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Effects of rainwater harvesting on plant growth, soil water dynamics and herbaceous biomass during rehabilitation of degraded hills in Rajasthan, India

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ABSTRACT

Degraded hills can be restored by afforestation and conserving soil and water through rainwater harvesting. Three slope categories viz. <10%, 10–20% and >20% of a degraded hill were treated with rainwater harvesting (RWH) structures: Contour trench (CT), Gradonie (GD), Box trench (BT) and V-ditch (VD) including a control with a view to rehabilitate it by conserving and minimizing gradient in soil water and nutrients. Soil water content (SWC), height and collar diameter of *Acacia catechu*, *Azadirachta indicia, Emblica officinalis*, *Holoptelia integrifolia* and *Zyziphus mauritiana* planted in August 2005, herbaceous biomass and photosynthetically active radiation (PAR) interceptions by tree, vegetation and tree-vegetation combine ($PAR_{intT/V/C}$) were monitored for suitability of RWH devices and tree species in rehabilitation. SWC decreased from December to June and it was linearly related to rainfall and vegetation height. PAR_{int} by tree, vegetation, and tree-vegetation combine were 30.0%, 54.6% and 84.6%, respectively and helped conserve soil water. SWC, plant and vegetation growth and PAR_{intT} were lowest ($P < 0.05$), whereas herbaceous biomass and PAR_{intV} were highest in 10–20% slope. Vegetation height and SWC were linearly related to biomass indicating improvement in micro-climate and herbaceous growth. Highest SWC in <10% slope promoted plant growth and mean annual increment (MAI) in height and collar diameter, which enhanced PAR_{intT} and PAR_{intC}. These variables were highest in CT/BT treatments and lowest in control plots. Characteristic root distribution of *Acacia catechu* and *A. indica* promoted growth in V-ditch, whereas *E. officinalis*, *Z. mauritiana* and *H. integrefolia* performed best in CT treatment. RWH enhanced herbaceous biomass between 22.4% and 60.7% over control. Conclusively, VD/GD structures found best for growth of herbaceous vegetation as well as *A. catechu* and *A. indica* plants, whereas CT/BT structures favoured growth of other tree species. Rainfall influenced SWC, but RWH helped conserve soil and water, promoted plantation and herbaceous growth and facilitated restoration process, and may be promoted to restore degrading lands.

1. Introduction

Growing demands for fodder and fuelwood are leading cause for over-exploitation and vegetation removal and are accelerating land degradation throughout the world (Gao et al., 2011). Severity of the degradation is relatively more in hill regions, which is an important landscape that maintains hydrological cycle, vegetation status and people livelihood (Runhaare et al., 1997; Rahman, 2011). The status of degradation of Indian hills is also on similar line and many hillocks of Aravalli hills-an oldest mountain system in India, are exposed and devoid of vegetation. Afforestation is common approach for restoration and biodiversity conservation (Cao, 2008; Cao et al., 2009a; Cao et al., 2011), eco-environmental improvement (Cao, 2011; Cao et al., 2011) and people livelihood (Cao et al., 2009b; Cao 2011). However, the establishment of vegetation on these degraded hills is constrained by the inadequate availability of soil as well as water (Li et al., 2008), whereas low and irregular rainfall affects plant growth too (Barron et al., 2003). In such limited resource availability, the only option for increasing biomass production is to increase the water availability through conservation of soil and water. Adoption of improved water conservation and harvesting technologies may contribute soil water storage, improve soil nutrients mobility, and supports a higher number of plants and biomass production (Gowing et al., 1999). Further, water harvesting supports flourishing agriculture in many dry areas (Suleman et al., 1995; Faroda et al., 2007). A huge literature exists on rain water harvesting throughout the world (Prinz, 2001; Mati, 2005; Waterfall, 2006), but much interest in this was developed predominantly because of migration of more

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and more people to live and utilize the meagre resources in dry areas. Many site-specific rainwater harvesting (RWH) structures have been designed to address the soil and water conservation issues and to improve crop yield (Li et al., 2000), plant growth (Gupta, 1995) and forage production (Jia et al., 2006).

Sustainability and eco-hydrological functioning of various RWH techniques depend upon the timing, number of rain days and the amount of rainfall (Cohen et al., 1995). There is a need to understand the complex interactions between ecology and hydrology involving rainwater harvesting micro-catchments and their influences on availability of soil water and corresponding improvement in plantation growth and vegetation status. Further research on soil and water conservation and its role on biological diversity improvement have also been emphasized in a conclusive review by Vohland and Barry (2009). Information on ecological and hydrological interaction may determine the resource use and its influence on plant growth (Ludwig et al., 2005; Yu et al., 2008). Further, rainwater harvesting devices differ in their effects depending upon slope gradient and characteristics of the planted species-rooting pattern and soil water use from soil profile. Experiments involving different RWH devices, slope categories and trees species may provide suitable combinations useful in restoring degraded forestlands and help in developing and extending water-adaptive forest management practices (Yanhui et al., 2012). The increase in water yield through micro-catchment RWH may enhance plantation growth and promote herbaceous vegetation, which help rehabilitate degraded hills/wastelands by conserving soil and water and generating biomass for local benefits (Zhuang, 1997; Cao, 2011).

Therefore, objectives of this study were: (i) to study the effects of rainfall pattern and different rainwater harvesting structures on soil water storage; (ii) to find out suitable combination of RWH device and tree species in a particular slope by observing the effects of soil water on the growth of plantation and herbaceous vegetation (Cao et al., 2010); and (iii) to observe role of herbaceous growth on soil water use and conservation.

2. Materials and methods

2.1. Site characteristics

The study was carried out at the junction of Aravalli Hills and Malwa Plateau covering an area of about 17 ha, which spread over 23° 25′ 27.0″ N to 23° 25′ 43.4″ N latitudes and 74° 24′ 00.5″ E to 74° 24′ 23.1″ E longitude. Altitude of the area ranged between 248 to 320 msl. The site is located 17 km south-west of Banswara (23° 32′ 28.2″ N and 74° 26′ 30.3″ E), Rajasthan, India. Air temperature varied from 4 °C in January to 42 °C in May. The mean minimum annual temperature during experimental period ranged from 18.7 °C in 2008 to 20.1 °C in 2006, whereas mean maximum annual temperature ranged from 32.8 °C in 2008 to 34.3 °C in 2010 (Table 1). Average annual rainfall from 1993 to 2004 was 960 ± 352 mm (mean ± standard deviation) with 54 numbers of rainy days. Rainfall varied from 562.5 to 2266.0 mm during 2005 to 2010 with average value of 1073 ± 626 mm (Table 1). Slope gradients of the hills and foot hills in the study area varied from 3% to 53%. These slopes were categorized into steep (>20%), medium (10–20%) and gentle (<10%) slopes. The surface of steep slope was covered with crystalline gravels and pebbles of varying size with randomly growing *Lantana camara* L. and sporadic *Themada quadrivelvis* (L.) Kuntze and *Apluda mutica* L. grasses. Medium slope had light textured sandy loam soils of shallow depth and was mostly covered by *Prosopis juliflora* (Sw.) DC. and occasional *L. camara* shrub and *Aristida funiculata* Trin. & Rupr. and *Heteropogon contortus* (L.) P. Beauv. ex Roem. & Schult. grasses. *Lantana camara* and *P. juliflora* are invasive to this region. Soils in gentle slope were loamy to clay loam in texture and shallow to deep in soil depth. This area was dominantly covered by *P. juliflora* and *L. camara* bushes and the grasses like *Dichanthium* spp. and *Cenchrus* spp. Soil pH was slight acidic to neutral in reaction (6.34–7.02). Average SOC, available NH_4–N, NO_3–N and PO_4–P of the site were 0.76%, 22.15 mg kg^{-1}, 2.50 mg kg^{-1} and 4.51 mg kg^{-1}, respectively (Singh, 2012).

2.2. Experimental design

The experiment was laid in a complete randomized block design in five replications because of hillocks of varying height and aspects associated with different drainage lines. Because of this major emphasis was given to have a plot of equal size though vary in shape to adjust between hillslopes and the drainage line. Seventy-five plots of 700 m^2 area were laid in the slope categories of <10%, 10–20% and >20% distributed in about 17 ha area covering almost all aspects. Each plot was separated by individual boundary of trench (2025 cm^2 cross section area, 45 cm × 45 cm) cum bund to prevent water flow into the plots from other areas or plots and divert the flowing water toward the drainage line. Four rainwater harvesting structure viz. contour trench (CT), gradonie (GD), Box trench (BT) and V-ditch (VD) of 30 running meter length were prepared to harvest rainwater in the plots (Supplementary Fig. 1). In addition there were control plots without any rainwater harvesting structures (Singh, 2009). Contour trenches were excavated at different contour levels to conserve the run-off water and the trenches were 45 cm × 45 cm in cross section. Box trenches were 2 m length trenches excavated intermittently at different contour levels and 15 in numbers with cross section area similar to that in the CT. Gradonie and V-ditches were across the contour and 1800 cm^2 cross section area, but differences were only in vertical cut of 30 cm height. In V-ditch the vertical cut was downside of the slope in VD, whereas in gradonie ditch the cut was upside of the slope (to reduce velocity of surface run-off water). The excavated soil was always kept downside of the dugout. A mixed plantation of *Acacia catechu* (L.f.) Willd, *Azadirachta indica* A. Juss., *Emblica officinalis* Gaertn., *Holoptelia integrifolia* (Roxb.) and *Zizyphus mauritiana* Lam.were carried out in August 2005. There were 35 seedlings of above-mentioned tree species planted in a 45 cm × 45 cm × 45 cm pit size at the rate of 500 plants per ha.

Table 1
Average annual temperature, number of rain days and cumulative monthly and annual rainfall (mm) near the experimental site, Banswara, Rajasthan, India.

Year	Average annual temp. (°C)		Rain days	Rainfall during monsoon (June–October) and annual (mm)						
	Max.	Min.		June	July	Aug.	September	October	Total	Annual
2005	33.2	19.9	42	82.6	290.0	169.1	483.5	–	1025.2	1026.7
2006	33.1	20.1	63	148.4	648.6	630.3	489.1	44.0	1960.4	2266.0
2007	33.5	19.0	44	102.0	232.0	565.0	254.0	–	1153	1391.0
2008	32.8	18.7	29	101.0	192.3	129.5	74.0	–	496.8	562.5
2009	33.9	19.1	30	69.0	457.0	333.0	–	–	859	859.0
2010	34.3	20.0	39	3.0	93.0	427.0	71.0	5.0	599	636.0
Average	–	–	41.2	84.3	318.8	375.7	228.6	8.2	1015.6	1123.5