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Soil loss hinders the restoration potential of tree plantations on highly eroded ravine slopes

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Abstract

Purpose Soil erosion and loss threatens vast tracts of agricultural and non-agricultural land, worldwide. High soil erosion severely affects establishment of vegetation via effects on plant growth and productivity on already degraded lands. However, information on soil loss impact on tree plantation and their relationships is scarce in the ravine lands. Therefore, we assessed soil loss effects on tree growth and soil characteristics, and role of conservation measures in degraded ravine land.

Methods The study consisted of comparing three systems, i.e., terracing, trenching, and sole slope to observe the effects on soil erosion and the resultant losses. In first system, a terraced land was designed from ravine top to bottom by dividing the slope into the four plots. In second system, ninety-seven trenches sized 2.0 m × 0.5 m × 0.5 m were designed on slope, while in third system, a continuous slope was maintained. Twenty-seven trees were planted at 8 m × 8 m spacing in each system. In all the systems, annual runoff, soil loss, tree growth, biomass and carbon stock, and soil properties were observed for the 7 years.

Results Annual soil loss was recorded highest (5.1 t ha^{-1} $year^{-1}$) in slope followed by trench (4.4 t ha^{-1} $year^{-1}$) and terrace (3.8 t ha^{-1} $year^{-1}$) systems, during the 7 years. In the slope system, increased soil loss resulted in the decreased tree height and collar diameter growth by 3–12% and 12–21%, respectively. Total biomass, carbon stock, and CO_2 sequestration declined by 44–86% with the increased soil loss on the slope during the same period. Tree canopy area was also recorded lower in the slope, compared to terrace and trench measures. The soil loss relationship with tree characteristics revealed that growth, biomass, carbon stock, and canopy area consistently declined with the increased soil loss. In soil, proportional loss of organic carbon (11–21%), nitrogen (10–13%), phosphorus (25–32%), and potassium (4–13%) was also observed with increased soil erosion on the slope, compared to conservation measures. In contrast, soil loss reduction in the terrace and trench based measures improved the tree growth, biomass, carbon stock, and soil properties during the same period.

Conclusion The soil loss negatively affected the tree growth, productivity and their restoration potential, while soil conservation measures showed strong potential to ameliorate the highly eroded ravine slopes. Therefore, tree plantations should be augmented with the appropriate soil and water conservation measures for achieving greater ecological and economic benefits in degraded ravine lands.

Keywords Soil loss · Growth · Productivity · Soil conservation · Restoration · Climate change mitigation

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1 Introduction

Soil erosion is a naturally occurring process that affects all the earth's landforms. Soil loss causes continuous degradation of land functions, some estimates suggest 10–20% of global ecosystems to be affected by soil erosion (Safriel et al. 2005), and thousands of hectares are getting degraded, not only in India but also in different regions of the world (Wang et al. 2015; Yan and Cai 2015). Due to the increasing pressure on food production systems, more and more land areas are being intensively cropped, thereby making productive lands prone to degradation. The already degraded ravine land of India is one such system where agricultural activity exaggerates soil erosion and loss, affecting the land fertility and productivity severely (Kumar et al. 2020a). Restoration of the biological functions of these lands is a priority item, worldwide.

Globally, a ravine landscape is considered one of the most degraded ecosystems, consisting of the intricate networks of large gullies (> 5 m depth) and representing extreme form of soil erosion. Anthropological activities such as intensive agriculture, mining, grazing, deforestation (Dagar and Singh 2018), overexploitation of natural resources (Chaturvedi et al. 2014), and absence of resource conservation measures (Bagdi et al. 2017) accelerate the erosion process that leads to the formation of highly fragile ravine landforms. High drainage density and multidirectional slopes induce higher soil erosion that causes the long-term changes in soils properties (Lal 2001). Continuous soil loss also reduces plant growth and development (Shrivastava and Kumar 2015), affects vegetation distribution patterns (Mehta et al. 2018), and influences plant biological and economic yield (Pande et al. 2013). Thus, erosion-induced land degradation not only alters ecosystem functions but also affects the regional economy, resulting in the increased poverty and outward population migration and posing greater risks for human civilization (Homer-Dixon 1994; Goldstone 2002).

Establishing vegetation particularly trees is considered as an important restoration strategy for highly eroded ravine lands (Kumar et al. 2020b). Sapota (*Achras zapota*) is one such tree species which has high restoration potential as well as economic value. It is widely adapted to tropics and subtropics conditions of India, South East Asia, Africa, and South America. This species is evergreen, deep rooted, hardy, and drought resistant and have great potential to ameliorate the degraded lands (Amutha 2014). However, continuous and high soil loss strongly affects the trees growth and productivity under degraded ravine conditions. Therefore, understanding the soil loss effects on the trees performance is required to restore and improve ravine land productivity, which is an important challenge for researchers to deal with the issue of erosion-induced land degradation. Earlier studies have shown that afforestation and land engineering measures can arrest the soil erosion on ravine slopes (Kurothe et al. 2014b; Ali et al. 2017; Kumar et al. 2020a). Studies in the Western India revealed that controlling soil erosion plays vital role in improving soil properties (Rao et al. 2015), promoting plant growth (Mehta et al. 2018), and enhancing biomass and carbon stock (Kumar et al. 2020b). However, soil erosion is considered the biggest challenge for establishment of planted trees. Plantation failure and low restoration and economic benefits from high input measures as a consequence of high soil erosion are the common issues which undermine afforestation efforts on ravine lands (Kurothe et al. 2013) or any other degraded land in general (García-Fayos et al. 1995; Espigares et al. 2011). Nevertheless, such lands have strong potential to sink and store atmospheric carbon in vegetation and soils (Franzluebbers and Doraiswamy 2007), and if sustainably managed, greater carbon sequestration in ravine lands can enormously contribute for climate change mitigation (Dagar and Singh 2018). Moreover, restoring highly eroded ravine land through best afforestation approaches is extremely important to conserve natural resources, improve ecosystem services, mitigate climate change, and meet the needs of regional population (de Moraes Sá et al. 2015; Roa-Fuentes et al. 2015; Prosdocimi et al. 2016).

A good deal of information is available on mechanisms and benefits of trees on soil erosion control (Xu et al. 2006), but in contrast, the soil erosion effects on tree growth, biomass, and carbon stock are not well established so far, except for effect of the slope without quantifying the actual soil erosion (Yang et al. 2000). Although the linkages between soil erosion and crop yield reduction or economic loss have been well documented (Larney et al. 1995; Bakker et al. 2004; Pande et al. 2013; Bouchoms et al. 2019), the relationship between soil erosion and tree growth also deserves immediate attention due to its scientific importance and practical applications (Jiao et al. 2009). In ravine lands, most tree plantation works are implemented on slopes, and therefore high erosion severely affects the afforestation success in long term. In general, afforestation on ravine slopes fails to provide restoration benefits in terms of time and quantum. A critical range of soil loss that significantly hampers achievement of trees ecological and economic benefits on ravine lands needs to be assessed. Further, it would be interesting to determine how soil loss affects the tree growth, biomass, carbon stock, and soil properties on ravine lands. Quantification of growth parameters at different soil loss levels is required to assess species suitability for afforestation and to design soil conservation measures. The resolution of these questions will provide important information about the tree growth patterns under different conditions that will help in ecological restoration planning for large-scale implementation. We hypothesized that over the years, soil loss on ravine slopes causes critical nutrient loss with the runoff water that would have direct relation with the trees growth, biomass, and carbon stock. Therefore, objectives of the present study were (i) to assess the impact of slope and soil conservation measures on tree growth patterns, canopy development, biomass, carbon stock, and soil properties and (ii) to establish the relationships of soil loss with tree growth, biomass, and carbon stocks on ravine lands. The present study aimed to report soil loss effects on tree growth, biomass, and carbon stock, under long-term exposure, and the need for designing conservation measures in the highly degraded ravines of Western India.

2 Materials and methods

2.1 Experimental site

The study was conducted in semi-arid degraded ravine landscape of the Western India (22°16′ N; 72°58′ E; 25 m amsl) during 2010–2016. During study period, the mean monthly minimum and maximum temperatures were 8.45 °C (in January) and 40 °C (in May), respectively, while average annual precipitation was 922 mm. Most (90%) of the rainfall is received during monsoon period (June–September) only and rarely any rainfall during rest of the year. In this region, high erosion occurred after every rainfall event that led to the formation of gullied ravines over long time period. The experiment site was a large gully overspread with undulating terrain consisting of 9–14% land slope. Soils were deep, less fertile, severely eroded, sandy loamy textured, and having low water holding capacity because of the high infiltration rate. The pre-existing (before establishing treatments) organic carbon (OC), nitrogen (N), phosphorus (P), potassium (K), and pH of the soils ranged between 0.46–0.51%, 95–101 kg ha^{-1}, 14–17 kg ha^{-1}, 186–196 kg ha^{-1}, and 8.1–8.2, respectively. Detailed site characteristics and initial site features after establishing conservation systems are presented in Table 1.

2.2 Experimental design

In ravine system, morphological characteristics of land consist of table land, slopes, and gully bed on top, side, and bottom, respectively (Fig. 1). Regional land use pattern consists of agriculture/agroforestry/plantations on table land, while grasslands, and open scrub forests on the slope. Majority of afforestation works in ravines are implemented on slopes and few on the table land and gully bed. All land use systems are prone to soil erosion that subsequently affects the growth and development of plants. Hence, to quantify soil erosion impact on tree growth characteristics, we considered the slope and terrace based land use systems. For the present study, a ravine with uniform morphological (topography and soil) and slope features was considered, and treatments were executed starting from the slope top to the bottom. The conservation measures, terrace and trench compared to the sole slope, were considered to observe their relative effectiveness in promoting tree growth, biomass production, and carbon stock in ravine lands (Fig. 2). All the treatments (systems) were separated by earthen bund sized 30 cm × 30 cm. In the first system, terraces were designed from top to bottom of the slope. Four terraces (16–19 m sized) were created by reshaping (cut and fill method) the slope into four nearly level sub-plots, keeping in consideration the tree-to-tree spacing and slope length and stability in the second system, ninety-seven trenches sized 2.0 m × 0.5 m × 0.5 m were dug in staggered manner on the whole slope. The density, size, pattern, and spacing of staggered trenches were designed considering the criterion like highest intensity storm, runoff coefficient, treatment area, land slope, and tree to tree spacing, similar to procedure elaborated by Ali et al. (2017) and Kurothe et al. (2014b). The size of trenches was designed to catch the 70% runoff generated from the rainfall events. The number of trenches were optimized considering the vertical interval and horizontal spacing between the trenches based on the land slope. In the third system, a uniform slope was maintained to assess tree plantations performance on the natural ravine slope. Each treatment was executed in 72 m × 24 m plot size, and the total area under experiment was 0.51 ha (0.17 ha under each treatment). Sapota (*Achras zapota*) trees were planted at 8 m × 8 m spacing during the year 2010, keeping the 4 m distance from each plot border. Twenty-seven trees were planted in each treatment, consisting of total eighty-one trees in the whole experiment.

2.3 Tree growth, biomass, and carbon stock determination

In this study, plant height and collar diameter of all trees were measured during the month of December (each year) to evaluate the Sapota growth and productivity. Collar diameter and tree

Table 1 Morphological characteristics and initial soil properties of the different systems. Numbers followed by means are ± SD

Treatment	Slope	Surface roughness	Soil texture	pH	EC (ds/m)	Organic carbon (%)
Terrace system	3–5% each subplot	No roughness	Fine loam	8.08 ± 0.07	0.17 ± 0.03	0.51 ± 0.06
Trench system	9–14%	Low roughness	Fine loam	8.05 ± 0.05	0.16 ± 0.03	0.54 ± 0.05
Slope system	9–14%	Low roughness	Fine loam	8.04 ± 0.04	0.18 ± 0.05	0.52 ± 0.06

Fig. 1 A general view of the ravine landscapes of Western India

height growth were measured using the procedure described by West (2009). Stem volume of each tree was determined from diameter and height to estimate stem biomass as per the methodology given by Tomar et al. (2015). Above ground (stem, branch wood, and leaves) and below ground biomass (root) components were estimated to determine total biomass (above + below), adopting the methodology described by Kumar et al. (2020a). Carbon stock and CO_2 sequestration in each tree were estimated from total biomass using the relationships suggested by Petersson et al. (2012). Carbon stock of each tree was estimated (biomass × 0.50) from total tree biomass, and carbon sequestration was determined (carbon stock × 3.67) from the biomass

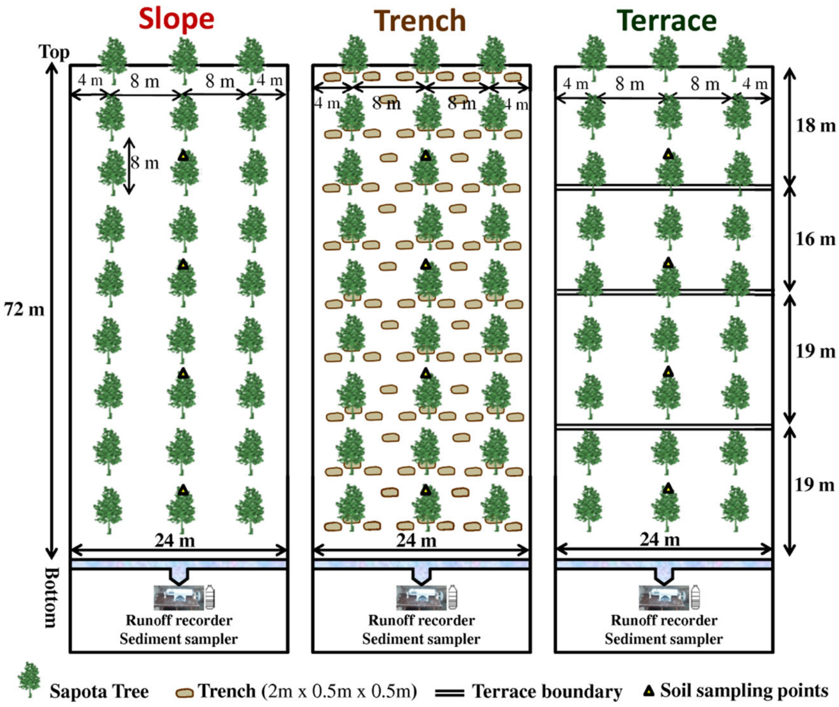

Fig. 2 Experiment layout with treatment details

carbon stock. Furthermore, total biomass, carbon stock, and carbon sequestration for each system were determined on hectare basis. Trees canopy area was calculated by measuring the East-West and North-South horizontal maximum spread of branches.

2.4 Runoff and soil loss estimation

A V-notch structure (90°) made of the iron sheet and automatic stage level recorder connected through stilling well were installed at each plot outlet to quantity runoff generated during the individual storm events. The runoff samples were collected manually during each rainfall event from V-notch at the each plot outlet. Samples were analyzed in the laboratory to estimate the soil loss as per methodology described by Fang et al. (1999). The runoff was determined from the charts fixed in stage level recorder after digitizing surfer software V 13.6 to obtain each event hydrograph following the procedure described by Pathak et al. (2004). Annual runoff was calculated as the percent of the total annual rainfall.

2.5 Soil sampling and analysis

Soil properties were evaluated after analyzing the soil samples in the laboratory, during Jan 2010 and Dec 2016. For each treatment, soil sample was collected at the four locations (top, upper-middle, lower-middle, and lower slope position). At each location, samples were drawn at 0–15, 15–30, and 30–45 cm depths using a tube auger and composited together for soil properties analysis. Soil pH and EC were determined using 1:2.5 soil-water suspension with a multimeter (Eutech Instruments, Singapore) (Jackson 1973). Organic carbon was determined following the wet digestion method (Walkley and Black 1954). Available N, P, and K were determined by alkaline permanganate (Subbiah and Asija 1956), $SnCl_2$ reduced phosphomolybdate (Jackson 1973) and flame photometer methods, respectively.

2.6 Statistical analysis

The Tukey's HSD (honest significant difference) was performed in conjunction with one-way ANOVA in quasi-randomized block design to detect differences among treatments for mean tree height, collar diameter, biomass, carbon stock, canopy area, and soil properties. The average annual collar diameter, height, canopy area, biomass, carbon stock of trees, and soil loss from second year (2011) to seventh year (2016) were derived from the mean of cumulative averages for the each treatment (Table 2). First year (2010) data was excluded in developing the relationships, as 1-year-old sapling was planted in treatments, and growth due to transplanting shock might not be proportional to the treatment effects including response to erosion. To eliminate this bias, the relationships were drawn only for the second year onward to the seventh year ($n = 6$) by combining particular parameter of each treatments ($n=3$) in single data set ($n = 18$). Significance among the treatments was tested at 5% level of significance. All these statistical analyses were performed using the SPSS 16.0 software.

3 Results

3.1 Soil loss and runoff trends

During the study period, annual rainfall was ranged minimum of 475 and maximum of 1611 mm during 2015 and 2013 year, respectively. Results explained that both mean soil loss and run-off decreased in the order of slope > trench > terrace, during the study period (Table 3). Each year, maximum runoff and soil loss were generated in the slope followed by trench system, while both parameters were recorded minimum in terrace system. Specifically, after 7 years, mean run-off and soil loss were recorded 18.5% and 3.8 t ha^{-1}, respectively, in the terrace; 23.6 and 4.8 t ha^{-1}, respectively, in the trench; and 29.6% and 5.1 t ha^{-1}, respectively, in the slope system. Overall, mean runoff and soil loss was recorded higher in the slope, compared to terrace and trench system.

3.2 Tree growth patterns

Significant ($P < 0.05$) effects of conservation measures on the mean plant height and collar diameter growth of Sapota tree were observed during different years. Mean height and collar diameter growth were observed lesser in sole slope, compared to terrace and trench, after 7 years (Fig. 3). In particular, mean height and collar diameter growth on slope was recorded 3–12% and 12–21% lower, respectively, compared to terrace and trench measures. Year-wise comparison showed that both plant diameter and height were lower on the slope than terrace and trench from the second year onward and stayed lower for all the years (Fig. 3). Few overlapping trends for plant height were also noted among the different treatments. The relationship between average annual soil loss and tree growth parameters explained that with increased average annual soil loss (Eq. (3)) from 3.81–7.78 t ha^{-1} $year^{-1}$, both the average annual collar diameter (Eq. (1)) and height growth (Eq. (2)) decreased consistently from 7.45 to 3.0 cm $year^{-1}$ and 233 to 110 cm $year^{-1}$, respectively (Fig. 4). The results showed that slope contributed lower growth value compared to terrace and trench measures, while soil loss had negative affect on the tree height and collar diameter growth, during the study period.

3.3 Tree biomass productions

Our results showed that soil conservation significantly ($P < 0.05$) affected the total tree biomass, during the study

Table 2 Formulae used for deriving different parameters (n, number of years)

Sr. no	Formulae	Remarks	Reference
1.	$DBH_{an} = \frac{\sum_{i=1}^{n} (DBH_m)}{n}$	DBH_{an} is the average annual diameter in ith year ; DBH_m is the mean DBH of nth year	Eq. (1)
2.	$H_{an} = \frac{\sum_{i=1}^{n} (H_m)}{n}$	H_{an} is the average annual plant height in ith year; H_m is the mean plant height of nth year	Eq. (2)
3.	$SL_{an} = \frac{\sum_{i=1}^{n} (SL_m)}{n}$	SL_{an} is the average annual soil loss in ith year ; SL_m is the mean soil loss of nth year	Eq. (3)
4.	$BM_{an} = \frac{\sum_{i=1}^{n} BM_m}{n}$	BM_{an} is the average annual biomass in ith year; BM_m is the mean biomass of nth year	Eq. (4)
5.	$CS_{an} = \frac{\sum_{i=1}^{n} CS_m}{n}$	CS_{an} is the average annual carbon stock in ith year; CS_m is the mean carbon stock of nth year	Eq. (5)
6.	$CA_{an} = \frac{\sum_{i=1}^{n} CA_m}{n}$	CA_{an} is the average annual canopy area in ith year; CA_m is the mean canopy area of nth year	Eq. (6)

period. In absolute terms, tree biomass was 44 and 86% lower on the slope, compared to terrace and trench, respectively, after 7 years (Fig. 3). In contrast, terrace produced 4.5 t ha^{-1} higher mean tree biomass, compared to trench, during the same period. We observed an increasing difference for biomass production among the treatments with increased plant age (2010 to 2016), and each year, biomass trend was in order of terrace > trench > slope (Fig. 3). Results further showed that increase in average annual soil loss (Eq. (3)) from 3.81 to 7.78 t ha^{-1} year^{-1} resulted in the decreased average annual biomass production (Eq. (4)) from 2.9 to 0.2 t ha^{-1} year^{-1}, during experiment period (Fig. 4).

3.4 Tree carbon stock accumulations

Present results showed significant ($P < 0.05$) effect of soil loss on standing biomass carbon stock in Sapota. Mean tree carbon stock was recorded lower in slope followed by the trench, while higher carbon stock was observed in terrace system (Fig. 3). In quantitative terms, terrace and trench measures accumulated 1.56 and 0.80 t ha^{-1} more carbon stock, respectively, compared to slope, after seven years. Each year (2011–2016), superiority of terrace over trench and trench over slope was observed for the carbon stock accumulation. Further, increase in average annual soil loss (Eq. (3)) showed strong negative effect on average annual carbon stock (Eq. (5)) during the study period (Fig. 4). Similarly, CO_2 sequestration reduction in trees was observed on slope, while increase was observed in terrace and trench systems (Fig. 5). These results indicate that soil loss decreased carbon stock and CO_2 sequestration potential in Sapota, while soil conservation measures improved both the parameters under these conditions.

Table 3 Rainfall, runoff, and soil loss parameters during the study period (2010–16)

Treatment	Year							Mean (2010–2016)
	2010	2011	2012	2013	2014	2015	2016	
	Annual rainfall (mm)							
	824.0	916.0	852.0	1611.0	1221.0	475.0	560.0	939.0
Run-off (%)								
Terrace	21.9	25.1	24.5	21.4	20.0	6.7	9.8	18.5
Trench	30.8	29.5	29.3	27.8	24.5	9.2	13.9	23.6
Slope	40.6	34.4	33.4	32.3	29.8	12.2	24.5	29.6
Soil loss (t ha^{-1})								
Terrace	4.9	5.3	5.2	4.7	4.8	1.9	0.1	3.8
Trench	6.9	5.5	6.0	4.9	5.1	2.1	0.2	4.4
Slope	9.2	5.8	6.2	5.8	5.8	2.9	0.2	5.1

3.5 Canopy developments

Significant effect ($P < 0.05$) of different treatments was observed on tree canopy area which was in the order of terrace > trench > slope (Fig. 6). Each year (2011–2016) and more importantly during 2016, mean tree canopy area was recorded highest in terrace followed by trench, and lowest value was observed on slope. Soil loss also exerted strong effect on tree canopy area (Eq. (6)), and the latter's value decreased with increased soil loss during the 7 years (Fig. 6).

3.6 Differences in soil properties

In our study, slope exerted significant negative ($P < 0.05$) effect on soil organic carbon (OC), nitrogen (N), phosphorus (P), and potassium (K), compared to terrace and trench (Table 4). Specifically, compared to terrace and trench, OC, N, P, and K on slope decreased by 11–21%, 10–13%, 25–32%, and 4–13%, respectively, after 7 years. However, non-significant differences between terrace and trench were observed with respect to the soil properties.

4 Discussion

Most of the ravine landscapes are characterized by the extreme rainfall events, high summer temperature, severe soil erosion, and high anthropogenic pressure. However, soil erosion is

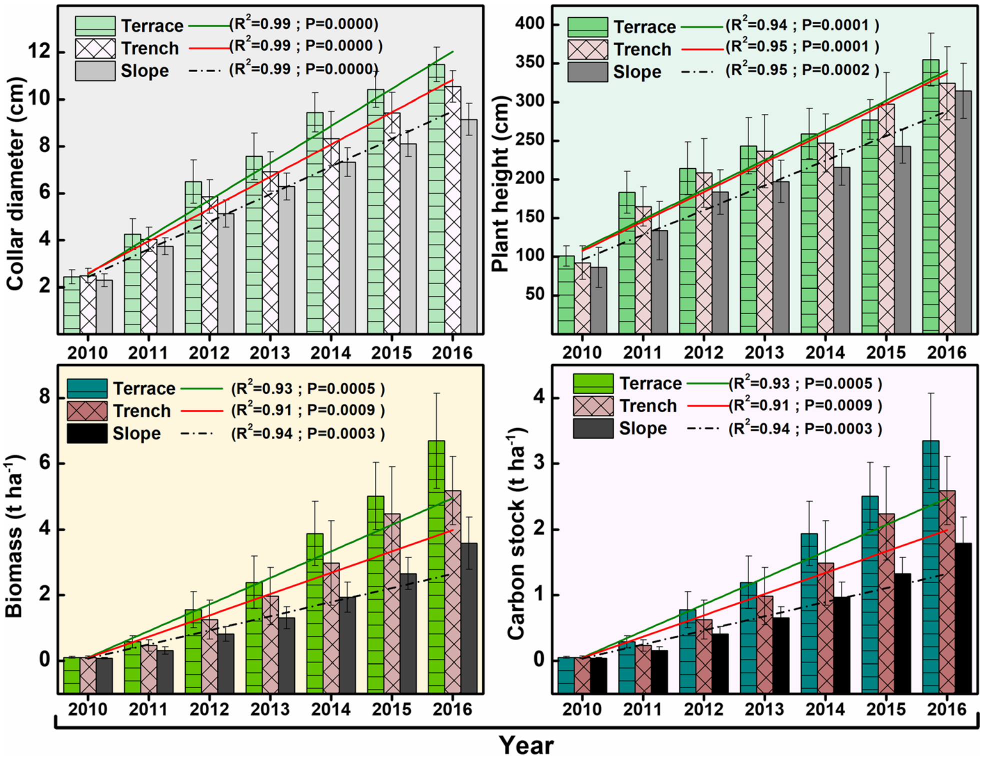

Fig. 3 Effects of conservation treatments and slope on collar diameter, plant height, biomass, and carbon stock. The error bars denote ± 1SE

considered most critical factors affecting the tree growth and biomass production on these lands. The degree of soil erosion varies from slight through moderate and strong to the extreme, depending on the slope, vegetation, topographic position, and rainfall intensity. In ravine systems, rainfall causes heavy soil erosion every year, leading to the extension of gullies to crop lands at the rate of about 8000 ha per annum (Pande et al. 2018). Soil conservation measures protect these landscapes

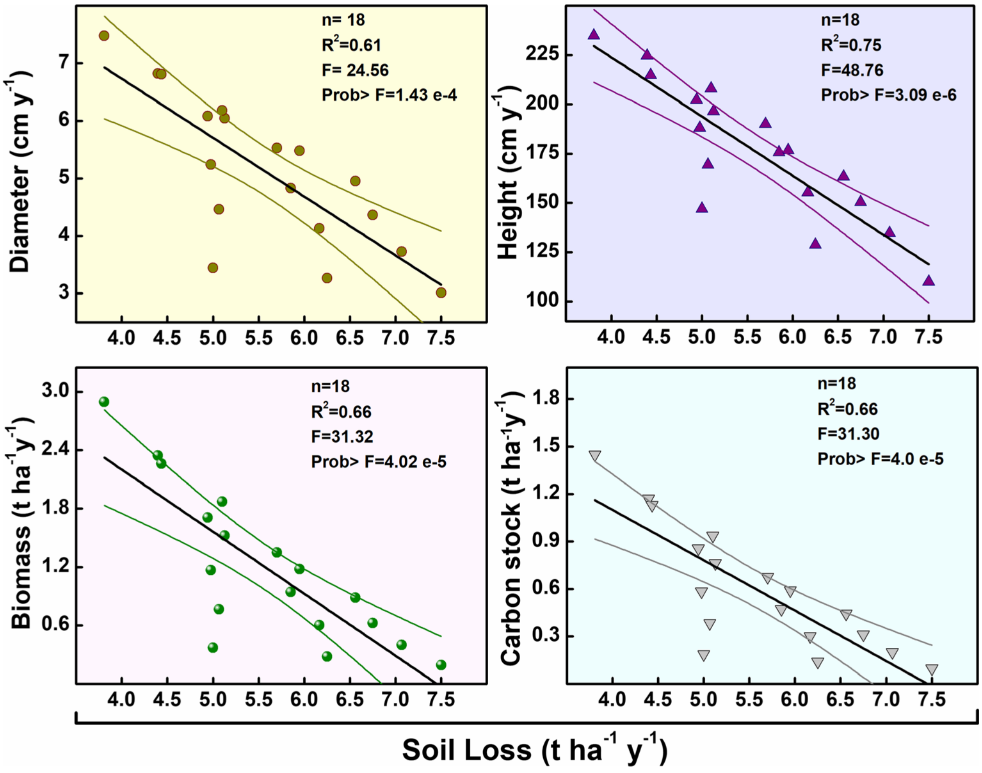

Fig. 4 Effects of average annual soil loss on average annual collar diameter, plant height, biomass, and carbon stock

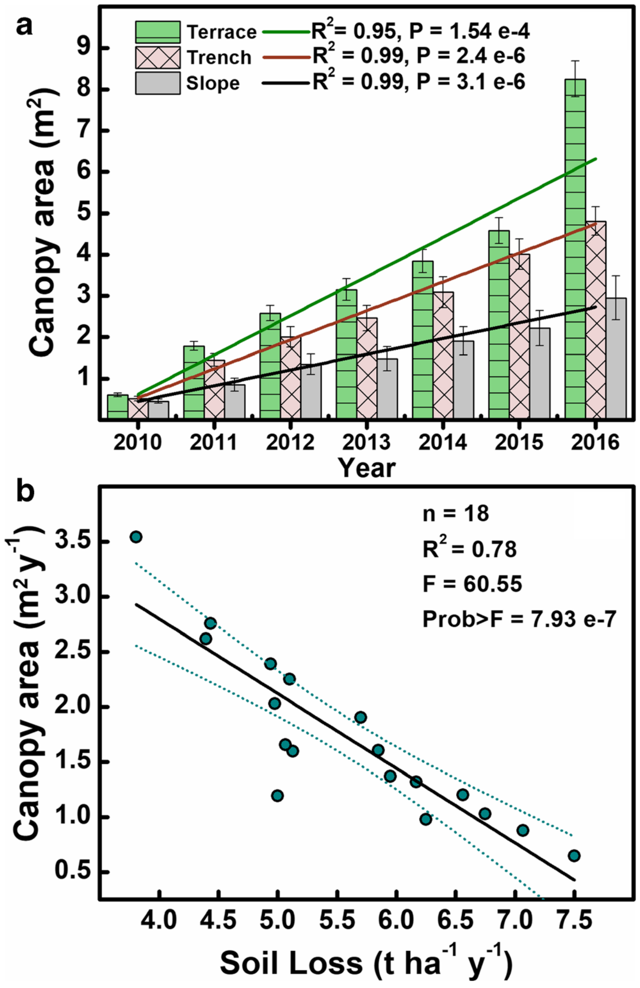

Fig. 5 Effects of conservation treatments and slope on tree canopy and its relation with soil loss. The error bars denote ± 1SE

by controlling erosion, while unprotected agricultural lands turn into highly eroded ravines during this period. The current study pointed to higher runoff and soil loss in sole slope system, compared to trenching (on slope) and terracing based soil conservation measures. In slope system, at the onset of rainfall, runoff water carries a significant load of soil, causing the instant formation of rills due to sheet erosion. Continuous soil erosion transforms these landscapes to small gullies in the short term and large gullies (ravine) in the long-term period. Heavy soil erosion also causes expansion of ravine area that consequently results in the villagers' migration to outside from the fringe area of the ravines (Saxena and Agarwal 1997). These processes also send soil-laden water downstream, creating heavy layers of sediments that prevent streams and rivers from flowing smoothly, eventually lead to out flow and flooding during the heavy rainfall events (Obhodas et al. 2020; Szalińska et al. 2020). In contrast, presents results showed that implementing terrace and trench measures helps to controls overland water flow, which enhances the surface water retention and rain water infiltration, thereby reduced the runoff (20–37%) and soil loss (14–25%). Previous studies under similar site conditions have reported that conservation tillage practices (terraced land) reduce the run off and soil loss by 17 and 37.2%, respectively, compared to conventional tillage operations (Kurothe et al. 2014a). Ali et al. (2017) also highlighted that under different trench densities reduction in the runoff and soil loss ranged between 37·7–86·1% and 40–125%, respectively, under over long-term period in ravine land. Tree plantations are also reported to contribute significantly in controlling soil erosion under such conditions (Kumar et al. 2020a). In this region (Western India), moderate rainfall and lesser annual rainy days also cause soil loss to the large extent. Soil erosion also consequently changes the soil properties as evidenced by the present results. Greater soil erosion on the slope declined soil OC, N, P, and K, compared to terrace and trench, after 7 years. Runoff water carries significant nutrients along with the soil particles that decrease the soil nutrients in slope systems (He et al. 2019). Kumar et al. (2014) and Rao et al. (2015) also reported high loss of nutrients with soil erosion under almost similar management practices and site conditions. Low land productivity coupled with the loss of top fertile soil and nutrients makes conditions worse to support the plant growth. In contrast, our findings proved that terrace and trench based conservation measures reduced the loss of soil OC (11–21%) and nutrients in erosion process. Kurothe et al. (2013) also explained the strong effect of agronomic, land engineering, and forestry based conservation measures in controlling soil erosion in the Indian ravine systems. These measures on such degraded ecosystems contribute to the land stabilization and productivity enhancement in long term due to their strong check on soil erosion processes.

In ravine lands, continuous and heavy soil erosion exerts adverse effect on the plant growth and development as well. The current study showed the negative effects of soil loss on tree growth parameters during the 7 years of experimentation. In

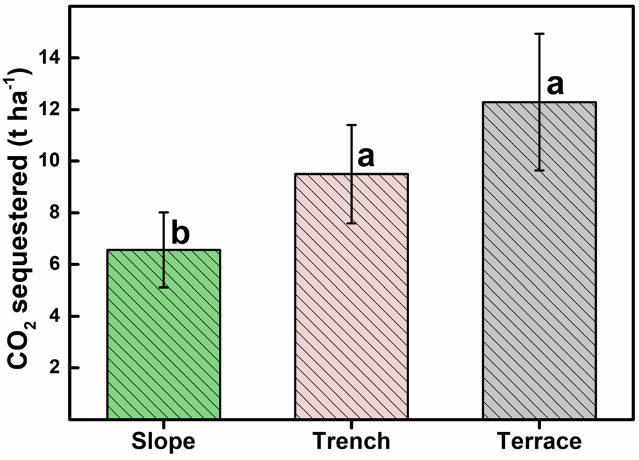

Fig. 6 Effects of conservation treatments and slope on CO_2 sequestration after 7 years

Table 4 Soil properties under different systems after 7 years

System	Organic carbon (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
Terrace	$0.64^{a} \pm 0.05$	$125.7^{a} \pm 6.8$	$19.1^{a} \pm 2.3$	$231.6^{a} \pm 15.5$
Trench	$0.59^{a} \pm 0.04$	$122.6^{a} \pm 5.6$	$18.1^{a} \pm 1.6$	$221.7^{a} \pm 8.6$
Slope	$0.53^{b} \pm 0.03$	$111.4^{b} \pm 4.6$	$14.5^{b} \pm 1.4$	$206.6^{b} \pm 9.8$

Numbers followed by means are ± SD. For a particular parameter, numbers with same letters are not significantly different at $P \leq 0.05$

particular, results suggested that more soil loss in slope system contributed to the lesser increment in tree height and diameter growth, compared to trenches and terrace measures. Not only loss of water which is vital for the plant growth but loss of nutrients might also have contributed to these effects. For example, erosion-induced soil nutrients loss also affected the growth of *Pseudotsuga menziesii* (Miles et al. 1984), *Eucalyptus camaldulensis* (Yang et al. 2000), and *Phyllostachys praecox* (Zhuang et al. 2016) under different scenarios of land degradation. Previous researchers also have investigated the significant effect of the slope and soil loss on trees growth and productivity in the region (Pradhan and Dayal 1973; Singh et al. 1977; Bagdi et al. 2017). Our analysis revealed an inverse relationship of soil loss with the tree height ($R^2 = 0.75$), diameter growth ($R^2 = 0.61$), and biomass production ($R^2 = 0.66$). Reduction in tree growth from 3.0 to 7.45 cm year^{-1} with increased erosion makes the sole tree based restoration efforts a difficult and challengeable task, in view of global acceptability of afforestation success in highly degraded and eroded lands. In particular, economic benefits of tree plantations on slopes will be lower even after longer time period due to lesser tree growth increments caused by continuous soil erosion. Pande et al. (2013) also highlighted high economic loss ranging from 50 to 75% in terms of agricultural production as a consequence of heavy soil erosion in these lands. Physical effect such as exposure and weakening of roots system as a consequence of extension of gullies makes trees prone to fall and increase susceptible to insect-pest and diseases. In the absence of other soil conservation measures, a critical soil loss limit needs to be determined above which there would be strong effect on the tree growth and beyond which soil conservation measures must be implemented. However, even in the absence of such limits, it seems imperative to implement trenching or terracing along with tree plantation particularly for highly erosion susceptible ravines of Western India, or any other similar degraded lands.

Biomass production is determined by the quantity of soil moisture and nutrients availability to plants during the active growing season. Present results showed a consistent decline in the tree biomass production from 0.2 to 2.8 t ha^{-1} year^{-1} with the increased soil loss from 3.8 to 7.8 t ha^{-1} year^{-1} in 7 years. Continuous soil erosion (every year) and poor soil fertility create conditions worst for the successful growing and establishing any kind of vegetation at such sites. Espigares et al. (2011) pointed out that soil erosion more than 17 t ha^{-1} year^{-1} and vegetation cover less than 30% inhibit plant growth and development on reclaimed slopes over the long-term period. Lower biomass production on slopes has serious implications for success of conservation and rehabilitation programs on ravines (Fig. 7). If the restoration benefits of plantations are not achieved within a reasonable time period, it discourages all the stakeholders, including farmers and policy implementers to adopt tree plantations in these lands. One of the primary targets in reclaiming eroded slopes is to reach an optimal level of vegetative cover (> 50%) to significant cut down the soil erosion (Andres and Jorba 2000). Lower biomass production in ravines also results in the impairment of other processes like microclimate and hydrology in particular, and regional ecology in general. On similar lines, Grime (2001) also suggested that reduction in soil fertility from increased erosion causes decline in the diversity of plant species, resulting in the negative effects on regional ecology processes. Similarly, biomass carbon stock, which is directly dependent on tree growth, would be severely impaired due to continuous erosion and soil loss. Decrease in biomass carbon sequestration and increase in carbon loss through soil erosion bears double importance of conservation measures that make significant impact, especially for ravines land, in extent to climate change mitigation and adaptation (Rao et al. 2013). Even small amount of nutrient

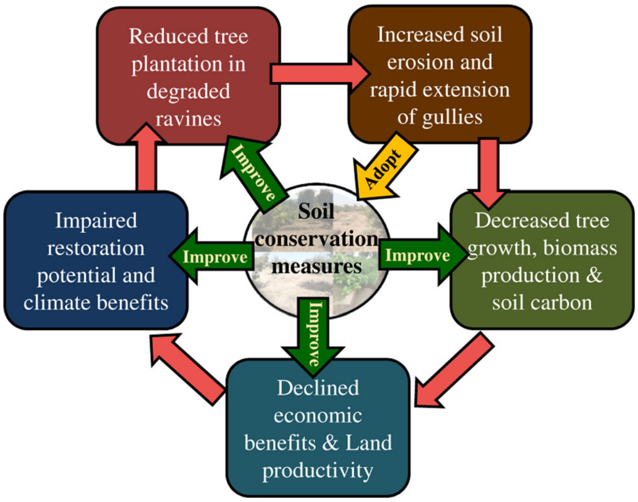

Fig. 7 Conceptual framework depicitng process of declining plantation restoration potential in ravine lands

conservation along with synergistic effect of conserved soil moisture can have profound effect on plant biomass production. Therefore, implementation of any measure that can results in slight favorable effect in terms of soil and nutrient conservation may contribute greatly in sustaining and restoring these ecosystems.

5 Conclusions

Rehabilitation of degraded ravine lands calls for fast establishment of trees and vegetation to check soil erosion and loss of water and nutrients. The study pointed out that soil erosion has negative effects on tree growth, and 7.5 t ha^{-1} $year^{-1}$ seems to be a critical limit to severely curtail the plant growth and biomass productions on the ravines of Western India. Tree establishment alone may not be an effective means to check soil loss and restore ravines of Western India. This has serious and long-term implications for conservation and rehabilitation of the degraded ravines. Soil conservation via terracing or trenching provides significant support for establishing trees on ravine slopes by decreasing soil and nutrient loss and thereby enhancing the plant growth. Therefore, tree plantation supported with the soil and water conservation measures provides best strategy for improving land productivity, climate change mitigation benefits, and ecological restoration of ravines.

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Data availability Raw data is available with ICAR-IISWC, Dehradun, India.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Authors' consent All authors give their consent for participation and publication.

Code availability N.A.

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