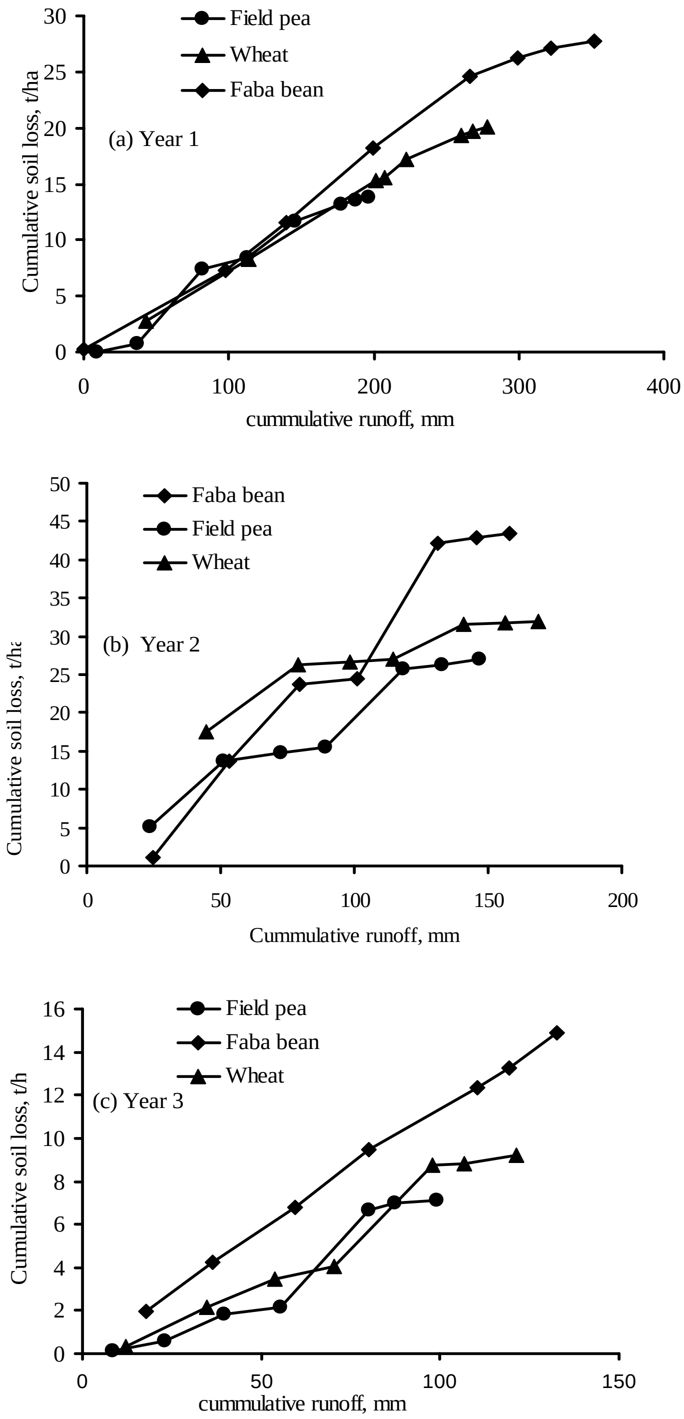

Figure 7. Distribution and relationship of cumulated runoff and soil loss.

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