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Full Length Research Paper

Effects of rainwater harvesting and afforestation on soil properties and growth of *Emblica officinalis* while restoring degraded hills in western India

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Effect of rainwater harvesting (RWH) structures like Contour trench (CT), gradonie (GD), box trench (BT), V-ditch (VD) and afforestation with *Emblica officinalis* Gaertn (planted in August, 2005) were studied in <10%, 10-20% and >20% slopes with a view to improve soil status, plant growth, sequester carbon and rehabilitate hills for local benefits. Soil pH and EC decreased and percent soil, SOC, NO_3-N and PO_4-P increased in June 2010 over 2005. Enhanced soil water and nutrients in <10% slope facilitated height and collar diameter growth of *E. officinalis*. Soil water was 14.0 and 51.4% greater in >20% and <10% slopes, respectively than in 10-20% slope, whereas it was 17.8, 16.1, 24.2 and 14.0% greater in CT, GD, BT and VD treatments, respectively over control. The highest plant growth was in CT plots in all slopes. Second best treatment was BT in <10% slope and VD in other slopes. Conclusively, RWH and afforestation facilitated soil improvement but CT/BT treatments were more efficient in conserving soil and water facilitating plant growth and helped restore the degraded hill. However, further research is required on soil water use and its partitioning in different vegetation component and the benefits accrued from it for the local people.

Key words: Plant growth, hill restoration, soil carbon, soil nutrients, water dynamics.

INTRODUCTION

A disturbance to the natural habitats in the form of illegal mining and vegetation removal is a common phenomenon in most of the hilly tract causing land degradation (Ajai et al., 2009). The Aravallis, most distinctive and ancient mountain chain of north western peninsular India, mark the site of one of the oldest geological formations in the world. A large number of mining, operation of stone crushers and pulverisers, deforestation and unplanned construction activities are causing environmental degradation (CPCB, 2010). Over-exploitation and over-grazing exacerbate this problem as a result one can see barren hills devoid of vegetation throughout the Aravalli ranges. When put under protection from human and livestock interferences, these disturbed habitats may take longer time to recover naturally by colonizing plant and animal species (Abede et al., 2006). The process of rehabilitation can be accelerated through human intervention like afforestation (Jha and Singh, 1992; Sharma and Sunderraj, 2005). This provides a basis for environmental improvement by way of avoiding desertification and facilitates carbon sequestration. However, inadequate availability of water and nutrients affect natural regeneration or plantation growths (Li et al., 2008; Gammoh, 2011) and there is need to supply additional water and nutrients. Rainwater harvesting (RWH) devices may be useful in increasing water supply and facilitating plant growth (Gupta, 1995; Prinz, 2001; Xiao-hui et al., 2005) and vegetation cover (Jia et al., 2006; Singh et al., 2010) by improving infiltration rate and soil nutrients (Ludwig et al., 2005; Liu et al., 2008; Vohland and Barry, 2009). However, the extent to which different RWH devices influence soil improvement, plant growth and rehabilitation process needs to be investigated under different topographical conditions particularly in the

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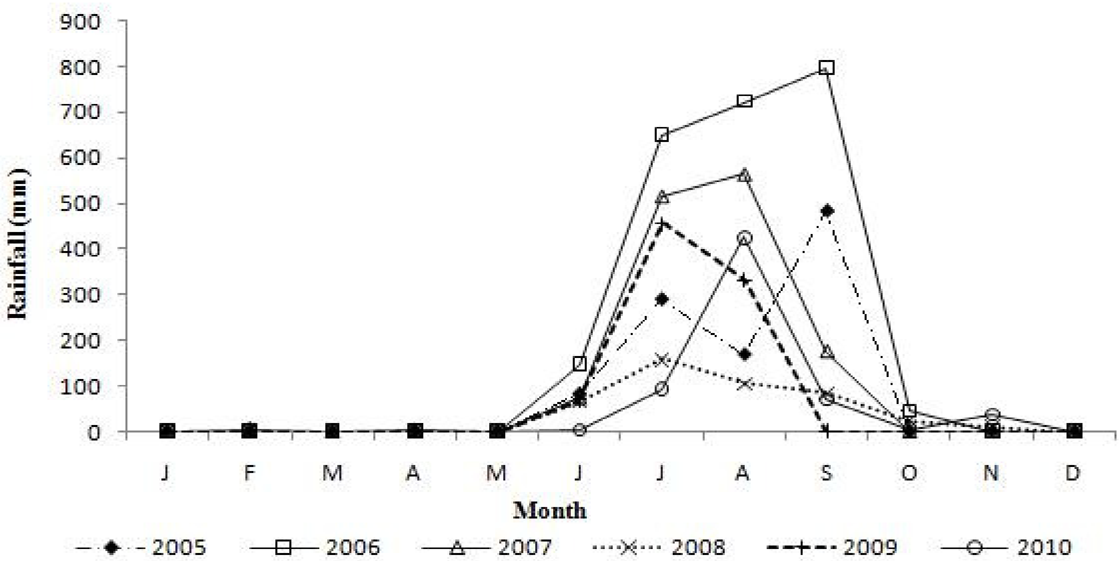

Figure 1. Monthly rainfall (mm) in different years near the experimental site, Banswara, Rajasthan, India.

degraded hills.

Emblica officinalis Gaertn is an important species used under afforestation in the degraded hills of Aravalli region along with *Acacia catechu*, *Azadirachta indica*, *Holoptelia integrifolia*, *Zizyphus mauritiana,* etc. *E. officinalis* is Indian gooseberry known as 'Aonla' belonging to family Euphorbiaceae. The plant is used both as a medicine (Kasabri et al., 2010; Krishnaveni and Mirunalini, 2010) and reclamation of mine dump area (Nandeshwar et al., 2006). *E. officinalis* is a medium size tree, normally reaching a height of 18 m and in rare instances up to 30 m. It is native to tropical south-eastern Asia commonly distributed in Bangladesh, China, India, Malaysia, Pakistan and Sri Lanka, but occurs occasionally under mixed dry deciduous forests in the Aravalli ranges 'Tropical dry deciduous forest' associated with *Anogeissus latifolia, Madhuca indica, Tectona grandis* etc (Champion and Seth, 1968). Because of the above-mentioned characteristics and hardy in nature of growing, *E. officinalis* was planted under mixed plantation with a view that this species may perform better under increased water availability through RWH devices and can help restoring the degraded hills.

Therefore, the objectives of this study were: (i) to compare the efficacy of different RWH devices in improving soil physico-chemical properties and water status, and (ii) the effect of these RWH devices on the survival and growth of *E. officinalis* on these degraded hills.

MATERIALS AND METHODS

Site characteristics

The site is a degraded forest land near Banswara (23° 32' 28.2'' N and 74°26'30.3'' E), in the southern part of Rajasthan, India. Altitude of the area ranged between 248 and 320 m msl. The mean minimum and maximum annual temperature was about 15 and 33°C, respectively. Average annual rainfall from 1993 to 2006 was 1055.4 mm with 54 numbers of rainy days. Most of the rainfall occurred during June to September (Figure 1). The site was categorized into steep (> 20%), medium (10-20%) and gentle slopes (<10%). Based on USDA Soil Taxonomy Classification, soils of steep slope are loamy to clayey (clayey, skeletal, hyperthermic family of Lithic Ustorthents). Soils of the medium slope are loamy sand (coarse loamy, skeletal, hyperthermic family of Lithic Ustorthents). Soils in gentle slope are loamy to clayey (loamy, hyperthermic family of Typic Ustorthents). The forest was under degradation stage (that is, dry deciduous scrub) of tropical dry deciduous forest (Champion and Seth, 1968) invaded by *Prosopis juliflora* (SW.) DC. and *Lantana camara* L.

Experimental design and harvesting structures

Seventy five plots each of 700 m^2 area were laid in <10%, 10-20% and >20% slopes categories in June 2005. Each plot was separated by individual boundary trench (45 × 45 cm) cum bund and had rainwater harvesting (RWH) structures of 30 running meters length except in the control plots. Contour trenches (CT) and Box trenches (BT) were similar in cross section and length but BT had 15 intermittent trenches of 2 m length (Figure 2). V-ditches (VD) and Gradonie (GD) had 1800 cm^2 cross section area, but the differences were vertical cut, which was upside of the slope in gradonie to reduce run-off velocity and downside of the slope in VD to facilitate improvement in surface soil water (Singh, 2009). The excavated soils of the RWH devices were heaped towards the down slope. Three microsites of 1 m^2 area were laid at the centre of upper one third, middle one third and lower one third of each plot for soil sampling and observations recording. Experiment was laid in complete randomized block design. Thirty five numbers of seedlings (500 plants ha^{-1}) of *Acacia catechu*, *Azadirachta indica*, *E. officinalis*, *Dendrocalamus strictus*, *Gmelina arborea*, *Holoptelia integrifolia* and *Syzigium cumini* were planted in each plot in August 2005. This mixed plantation had an average population of 8 plants of *E. officinalis* Gaertn. Seed grown seedlings of 45 cm height and

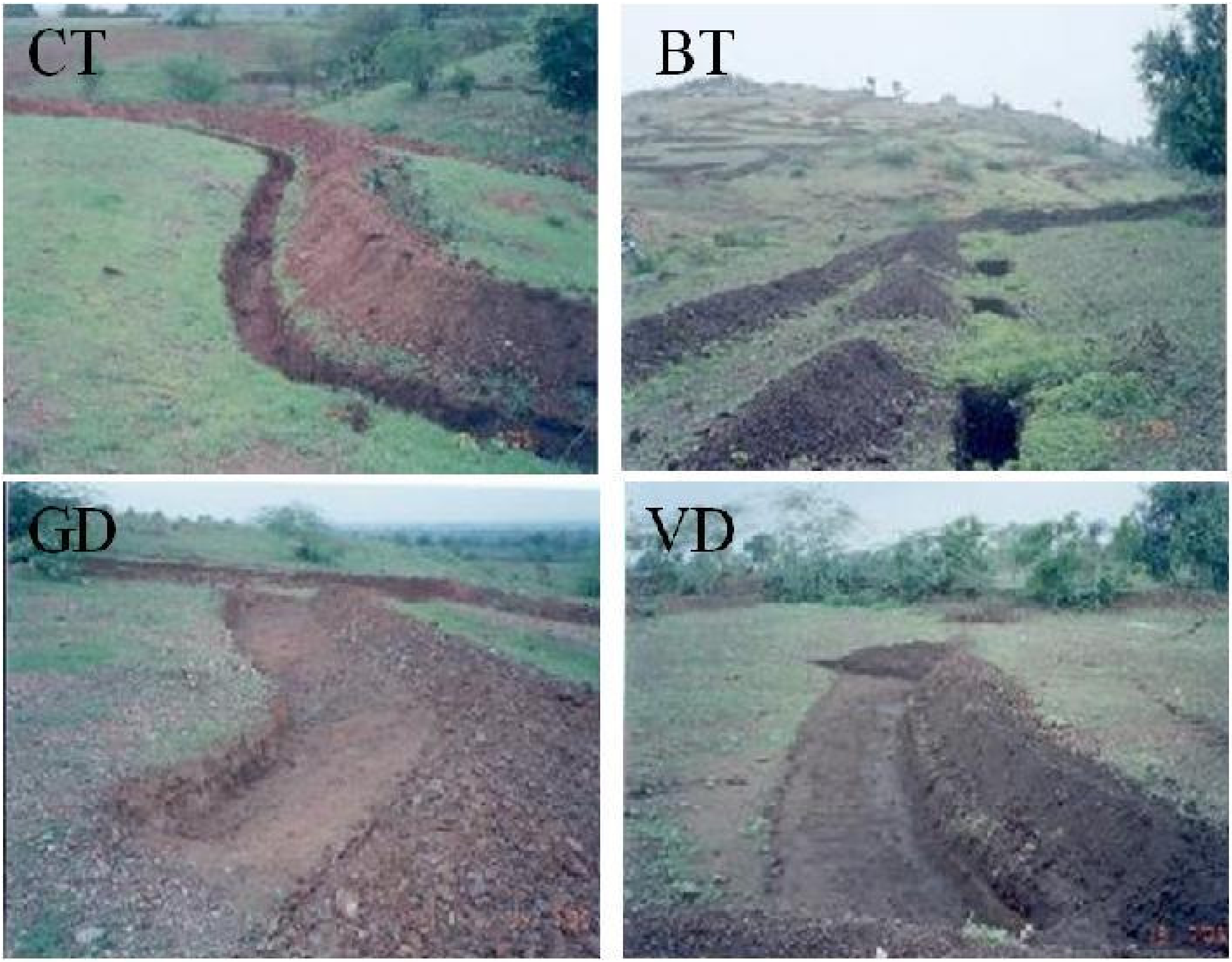

Figure 2. Rainwater harvesting devices applied under afforestation in degraded Aravalli, Rajasthan, India. CT, contour trench; BT, Box trench; GD, Gradonie; and VD, V-ditch.

0.40 cm collar diameter were planted in a pit of size 45 × 45 × 45 cm. There were three slope categories that is, <10% slope, 10-20% slope and >20% and five rainwater harvesting treatments plots replicated five times (distributed in about 17 ha area) to provide 75 plots.

Observations recording

Height and collar diameter (15 cm above from the soil surface) of *E. officinalis* were recorded before monsoon (June) and after monsoon (December) each year to monitor seasonal growth of spring and monsoon. Mean annual increments (MAI) in height and collar diameter were calculated. For soil water content (SWC) determination, soil samples were collected in 0-40 cm soil layer from the three sampling position (that is, upper, middle and lower one third parts of each plot). The samples were collected 10 times that is, in June (before monsoon) and December (after monsoon and recession of plant growth during winter) each year. The collected soil samples were put immediately into polythene bag to avoid water loss during transport to laboratory. Soil water content was estimated by oven drying of the sample at 110°C to a constant weight (Gupta, 1995).

Soil physico-chemical analysis

Initial soil sampling and soil texture analysis was done in June 2005. Soil samples were again collected in June 2010 before monsoon from the three sampling positions as mentioned above and homogenized to form a composite sample of each plot. Soil samples were dried and passed to a 2 mm sieve for separation of gravel and soil. Soil pH, electrical conductivity (EC) soil organic carbon (SOC), ammonical nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) were determined using standard procedures (Jackson, 1973; Cataldo et al., 1975; Baruah and Barthkumar, 1999). Extractable phosphorus (PO_4-P) was determined by the Olson's extraction method (Jackson, 1973) using uv-vis-spectrophotometer Model Shimadzu-1650PC.

Statistical analysis

The data collected were statistically analyzed using SPSS statistical package version 8.0 for "Windows 2000". Data on soil pH, EC, SOC and nutrients were analyzed using a two-way ANOVA considering above-mentioned parameters as the dependent variables. Plots slope category and rainwater harvesting treatments were the fixed factors. To monitor the changes in these soil variables between 2005 and 2010, the above-mentioned soil variables were tested using paired T-test. Since height, collar diameter and soil water content were determined repeatedly 10 times in five years; the data were analyzed using a repeated measure ANOVA considering seasons (winter and summer)/years as tests of within-subjects effects and slope and treatments as tests of between-subjects effects. Percent soil water was square root transformed before statistical analysis to reduce heterocedasticity (Sokal and Rolf, 1981). To obtain relations between plant growth, soil water content and soil nutrients, Pearson correlation coefficient were calculated.

RESULTS

Soil water dynamics

Multivariate analysis of soil water content (SWC) indicated significant temporal changes between seasons and the slopes (Table 1). Average SWC varied from the highest value of 5.45% in December 2006 to the lowest value of 0.84% in June 2009. Season × slope ($P < 0.01$) and season × treatment ($P<0.05$) interactions indicated that variations in soil water content between slopes and RWH treatments depended on season (rainfall). The highest SWC was in the plots of <10% slope in December 2006 and the lowest SWC in >20% slope plots in June 2010, whereas SWC was highest in the plots with BT treatments in December 2006 and in gradoni treatment in June 2010 among the RWH treatments. Across the treatments, SWC increased by 17.3 and 51.0% in >20% slope and <10% slope, respectively as compared to 2.08% ($P<0.01$) SWC in 10-20% slope. Pooled data of 10 observations did not differ ($P>0.05$) between the RWH treatments, but SWC was the lowest in the control plots. When compared with the SWC in the control plots, there were increases in SWC by 17.6, 14.9, 23.4 and 13.5% in CT, GD, BT and VD treatments, respectively. The highest ($P<0.05$) SWC was in the plots of BT treatment in December 2005, December 2006, June 2007, December 2008 and June 2009, in CT treatment in June 2006, in VD treatment in December 2007 and in gradonie treatment in June 2008 and December 2009. The average value of SWC was highest in BT and lowest in the VD treatments in both December and June (pooled data of five year for each December and June). Slope × treatment interaction was not significant ($P>0.05$) but an average SWC was the highest in BT treatment in <10% slope, CT treatment in >20% slope and gradonie treatment in 10-20% slope.

Soil properties

In June 2005, soil pH, SOC, NH_4-N, NO_3-N and PO_4-P varied significantly ($P<0.05$) between the slopes and the highest values of these variables were in the plots of <10% slope. Percent soil (soil content after sieving with 2 mm sieve) was greater in the plots of 10-20% slope than the plots of other slope categories. Soil pH, EC, SOC and NO_3-N were lowest in the plots of 10-20% slope, whereas NH_4-N and PO_4-P were lowest in >20% slope plots (Table 2). In June 2005, these soil variables did not differ ($P>0.05$) between the RWH treatments. Soil pH, EC, NO_3-N and PO_4-P remained highest in <10% slope plots in June 2010 also, but per cent soil, SOC and NH_4-N showed their highest concentration in >20% slope plots. Percent soil and NH_4-N were lowest in <10% slope, SOC was lowest in 10-20% slope and other variables were lowest in >20% slope plots. As compared to the values in June 2005, the extent of decrease in soil pH and EC (except in <10% slope where EC increased) were greater in >20% slope (by 4.1 and 29.2%, respectively), whereas NH_4-N concentration decreased by 44.5% in <10% slope in June 2010. Likewise SOC increased by 40.1% and 30.6% in >20% slope and 10-20% slope, respectively, but SOC decreased in <10% slope. The increases in percent soil and PO_4-P were also greater in >20% slope (4.2- and 2.8-fold), but the increase (by 2.5-fold) in NO_3-N concentration was greater in <10% slope than in the other slope categories.

Among RWH treatments (across the slopes), the availability of PO_4-P was highest, whereas percent soil and NH_4-N concentrations were lowest in the control plots (Table 3). Soil pH and EC were greater in the VD as compared to the other treatments. The concentrations of SOC and NO_3-N were highest in BT treatment, whereas percent soil and NH_4-N concentrations were greater in gradonie treatment as compared to the other treatments. While comparing changes overtime, there were significant ($P < 0.01$, paired t-test) decreases in soil pH, EC and NH_4-N (by 0.20 point, 11.12 and 33.80%, respectively) and increases in percent soil, SOC, NO_3-N and PO_4-P (by 3.68, 20.50, 2.38 and 2.04-fold, respectively) in June 2010 than their values in June 2005 (irrespective of the slopes and the treatments). Among the treatments, the decrease in soil pH, EC and NH_4-N ranged from 0.6 to 5.7% (GD plots), 1.5 to 40.1% (CT plots) and 27.8 to 45.1% (control plots). But the increase in the concentrations of percent soil, SOC, NO_3-N and PO_4-P ranged from 3.4- to 4.2-fold, 11.8- to 28.5%, 2.2- to 2.6 fold and 1.8- to 2.3-fold with the highest increase in contour trench, V-ditch, box trench and control plots, respectively.

Survival of *E. officinalis* plants

Survival of *E. officinalis* plants in June 2010 was 87.7%. The survival percent did not vary ($P>0.05$) due to both slope gradient and RWH treatments (Table 4). Survival percent was the highest in the plots with <10% slope and decreased to the lowest value in the plots with slope

Table 1. Changes in soil physico-chemical characteristics influenced by rainwater harvesting, slope and afforestation during restoration of degraded hills. Values are mean with ±SE of five replications.

Slope	RWH treatment	% Soil		pH		EC (dSm^{-1})		SOC (%)	
		June 2005	June 2010	June 2005	June 2010	June 2005	June 2010	June 2005	June 2010
<10%	Control	18.69±2.43	53.73±2.38	6.78±0.23	6.76±0.09	0.15±0.03	0.22±0.04	0.98±0.10	0.86±0.05
	C. trench	14.28±0.90	63.54±2.17	6.79±0.31	6.62±0.18	0.25±0.13	0.13±0.01	0.78±0.14	0.88±0.24
	Gradonie	17.81±3.27	60.31±2.33	7.02±0.28	6.40±0.16	0.14±0.02	0.19±0.05	0.98±0.16	0.86±0.15
	B. trench	14.79±3.58	59.06±4.77	7.00±0.15	6.80±0.19	0.28±0.09	0.27±0.09	0.92±0.10	0.90±0.08
	V-ditch	13.71±2.13	58.04±3.96	6.91±0.08	6.78±0.20	0.18±0.04	0.21±0.01	0.87±0.06	0.88±0.07
10-20%	Control	18.54±3.52	66.92±1.09	6.64±0.16	6.48±0.22	0.13±0.01	0.10±0.02	0.58±0.05	0.93±0.10
	C. trench	21.19±2.35	59.19±2.28	6.80±0.28	6.45±0.08	0.13±0.02	0.11±0.02	0.49±0.08	0.75±0.16
	Gradonie	18.15±2.48	63.90±3.02	6.68±0.24	6.48±0.17	0.14±0.03	0.16±0.06	0.69±0.11	0.85±0.10
	B. trench	21.60±1.69	63.64±0.93	6.52±0.24	6.46±0.21	0.14±0.03	0.11±0.03	0.69±0.10	0.93±0.10
	V-ditch	19.54±2.24	66.36±3.04	6.35±0.25	6.60±0.22	0.31±0.09	0.28±0.02	0.83±0.13	0.83±0.09
>20%	Control	15.84±1.88	58.77±0.93	6.66±0.15	6.39±0.07	0.15±0.02	0.20±0.06	0.69±0.13	0.95±0.11
	C. trench	16.91±2.07	70.45±2.43	6.57±0.25	6.43±0.09	0.21±0.04	0.10±0.01	0.86±0.12	1.11±0.10
	Gradonie	16.59±2.70	71.98±1.18	6.92±0.10	6.54±0.11	0.27±0.07	0.11±0.03	0.62±0.15	1.08±0.24
	B. trench	18.68±2.79	70.66±2.24	6.68±0.23	6.34±0.16	0.17±0.04	0.14±0.03	0.85±0.16	0.93±0.08
	V-ditch	12.26±1.36	64.53±2.05	6.75±0.06	6.45±0.03	0.13±0.03	0.13±0.04	0.59±0.17	1.03±0.04
F values of two-way ANOVA									
Slope		4.06**	13.64**	2.530NS	3.01*	0.37NS	2.03NS	5.58**	3.20*
RWH treatment		0.72NS	2.22NS	0.42NS	0.29NS	0.63NS	1.11NS	0.32NS	0.02NS
Slope × treat		0.71NS	2.98**	0.44NS	0.62NS	1.81NS	0.89NS	1.13NS	0.48NS

*significant value of F at P<0.05; **, significant value of F at P<0.01; NS, non-significant F value at P>0.05. Paired t-test indicated significant (P<0.05) difference in soil variables between the years i.e., 2005 and 2010 except for electrical conductivity (EC).

>20%. Among the RWH treatments (irrespective of slopes), the survival of *E. officinalis* ranged from 79.4% in the control plots to 94.7% in BT treatment. The order of treatments for the survival percent was control< G<CT<VD<BT.

Growth of *E. officinalis* plants

Repeated measure ANOVA indicated a significant (P<0.01) difference in height and collar diameter of *E. officinalis* plants between the seasons (Table 4) showing a clear seasonal pattern. The growth was greater during July to December (that is, monsoon) as compared to January to June (that is, spring). Initial plant height and collar diameter in December 2005 did not differ significantly between the slopes and the RWH treatments, but the subsequent growth was influenced (P<0.05) by both slopes and RWH treatments (Figure 3). Significant (P<0.05) season × slope interaction for height and collar diameter of *E. officinalis* plants indicated highest growth in <10% slope whereas season × RWH treatment inter-action showed highest growth of these variables in CT treatments. In June 2010, plants were shorter in 10-20% slope, but thinner in >20% slope (Table 4). However, DMRT showed non-significant

Table 2. Changes in soil physico-chemical characteristics influenced by rainwater harvesting, slope and afforestation during restoration of degraded hills. Values are mean with ±SE of five replications.

Slope	RWH treatment	% Soil		pH		Ec (dSm^{-1})		SOC (%)	
		June 2005	June 2010	June 2005	June 2010	June 2005	June 2010	June 2005	June 2010
	Control	18.69±2.43	53.73±2.38	6.78±0.23	6.76±0.09	0.15±0.03	0.22±0.04	0.98±0.10	0.86±0.05
	C. trench	14.28±0.90	63.54±2.17	6.79±0.31	6.62±0.18	0.25±0.13	0.13±0.01	0.78±0.14	0.88±0.24
<10%	Gradonie	17.81±3.27	60.31±2.33	7.02±0.28	6.40±0.16	0.14±0.02	0.19±0.05	0.98±0.16	0.86±0.15
	B. trench	14.79±3.58	59.06±4.77	7.00±0.15	6.80±0.19	0.28±0.09	0.27±0.09	0.92±0.10	0.90±0.08
	V-ditch	13.71±2.13	58.04±3.96	6.91±0.08	6.78±0.20	0.18±0.04	0.21±0.01	0.87±0.06	0.88±0.07
	Control	18.54±3.52	66.92±1.09	6.64±0.16	6.48±0.22	0.13±0.01	0.10±0.02	0.58±0.05	0.93±0.10
	C. trench	21.19±2.35	59.19±2.28	6.80±0.28	6.45±0.08	0.13±0.02	0.11±0.02	0.49±0.08	0.75±0.16
10-20%	Gradonie	18.15±2.48	63.90±3.02	6.68±0.24	6.48±0.17	0.14±0.03	0.16±0.06	0.69±0.11	0.85±0.10
	B. trench	21.60±1.69	63.64±0.93	6.52±0.24	6.46±0.21	0.14±0.03	0.11±0.03	0.69±0.10	0.93±0.10
	V-ditch	19.54±2.24	66.36±3.04	6.35±0.25	6.60±0.22	0.31±0.09	0.28±0.02	0.83±0.13	0.83±0.09
	Control	15.84±1.88	58.77±0.93	6.66±0.15	6.39±0.07	0.15±0.02	0.20±0.06	0.69±0.13	0.95±0.11
	C. trench	16.91±2.07	70.45±2.43	6.57±0.25	6.43±0.09	0.21±0.04	0.10±0.01	0.86±0.12	1.11±0.10
>20%	Gradonie	16.59±2.70	71.98±1.18	6.92±0.10	6.54±0.11	0.27±0.07	0.11±0.03	0.62±0.15	1.08±0.24
	B. trench	18.68±2.79	70.66±2.24	6.68±0.23	6.34±0.16	0.17±0.04	0.14±0.03	0.85±0.16	0.93±0.08
	V-ditch	12.26±1.36	64.53±2.05	6.75±0.06	6.45±0.03	0.13±0.03	0.13±0.04	0.59±0.17	1.03±0.04
F values of two-way ANOVA									
Slope		4.06**	13.64**	2.530NS	3.01*	0.37NS	2.03NS	5.58**	3.20*
RWH treatment		0.72NS	2.22NS	0.42NS	0.29NS	0.63NS	1.11NS	0.32NS	0.02NS
Slope × treat		0.71NS	2.98**	0.44NS	0.62NS	1.81NS	0.89NS	1.13NS	0.48NS

*significant value of F at P<0.05; **, significant value of F at P<0.01; NS, non-significant F value at P>0.05. Paired t-test indicated significant (P<0.05) difference in soil variables between the years i.e., 2005 and 2010 except for electrical conductivity (Ec).

(P>0.05) differences in the height and collar diameter of the plant between 10-20% and >20% slopes across the RWH treatments. Plant height and collar diameter were greater (P<0.05) in <10% slope than the plots with other slopes. Among the treatments, plant height and collar diameter were lowest in the control and increased significantly (P<0.05) in the RWH treated plots. Plants were taller and thicker (P<0.05) in CT than those in the other treatments. The treatments order in term of growth was C<G<VD<BT<CT. When compared with the plants in the control plots, plant were taller in height by 32.1, 19.1, 13.4 and 11.1% and thicker in collar diameter by 29.6, 15.1, 22.1 and 11.5%, respectively in CT, VD, BT and GD plots. Slope × treatment interactions were not significant (P>0.05).

Growth increments

Mean annual increment (MAI) in height and collar diameter of *E. officinalis* was 33.5 and 0.7 cm per year, respectively. The increments were greatest

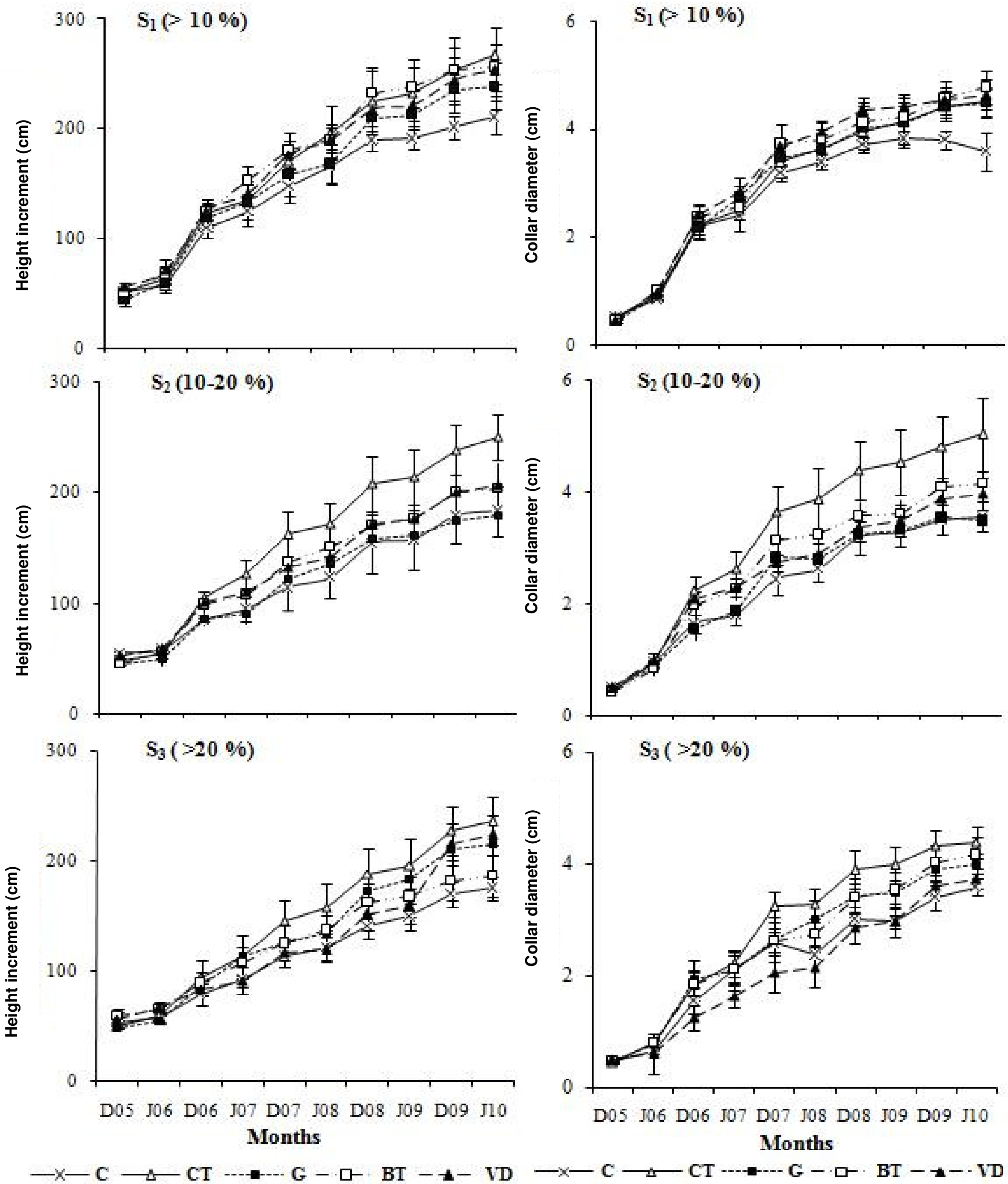

Figure 3. Growth pattern in height (left panels) and collar diameter (right panels) influenced by season, natural slope gradient and rainwater harvesting treatments in different years. Error bars are ±SE of five replications.

in <10% slope and the lowest were in >20% slope. While considering RWH treatments, MAIs were highest in the CT plots and lowest in the control plots (Table 5). Slope × treatment interactions indicated highest MAIs in CT plots in all slopes (except for collar diameter in <10% slope plots where BT structure performed the best).

Correlations in plant growth and soil variables

Slope gradient of the plots showed a positive correlation to percent soil ($r=0.327$, $P<0.01$) and SOC ($r=0.343$, $P<0.05$, $n=74$) and negative correlation to SWC ($r=-0.303$, $P < 0.01$), MAI in height ($r=-0.302$, $P < 0.01$) and

Table 3. Changes in soil nutrient status influenced by rainwater harvesting, slope and afforestation during restoration of degraded hills. Values are mean with ±SE of five replications.

Slope	RWH treatment	NH_4-N (mg kg^{-1})		NO_3-N (mg kg^{-1})		PO_4-P (mg kg^{-1})	
		June 2005	June 2010	June 2005	June 2010	June 2005	June 2010
<10%	Control	27.47±2.18	11.98±1.65	2.85±0.27	6.95±0.50	7.73±0.23	10.05±1.31
	C. trench	20.31±1.67	14.29±2.34	2.40±0.36	7.08±1.28	5.07±0.52	10.43±1.39
	Gradonie	23.99±3.11	15.46±1.20	2.83±0.25	5.75±0.85	6.42+1.57	9.66±1.67
	B. trench	24.39±2.75	13.49±1.64	2.97±0.23	6.65±0.87	6.06+1.05	8.35±0.72
	V-ditch	25.08±3.28	12.86±1.91	2.82±0.37	6.94±1.04	4.93+0.72	10.26±0.36
10-20%	Control	23.42±3.48	13.31±1.41	2.44±0.26	5.91±1.24	3.70+0.50	8.80±1.26
	C. trench	18.94±1.65	16.98±0.74	2.16±0.20	5.42±1.23	5.27+1.21	6.56±1.01
	Gradonie	20.05±1.72	16.28±1.47	2.27±0.15	5.43±0.62	5.36+0.76	6.67±0.76
	B. trench	20.91±2.38	15.54±0.74	2.13±0.05	8.55±2.07	4.30+0.23	7.69±1.17
	V-ditch	25.91±2.87	15.41±0.82	2.39±0.12	5.09±0.93	4.01+0.45	8.41±1.19
>20%	Control	19.13±2.44	13.14±1.35	2.50±0.26	5.64±0.72	2.41+0.30	6.61±0.38
	C. trench	25.66±3.00	15.79±1.63	2.64± 0.13	6.23±0.32	2.32+0.25	8.85± 0.44
	Gradonie	22.07±3.21	16.01±1.15	2.45±0.23	5.35±0.68	2.63+0.48	7.00±0.63
	B. trench	17.50±1.53	16.24±0.82	2.41±0.29	4.24±0.58	3.29+0.68	9.14±0.60
	V-ditch	17.33±1.57	17.15±0.55	2.17±0.16	5.96±0.31	3.10+0.64	7.22±0.57
F values of two-way ANOVA							
Slope		3.00*	2.55NS	5.71**	4.05*	21.90**	1.81NS
RWH treatment		0.41NS	1.93NS	0.28NS	0.47NS	0.78NS	0.83NS
Slope × treatment		1.88NS	0.46NS	0.70NS	0.86NS	1.91NS	2.81**

*, significant at P<0.05; **, significant at P<0.01; NS, not-significant (P>0.05). Paired t-test indicated significant (P<0.05) difference in soil variables between the years that is, 2005 and 2010.

concentrations of NH_4-N (r=-0.244, P<0.05) and PO_4-P (r=-0.573, P<0.01) in June 2005 and NO_3-N (r=-0.330, P<0.05) in June 2010. Soil available PO_4-P and SOC in June 2005 were positively related to plant height and collar diameter, which had positive correlation to SWC in both December and June. MAI in height showed a positive correlation to SWC (r=0.467, P<0.01). SOC in June 2005 was positively correlated to MAI (r=0.296, P<0.05), SWC (r=0.333, P < 0.01), but a negative correlation to percent soil in June 2005 (r=-0.279, P<0.05). SWC was positively related (r=0.245, P<0.05) to NO_3-N in June 2005. Percent soil had negative correlations to soil pH (r=-0.260, P<0.05 in June 2005 and r=-0.268, P<0.05 in June 2010) and SWC (r=-0.299, P<0.01 in June 2005 and r=-0.278, P<0.01 in June 2010). Electrical conductivity and NO_3-N were positively correlated both in June 2005 (r=0.256, P<0.05) and June 2010 (r=0.389, P<0.01), whereas EC of June 2010 showed negative correlation to NH_4-N (r=-0.300, P<0.05).

DISCUSSION

Soil water dynamics

Adoption of RWH enhanced soil water but SWC was mainly influenced by amount of rainfall indicated by the highest SWC in December 2006 with highest rainfall in 2006 (Figure 1). And lesser rainfall during June to December 2008 resulted in the lowest SWC in June 2009. The highest SWC in the plots of <10% slope than the plots of the other slopes was due to relatively uniform distribution, reduced run-off losses and increased infiltration of the water because of low slope gradient (r=-0.303, P<0.01). However, relatively greater SWC in >20% slope in June 2006 was due to presence of gravel/stone on the soil surface that facilitated water infiltration because of increased surface roughness during rain and reduced evaporation loss during water stress period. Stony soil or rock fragments on dry hill slopes affect rainwater redistribution and overland flow that helps in conserving soil water (Danalatos et al., 1995; Katra et al., 2008). However, difference in SWC between the slopes (that is, 10-20% and >20% slope plots) was due to variations in soil texture and silt/clay content, which was greater in >20% slope influencing vegetation cover and soil water status (Singh et al., 1998). This showed that soil texture is another factor (in addition to natural slope gradient) that influenced SWC. It was indicated by a greater SWC in the plots of >20 (despite of higher slope gradient) than the plots of 10-20% slope. Most interesting effect of RWH was the

Table 4. Average survival, height and collar diameter of *E. officinalis* seedlings influenced by natural slopes gradient and rainwater harvesting treatments in degraded hills of Aravalli, India. Values are mean ±SE of five replicates.

Slope	RWH treatment	Survival (%)	Height (cm)		Collar girth (cm)	
		June 2010	Dec 2005	June 2010	Dec 2005	June 2010
	Control	88.8±08.1	51.4±2.30	210.4±15.8	0.5±0.0	3.7±0.4
	Contour trench	97.5±05.8	51.0±2.6	266.6±26.3	0.5±0.0	4.5±0.3
<10%	Gradonie	87.8±13.8	44.0±5.3	238.8±21.2	0.4±0.0	4.5±0.3
	Box trench	95.9±06.3	50.4±4.0	256.2±21.0	0.4±0.0	4.8±0.3
	V-ditch	84.9±19.8	56.2±3.6	253.2±23.4	0.45±0.1	4.6±0.3
	Control	80.0±23.7	55.1±1.1	183.3±23.1	0.5±0.0	3.6±0.3
	Contour trench	80.8±16.4	48.2±3.6	250.6±20.3	0.5±0.0	5.0±0.7
10-20%	Gradonie	97.1±06.4	45.7±5.7	179.7±05.4	0.5±0.0	3.5±0.1
	Box trench	94.3±12.8	46.1±5.7	203.6±15.7	0.4±0.0	4.2±0.3
	V-ditch	100.0±02.1	53.7±2.0	206.9±19.5	0.5±0.0	4.0±0.3
	Control	69.3±25.5	53.5±5.1	174.8±11.1	0.5±0.1	3.6±0.2
	Contour trench	81.7±20.5	50.8±1.4	235.6±22.1	0.5±0.0	4.4±0.3
>20%	Gradonie	69.1±29.5	49.1±2.2	214.3±27.6	0.5±0.0	4.0±0.2
	Box trench	93.9±13.5	58.9±3.3	186.1±18.6	0.5±0.0	4.2±0.3
	V-ditch	91.1±13.3	56.5±8.8	223.3±17.7	0.5±0.1	3.7±0.2
Tests of within-subjects effects						
	df	**F value**	**MS**	**F value**	**MS**	**F value**
Month (M)	9	-	256082.1	743.3**	121.6	1095.0**
M × Slope (S)	18	-	2356.9	6.8**	0.5	4.6*
M× treatment (T)	36	-	1049.3	3.1**	0.3	2.7**
M × S × T	72	-	230.8	0.7NS	0.1	1.1NS
Tests of between-subjects effects						
S	2	1.41NS	79678.5	8.6**	18.0	7.8**
T	4	1.00NS	19796.8	2.1NS	6.6	2.9*
S ×T	8	0.63NS	2625.7	0.3NS	2.2	1.0NS

df, degree of freedom; MS, mean square; *, significant at P<0.01; **, significant at P<0.01; NS, not significant (P>0.05).

reduction in soil water gradient from 55% in December 2005 to 28% in December 2009. Unrestricted water flow and loss was the reason for low SWC in the control plots, but the impact of growing tree seedlings and the herbaceous vegetation in reducing soil water cannot be ruled out. An increase in SWC by 13.5 to 23.4% in RWH treated plots as compared to the control plots showed the beneficial effects of rainwater harvesting devices in improving soil water status. The highest SWC in BT/CT plots than in the GD/VD plots was due to their greater capacity of water storage and conservation of run-off water by reducing water velocity and distributing the water into the soil profile.

However, soil water use by the planted seedlings, growing herbaceous vegetation and the efficiency of RWH devices in water infiltration into deep soil profile were the major factors responsible for the SWC variations between the RWH treatments. Roldan et al. (2007) also observed differences in soil water content among the range condition classes that appeared to be related to morphological and physio-logical traits associated with the dominant species cover. However, relatively greater SWC in BT plots in <10% slope and in GD plots in 10-20% slope indicated that these RWH structures were efficient in conserving water in the respective slope category.

Changes in soil properties

Existing slope gradient resulted in higher soil pH, EC, SOC, NH_4-N, NO_3-N and PO_4-P in down slope (<10% slope plots). This was due to accumulation of salts and nutrients transported along with water from upslope to the down slope area resulting in a decrease in these soil variables in upslopes that is, 10 - 20% slope and >20%

Table 5. Growth increment in height and collar diameter of *E. officinalis* seedlings influenced by natural slopes gradient and rainwater harvesting treatments in degraded hills of Aravalli, India. Values are mean ±SE of five replicates.

Slope	RWH treatment	MAI (cm /year)		Increment (fold over data in December 2005)	
		Height	Collar dia	Height	Collar dia
<10%	Control	31.8±2.9	0.6±0.1	4.1±0.2	7.2±0.7
	Contour trench	43.1±5.2	0.8±0.1	5.3±0.5	8.9±0.3
	Gradonie	39.0±3.2	0.8±0.1	5.5±0.2	10.3±0.2
	Box trench	41.2±3.5	0.9±0.1	5.1±0.2	11.1±1.3
	V-ditch	39.4±4.4	0.8±0.1	4.5±0.3	10.7±1.5
10-20%	Control	25.6±4.5	0.6±0.1	3.3±0.4	7.1±0.5
	Contour trench	40.5±3.6	0.9±0.1	5.2±0.3	11.3±1.6
	Gradonie	26.8±1.3	0.6±0.0	4.3±0.7	8.1±0.9
	Box trench	31.5±2.3	0.8±0.1	4.6±0.4	10.2±1.6
	V-ditch	30.6±4.0	0.7±0.1	3.9±0.4	7.8±0.6
>20%	Control	24.5±1.8	0.6±0.0	3.3±0.2	8.0±0.7
	Contour trench	37.0±4.2	0.8±0.1	4.6±0.4	9.9±0.8
	Gradonie	33.0±5.9	0.7±0.0	4.5±0.7	8.8±0.6
	Box trench	25.4±3.6	0.7±0.1	3.2±0.3	9.1±0.7
	V-ditch	33.4±5.2	0.7±0.1	4.4±0.9	8.0±1.1
Two-way ANOVA					
	df	**F value**	**F value**	**F value**	**F value**
Slope (S)	2	7.3**	2.4NS	5.2**	1.2NS
RWH treatment (T)	4	4.4**	5.0**	4.6**	3.8**
S ×T	8	0.6NS	1.2NS	0.9NS	1.5NS

df, degree of freedom; MS, mean square; *, significant at P<0.01; **, significant at P<0.01; NS, not significant (P>0.05).

slope area. The trend of increasing values of the above-mentioned soil variables towards <10% slope area is indicated by a negative correlation between slope gradient and the soil variables. Yong et al. (2006) and Ge et al. (2007) observed that almost similar distribution and infiltration of water together with soil and nutrients (received from the upslope) enhanced the SOM and nutrients at down slope region. Soil pH, EC, NO_3-N and PO_4-P exhibited similar pattern in June 2010 as in June 2005, but a decrease in the gradient as compared to those existed in 2005 suggested an improvement soil conditions. Significantly (P<0.01) greater increase in SOC and percent soil in the plots of >20% slope was due to rainwater harvesting that facilitated soil formation, soil water retention and nutrient mobilization enhancing vegetation cover and turnover of roots and litter. Juwarker et al. (2010) observed enhanced carbon accumulation while restoring manganese mine land, whereas Phillips et al. (2008) observed a rapid rate (5 to 10 mm year^{-1}) of soil formation facilitated by a weathering (favourable regional climate), local topography favouring moisture and sediment accumulation, and vegetation colonization. However, increased soil pH, EC, NO_3-N and PO_4-P with simultaneous decrease in SOC suggested a pH/EC-stimulated mineralization of organic matter releasing nutrients to the soil (Xiao-gang et al., 2007). A decrease in soil pH, EC and NH_4-N in June 2010 than those in June 2005 were due to withdrawal of salts and nutrient by the growing plants and herbaceous vegetation. However, dilution effects (r=-0.0.268, P<0.05) due to increased soil fraction (% soil) in the process of soil formation was also responsible for lowering in the values of these soil variables. Significant (P<0.01) increase in the concentrations of SOC, NO_3-N and PO_4-P showed a positive impact of afforestation and RWH on the soil. Relatively greater increase (P<0.05) in soil percent, SOC, NH_4-N and PO_4-P in the plots of >20% slope than in the <10% slope showed improvement in soil properties in this slope and was due to the conducive environment. The highest availability of PO_4-P in the control plots was supported by lesser plant growth (and thus less nutrient use) in control than in the other RWH treatment. A lesser decrease in soil pH and EC in the plots of VD treatment than in the other treatments were because of surface distribution of salt accompanied with water. However, the highest concentrations of SOC and NO_3-N in the plots with BT treatment and that of NH_4-N in GD treatment were due the availability of soil water, the type of vegetation growing the plots and their decomposition to release organic matter and nutrients. This was indicated by a positive relation between SWC and SOC (r=0.333, P<0.01). Impact of increased soil water availability on soil carbon sequestration has also been observed in a study on irrigated plantation in Indian desert (Singh et al., 2004).

Survival and growth of *E. officinalis*

Rainwater harvesting and natural slope gradient influenced survival and growth of *E. officinalis* because of increased soil water and nutrients availability. Greater survival of plant in the plots of <10% slope among the slope categories and in BT treatment among the RWH treatments was due to enhanced availability of soil water and nutrients under RWH devices discussed above. The highest (P<0.05) growth during June to December as compared to that in January to June was due to greater soil water availability through rainfall that influenced nutrient mobility and its utilization (Marion and Everett, 2006). The highest concentrations of soil nutrients together with soil water in the plots of <10% slope facilitated growth of *E. officinalis* significantly (P<0.05). This was indicated by positive correlations of plant growth variables to SWC (r=0.270, P<0.05), SOC (r=0.285, P<0.05) and PO_4-P (r=0.224, P=0.052). Tsui et al. (2004) and Yong et al. (2006) observed highest accumulation of nutrients and soil water on the lower slope position under redistribution of surface run-off that contributed to the vegetation growth in lower slope area. Thus the highest increments in height and collar diameter in <10% slope area was related with highest soil water and nutrients in this slope as shown by a positive relation between plant growth and SWC (r=0.284, P<0.05). The decrease in growth of *E. officinalis* in higher slopes was due to a reduction in soil water and nutrient in higher slopes as compared to that in <10% slope plots. Smaller plants due to less fertile soils have also been observed in Ghanian tropical rainforest (Baker et al., 2003). Though plants in >20% slope area were taller than the plants in 10-20% slope particularly in December 2009 and June 2010, but greater growth in 10-20% slope in most of the observations was due to greater use of soil water and nutrients in this slope. Nippert and Knapp (2007) reported variation in precipitation history and landscape positions as the greater determinants of water-use patterns than the absolute rooting depth. Significantly (P<0.05) greater height, collar diameter and MAIs in RWH treated plots than in the control plots clearly showed the effects of water on growth of *E. officinalis*. The highest plant growth in CT/BT plots was associated with the deep rooting pattern to utilize the maximum available water and nutrients in the deeper soil profile even during rainfed period. However, a positive correlation between soil water and plant growth (r=0.284, P<0.05) suggested that this species requires sufficient soil water for growth. Significantly (P<0.05) greater growth of *E. officinalis* in CT and BT treatments than in the GD or V-ditch treatments showed that former two RWH structures were more efficient in conserving soil resources and facilitated growth of *E. officinalis*.

CONCLUSIONS AND RECOMMENDATIONS

Rainwater harvesting devices and their efficiency in water storage and retention influenced soil water and nutrients. Weathering and disintegration of gravels/rock fragments under favourable soil moisture conditions and consequent vegetation colonization affected soil pH and EC negatively and percent soil, SOC NO_3-N and PO_4-P availability positively. Relative carbon accumulation and nutrient build up was greater in highly degraded up slope than down slope areas. The improved soil water and nutrients in <10% slopes with well drained clayey loam soil augmented survival and growth, which decreased with increase in slope gradient. Slope gradient in a plot had greater influence on soil water, nutrient distribution and plant growth, but silt/clay concentration (soil texture) is another factor that influenced soil water and nutrient retention enhancing plant growth in >20% slope as compared to 10-20% slope. RWH enhanced growth of *E. officinalis* significantly by improving soil condition, water and nutrients. Contour trench reduced surface water flow facilitating water infiltration into deeper soil profile and resulted in the highest growth of *E. officinalis* in all slope categories. Conclusively, RWH in afforestation improved soil properties and enhanced carbon and nutrients status that facilitated plant growth. Contour trench was the most efficient in terms of soil and water conservation and plant growth in all slopes. The second best RWH treatments was Box trench in <10% slope and V-ditch in other slopes for height growth under rehabilitation of degraded hills. However, further research is required on hydrological aspect that is, soil water use and its partitioning in different vegetation component, their role in carbon sequestration and the benefits accrued from the work in benefits of local people.

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