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RESEARCH ARTICLE

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Resource availability through rainwater harvesting influenced vegetation diversity and herbage yield in hillslope of Aravalli in India

Abstract Recent decline in biological diversity has stimulated the research on the effects of resource conservation on biodiversity and vice versa. We examined soil water and nutrients influenced by rainwater harvesting (RWH) in hillslope and its effects on herbage diversity and productivity at up (USP), middle (MSP) and lower position (LSP) in 75 plots, each of 700-m^2 area laid in $< 10\%$, 10%–20% and $> 20\%$ slopes, respectively. The five RWH treatments were Contour trench (CT), Gradonie (G), Box trench (BT), V-ditch (VD) and control. Soil water content (SWC), species number, population, diversity and herbage yield increased ($P < 0.05$) downward suggesting positive relations between soil resource and diversity/productivity. The highest species number, population, richness and diversity in 10%–20% slope were associated with soil water usage and NO_3-N and NH_4-N concentrations. SWC was 5.0%–19.0% greater in RWH areas than in control influencing herbage species, population, growth and yields. The increase in diversity and yields was the highest ($P < 0.05$) in V-ditch reinforced by soil fertility. The positive effect of diversity on yield increased with resources, and the effect was compositional rather than that of species richness. Conclusively, slope gradient and soil texture influenced herbage regeneration, diversity and productivity, which were positively affected by existing soil fertility and applied RWH and mobilizing soil water and nutrients. The effect of V-ditch was the highest on composition and yield. Thus, RWH enhanced herbaceous vegetation and restoration of degraded forest/rangelands. But long-term effects of diversity in restoring ecosystem productivity could be established through long-term data collections on optimum water/nutrient usage, diversity and productivity.

Keywords diversity-productivity relation, herbage diversity, herbage drymass, soil nutrients, soil water dynamics

1 Introduction

Increases in plant species diversity usually reduce soil and nutrient losses as well as improve herbage production, yield stability, and aesthetic value (Watkinson and Ormerod, 2001; Krueger et al., 2002) of an ecosystem. Production is directly linked to availability of soil water and nutrients, which are main limiting factors particularly in overexploited and degraded hills like Aravalli in India. The best options to restore the available resources, enhance vegetation cover and increase biomass production are afforestation and promoting regeneration of natural flora through increased water and nutrient availability (Gregory, 1989). Rainwater harvesting (RWH) is useful in conserving soil and water resource, enhancing nutrient mobility and soil moisture storage, and prolonging the period of moisture availability in soil (Boers et al., 1986; Cater and Miller, 1991; Wani et al., 2002).

Extensive researches have been carried out in different parts of the world (UNEP, 1983; Prinz et al., 1998; Oweis et al., 1999), but much interest in water harvesting has been developed in dry areas predominantly because of migration of more and more people to live and utilize the meagre resources. Water harvesting supports flourishing agriculture in many dry areas (Katyal et al., 1993; Suleman et al., 1995; Oweis and Taimeh, 1996; Faroda et al., 2007). Many site-specific rainwater harvesting (RWH) structures have been designed to address the soil and water conservation issues and to improve vegetation management practices,

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including crop production (Vashistha et al., 1980; Li et al., 2000), tree growth (Gupta, 1995; Prinz, 2001) and forage yield (Jia et al., 2006). In addition, *in situ* rain water harvesting practices can improve hydrological indicators like infiltration and groundwater recharge, soil nutrients and biomass production, and support a higher number of plants and animals (Vohland and Barry, 2009). However, sustainability and eco-hydrological functioning of various water harvesting techniques depend upon the timing and the amount of rainfall (Cohen et al., 1995). Thus, there is a need to understand the complex interactions between ecology and hydrology involving rainwater harvesting micro-catchments and their influences on resource availability and herbage regeneration/production. Contour trench, Gradonie, Box trench/staggered trenches and V-ditches RWH structures are in use to conserve soil and water and to enhance the establishment and growth of tree seedlings in degraded forest lands, but the effects of these structures on regeneration and production efficiency have not been scientifically analyzed for better understanding and management of these degraded lands. Studies on the ecological and hydrological interaction may determine the resource use and influence vegetation composition and diversity (Ludwig et al., 2005; Yu et al., 2008). Further, quantification of the RWH effects on soil nutrient and water status and ultimately on the improvement of vegetation diversity and productivity requires additional research to integrate the ecological and hydrological processes in such degraded lands.

Keeping this in view, an experiment was started with application of different RWH devices and afforestation with different tree species in a degraded forest land in 2005. The area was kept free from human and livestock interferences to promote the regeneration of natural vegetation. The present study was carried out in 2007 with an objective to monitor the influence of RWH on changes in soil water and nutrient availability and their effects on diversity and productivity of regenerated vegetation for better management of resources in eco-restoration of degraded forest/rangelands.

2 Materials and methods

2.1 Site description

The experimental site is a degraded forest land situated in 17 km southwest of Banswara (23°32′8.2″N and 74°26′30.3″E) in the southern part of Rajasthan. It is spread over 23°25′27.0″N to 23°25′43.4″N latitude and 74°24′00.5″E to 74°24′23.1″E longitude. The altitude of the area ranges between 248 and 320 m msl. The variation in air temperature is very large, from 4°C in January to 42°C in May. The mean minimum and maximum annual temperature is about 15°C and 33°C, respectively. The average annual rainfall from 1993 to 2006 is 1055.4 mm with 54 rainy days. However, the year 2007 received 1391-mm rainfall in 44 events. Out of this, 1153-mm rainfall was received during June to September 2007.

Slopes of the hills were categorized into steep ($>20°$), medium (10%–20%) and gentle slopes ($<10\%$). Based on USDA Soil Taxonomy Classification, soils of steep slope area are classified as loam to clay (clayey, skeletal, hyperthermic family of Lithic Ustorthents), developed on basaltic materials covered with surface-exposed pebbles of varying size. Soils of the medium slope are classified as loamy sand (coarse loamy, skeletal, hyperthermic family of Lithic Ustorthents) with limited numbers of surface-exposed cobbles. Soils in the gentle slope belong to loamy, hyperthermic family of Typic Ustorthents. This forest area comes under degradation stage (i.e., dry deciduous scrub) of tropical dry deciduous forest (Champion and Seth, 1968). However, due to overexploitation and removal of vegetation, the area was invaded by *Prosopis juliflora* (SW.) DC. and *Lantana camara* L. as observed in 2005. Other species with very limited number were shrubby *Acacia leucophloea* Roxb. Willd. *Butea monosperma* (Lam.) Taub., *Acacia nilotica* L. and *Phoenix sylvestris* Roxb. The soils are dark brown to black in colour in steep and gentle slopes, whereas they were light brown to light red in colour in medium slope.

2.2 Experimental design and harvesting structures

A total of 75 plots each of 700-m^2 area were laid in $<10\%$, 10%–20% and $>20\%$ slopes in June 2005. Each plot was separated by individual boundary of trench (45 cm × 45 cm) cum bund to avoid water intrusion from other plots and had rainwater harvesting (RWH) structures of 30 running meters length except in the control plots, which was only with plot boundary. Contour trenches (CT) and Box trenches (BT) were similar in cross section and length, but BT had 15 intermittent trenches of 2-m length (Fig. 1a and c).

V-ditches (VD) and Gradonie (G) were across the contour and 1800 cm^2 in cross-section area, but the differences were vertical cut, which was upside of the slope in G to reduce run-off velocity and downside of the slope in VD to facilitate improvement in surface soil water (Fig. 1b and d). The excavated soil was heaped towards the down slope. Three microsites of 1-m^2 area were laid at the centre of upper one third (USP), middle one third (MSP, downside of RWH structure) and lower one third (LSP) of each plot for soil sampling and observation recording (Fig. 1e). The experiment was laid in a complete randomized block design, and 35 numbers of seedlings (500 plants$\cdot$ha^{-1}) of different tree species were planted in each plot in August 2005 to rehabilitate the area through afforestation and promotion of regeneration under protection against human and livestock interferences. Five RWH

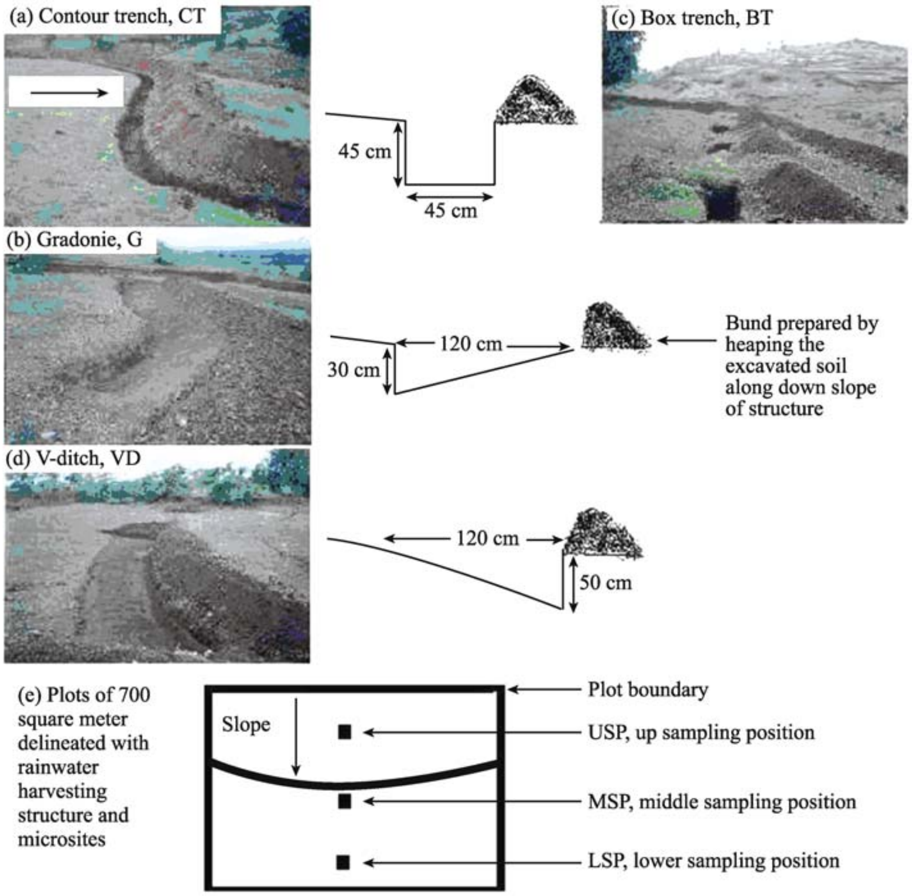

Fig. 1 Rainwater harvesting structures

Note: (a), (b), (c) and (d) represent contour trench, gradoni, box trench and V-ditch, respectively, laid out in the experimental area at Banswara, Rajasthan, India. (e) means a plot of 700-m^2 area delineated with plot boundary, rainwater harvesting structure and up, middle and lower sampling positions in the plot.

treatments in five replications and three slope gradients gave 75 plots distributed in an about 17-ha area. *Prosopis juliflora* and *Lantana camara* were removed sequentially to facilitate the regeneration of natural vegetations.

2.3 Observations recording

Initial soil sampling and soil texture analysis were done in June 2005. For the present study of soil resource and vegetation diversity relation, soil sampling was done in June 2007 before monsoon from the three microsites mentioned above (Fig. 1e) and homogenized to form a composite sample for each plot. Soil samples were dried and passed through a 2-mm sieve for separation of gravel and soil. Soil pH, soil organic carbon, NH_4-N and NO_3-N were determined using standard procedures (Jackson, 1973; Cataldo et al., 1975; Baruah and Barthkumar, 1999). Extractable phosphorus was determined by the Olson's extraction method (Jackson, 1973) using uv-vis-spectrophotometer Model Shimadzu-1650PC. For soil water content (SWC) determination, sampling was done in June, July, August, September and December in 2007. Soil water content was estimated by oven-drying of the sample at 110°C to a constant weight. Soil water depletion during vegetation growth was calculated as per cent decrease in SWC from August to December. Photosynthetically active radiations (PAR) were measured above and inside vegetation (at soil surface) at above-mentioned microsites in September 2007 using portable CO_2 gas analyzer (Model CI-301).

The above-ground-living vascular vegetations from microsites (1 m^2 area) were clipped just above the soil surface and sorted to species in October 2007. Vegetation was identified as per taxonomical classification using standard literatures (Bhandari, 1990; Shetty and Singh, 1993). These species were counted manually for the number of species and their population. Green herbage biomass was recorded after shorting to a species level and summing up of all. Dry mass of individual species was recorded after drying the sample at 80°C, and summed dry mass of all the species was recorded as herbage dry biomass. Species richness and composition were calculated following standard literatures (Simpson, 1949; Margalef, 1958; Shannon and Wiener, 1963; Pielou, 1966).

2.4 Statistical analysis

Data were analyzed using SPSS statistical package version 8.0 for Windows 2000. Soil nutrients and soil water depletion were analyzed using a two-way ANOVA. Above-mentioned parameters were the dependent variables and slope, and RWH treatments were the fixed factors. Since SWC was determined repeatedly for five months, it was analyzed using repeated-measure ANOVA. However, SWC of June, September and December in 2007, the number of species, species population, green and dry herbage yields and species richness, diversity, dominance and evenness were recorded/calculated from three microsites; these data were analyzed using repeated-measure ANOVA considering different microsites as the tests of within-subjects effects. Percent soil water was square root transformed before statistical analysis to reduce heteroscenesdity (Sokal and Rolf, 1981). To obtain the relations between SWC, soil nutrients and vegetation diversity and yield, Pearson correlation coefficients were calculated. The least significant difference test was used to compare microsite, slope and treatments at the $P < 0.05$ levels. Regression equations were also developed to find out relationship in number of species, population, species richness and species composition with soil resources and herbage yield keeping soil resource and yield as dependent variables.

3 Results

3.1 Soil properties

In June 2005, gravel content ranged from 78.4% to 87.7% being the highest in > 20% slope. Sand content was the highest in 10%–20% slope, ranging from 7.5% to 17.3%. Silt and clay content were greater in < 10% and > 20% slopes than in 10%–20% slope. Soil was acidic in reaction (pH = 6.88), whereas the average concentrations of soil organic carbon (SOC), ammonical nitrogen (NH_4-N), nitrate nitrogen (NO_3-N) and phosphate phosphorus (PO_4-P) were 0.760%, 22.15 $mg \cdot kg^{-1}$, 2.50 $mg \cdot kg^{-1}$ and 4.51 $mg \cdot kg^{-1}$, respectively. In June 2007, soil PO_4-P ($P < 0.05$) increased from > 20% to < 10% slope. Soil pH was the highest in the < 10% slope, electrical conductivity (EC), NO_3-N ($P < 0.05$) and NH_4-N ($P < 0.05$) were the highest in 10%–20% slope, and SOC was the highest ($P < 0.05$) in > 20% slope (Table 1). The lowest pH and SOC were in 10%–20%, and EC, NO_3-N and NH_4-N were the lowest in < 10%.

In RWH treatments, concentrations of SOC ($P < 0.05$), PO_4-P ($P < 0.05$) and NH_4-N were the highest in VD plots, whereas pH and EC were the highest in CT plots. Concentration of NO_3-N was the highest ($P < 0.01$) in BT plots. The lowest EC and nitrogen concentrations were in control plots, whereas SOC and PO_4-P were the lowest in CT plots. SOC and PO_4-P concentration showed positive ($r = 0.435$, $P < 0.01$, $n = 75$) and negative ($r = -0.360$, $P < 0.01$) relations, respectively, with slope gradient, whereas soil pH ($r = -0.359$, $P < 0.01$) and SOC ($r = -0.236$, $P < 0.05$) were negatively related with NH_4-N.

3.2 Soil water dynamics

Regular rain from June to September increased soil water content (SWC), which was the highest in August (12.28% to 19.82%) followed by July (12.29% to 18.43%). It was associated with the highest rainfall (Fig. 2a). SWC increased ($P < 0.05$) downward by 7.4% and 21.4% in June, 5.9% and 17.2% in September, and 23.8% and 20.7% in December at MSP and LSP, respectively, than at USP (Fig. 2b–d). SWC varied ($P < 0.05$) from 1.34% in June to 16.81% in August with significant ($P < 0.05$) month × slope interaction. SWC was the highest ($P < 0.05$) in < 10% slope in all observations except in August 2007, when SWC was the highest ($P < 0.05$) in > 20% slope. The lowest ($P < 0.05$) SWC was in 10%–20% slope in all observations. The average decrease in SWC was 19.0% in 10%–20% slope and 5.0% in > 20% slope lower than in < 10% slope. We did not find significant treatment effect on SWC, though it was the highest in BT plots in June, July and September, in Gradonie plots in August and in VD plots in December 2007. The increase in SWC over control was 5.0% in VD to 15.0% in BT plots. The soil water depletion during August to December was the highest ($P < 0.05$) in 10%–20% slope (82.7%) and lowest in < 10% slope (73.6%). Among RWH treatments, the soil water depletion was the highest ($P < 0.05$) in G (83.1%) and the lowest in VD (76.7%) plots (Table 1). Gravel content ($r = 0.247$, $P < 0.05$) showed a positive relation with SWC, whereas sand content ($r = -0.265$, $P < 0.05$), NH_4-N ($r = -0.380$, $P < 0.01$) and NO_3-N ($r = -0.286$, $P < 0.05$) showed a negative relation with SWC.

3.3 Photo-synthetically active radiations

Photo-synthetically active radiations (PAR) in September 2007 ranged from 1429.6 to 1651.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Growing vegetation and plants reduced PAR reaching to the ground surface, and the reduction was highest in < 10% slope ($P < 0.05$ at MSP). The lowest reduction in PAR was in 10%–20% slope at all microsites (Fig. 3a). Among the treatments, PAR reduction was the lowest in control and the highest in G plots. PAR reduction increased in the order of USP < MSP < LSP in < 10% slope and in CT and BT treatments.

Table 1 Soil physico-chemical properties in June 2007 and soil water depletion during August to December 2007 influenced by natural slopes and rainwater harvesting treatments in Aravalli hills

slope	RWH treat.	pH	EC/(mS·m^{-1})	SOC/%	NO$_3$-N /(mg·kg^{-1})	NH$_4$-N /(mg·kg^{-1})	PO$_4$-P /(mg·kg^{-1})	water depletion Aug. to Dec.
S$_1$	control	7.02±0.04	0.22±0.03	0.85±0.07	1.41±0.33	11.84±1.39	7.77±0.74	78.08±3.34
	C. trench	6.84±0.07	0.21±0.03	0.68±0.03	4.45±1.48	14.41±1.64	7.22±0.43	76.33±3.43
	Gradonie	6.70±0.11	0.20±0.04	0.77±0.12	3.52±0.72	18.10±2.89	7.00±0.99	79.50±3.59
	B. trench	6.82±0.12	0.30±0.08	0.93±0.02	4.98±1.26	16.56±1.38	9.95±1.16	68.11±2.29
	V-ditch	7.05±0.04	0.24±0.04	0.91±0.04	4.33±1.20	14.73±1.77	10.1±0.79	65.97±3.00
S$_2$	control	6.65±0.19	0.24±0.04	0.67±0.06	4.10±0.64	24.09±3.17	5.28±1.03	85.47±3.73
	C. trench	7.06±0.15	0.30±0.04	0.72±0.04	6.80±0.76	18.07±0.54	6.70±0.81	79.36±4.90
	Gradonie	6.72±0.18	0.30±0.02	0.78±0.07	4.68±0.38	18.07±1.48	6.68±0.36	83.36±1.86
	B. trench	6.64±0.13	0.27±0.04	0.83±0.06	7.78±1.30	23.02±1.40	7.38±0.87	84.04±2.06
	V-ditch	6.56±0.19	0.21±0.05	0.92±0.06	4.18±0.42	18.33±2.58	6.89±0.84	81.42±1.70
S$_3$	control	6.69±0.16	0.24±0.05	0.92±0.06	4.84±0.72	11.75±4.18	6.23±0.93	78.01±4.98
	C. trench	6.88±0.04	0.25±0.06	0.98±0.05	5.54±0.83	16.86±2.89	6.14±0.40	80.09±3.22
	Gradonie	6.80±0.20	0.24±0.05	0.89±0.10	5.84±1.06	17.72±3.71	5.74±0.60	86.37±2.97
	B. trench	6.76±0.11	0.20±0.03	1.02±0.10	5.23±0.88	13.68±1.48	6.11±0.21	87.55±1.78
	V-ditch	6.89±0.08	0.26±0.03	0.99±0.10	4.79±0.30	21.09±3.58	6.71±0.89	82.56±0.97
Two-way ANOVA								
F value								
slope		1.844	0.707	8.309	5.679	5.980	12.386	14.52
treatment		1.073	0.164	2.821	3.751	0.466	3.097	1.74
slope × treatment		1.382	0.834	0.816	1.218	1.984	1.053	2.19
P value								
slope		0.167NS	0.497NS	0.001**	0.006**	0.004**	0.000**	0.003**
treatment		0.378NS	0.956NS	0.033*	0.009**	0.761NS	0.022*	0.122NS
slope × treatment		0.223NS	0.576NS	0.592NS	0.304NS	0.064NS	0.408NS	0.035*

Note: S1: $<10\%$ slope, S2: 10%–20% slope, and S3: $>20\%$ slope. Values are means±*SE* of five replications. * and ** represent significance at 0.05 and 0.01 probability levels, respectively.

3.4 Vegetation growth and composition

The average vegetation height increased upward from LSP to USP except in the control plots (Fig. 3b). In $>20\%$ slope, the tallest ($P<0.05$) vegetation was at MSP. Vegetation height increased with slope gradient (R^2 = 0.100, F = 8.10, P = 0.006). The vegetation was taller by 3.96% in 10%–20% and by 33.68% in $>20\%$ when compared with that in $<10\%$ slope, and shorter in CT and taller in BT than that in the other treatments. The vegetation height showed a positive relation with PAR reduction ($r=0.266$, $P<0.05$) and SWC in December (r = 0.344, $P<0.01$) and a negative (r = -0.252, $P<0.05$) relation with NH$_4$-N.

Eighty one herbs and grasses species were recorded in the plots. Species number and populations ($P<0.05$) increased from USP to LSP among microsites. These variables were the highest ($P<0.05$) in 10%–20% slope and the lowest in $>20\%$ slope (Fig. 3c-d). The lowest species number and species population were in control ($P<0.05$), with the highest in VD plots. The increase in the species number and their population in RWH-treated plots were 1.2- to 1.5-fold and 1.1- to 1.6-fold, respectively, higher than that in the control plots. These variables were positively ($r=0.536$, $P<0.01$) related with soil sand content (r = 0.277 and 0.350, $P<0.05$), NH$_4$-N (r = 0.207 and 0.258, $P<0.05$) and NO$_3$-N (r = 0.200 and 0.185, $P<0.10$) concentrations; but showed negative relations with PAR reduction (r = -0.249 and r = -0.232, $P<0.05$) and SWC in August (r = -0.312, $P<0.01$) and December (r = -0.302, $P<0.01$).

3.5 Vegetation diversity

The average species richness decreased and diversity increased from USP to LSP, whereas species dominance and evenness did not show a clear trend among microsites (Fig. 4). While considering slope, the highest species richness and diversity ($P<0.05$) were in 10%–20%, dominance in $>20\%$ and evenness in $<10\%$ slopes.

Among RWH, the highest species richness and diversity

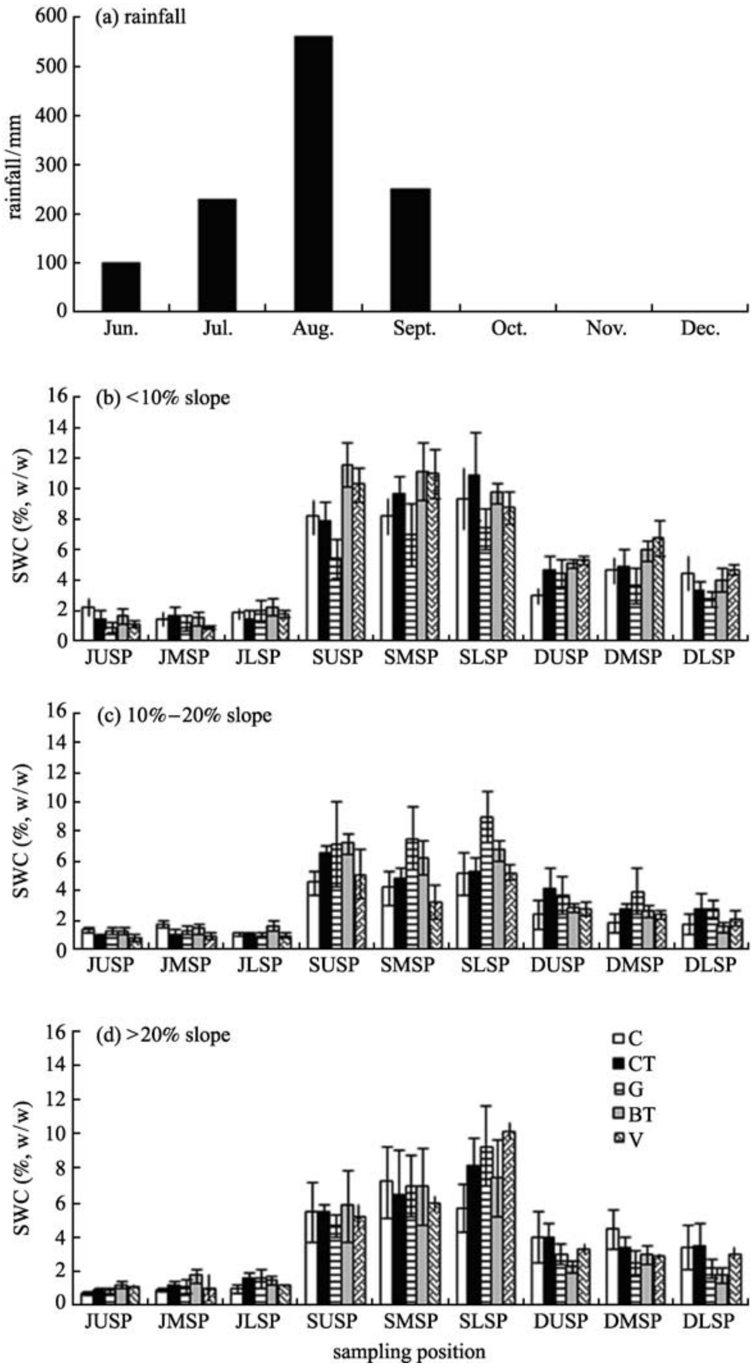

Fig. 2 Changes in rainfall and soil water content

Note: (a) is rainfall during June to December 2007, and (b–d) are changes in soil water content due to microsite, slope gradient and rainwater harvesting treatment in June, September and December 2007. Values are mean with error bars of ±*SE* of five replications. J, S and D are January, September and December, respectively. USP, MSP and LSP are up, middle and lower sampling positions in a plot.

were in VD and the lowest in control plots. The highest dominance and evenness appeared in control and G plots, respectively. Microsite × slope interaction and microsite × treatment interaction were significant ($P < 0.05$). Species richness and diversity were positively related with sand content ($r = 0.270$ and 0.321, $P < 0.05$), NH_4-N ($r = 0.280$ and 0.260, $P < 0.05$), species number ($r = 0.918$ and 0.920, $P < 0.001$) and population ($r = 0.293$ and 0.455, $P < 0.01$, respectively). But both these variables were negatively related with gravel content ($r = -0.237$ and -0.283, $P < 0.05$) and vegetation height ($r = -0.473$ and -0.433, $P < 0.01$).

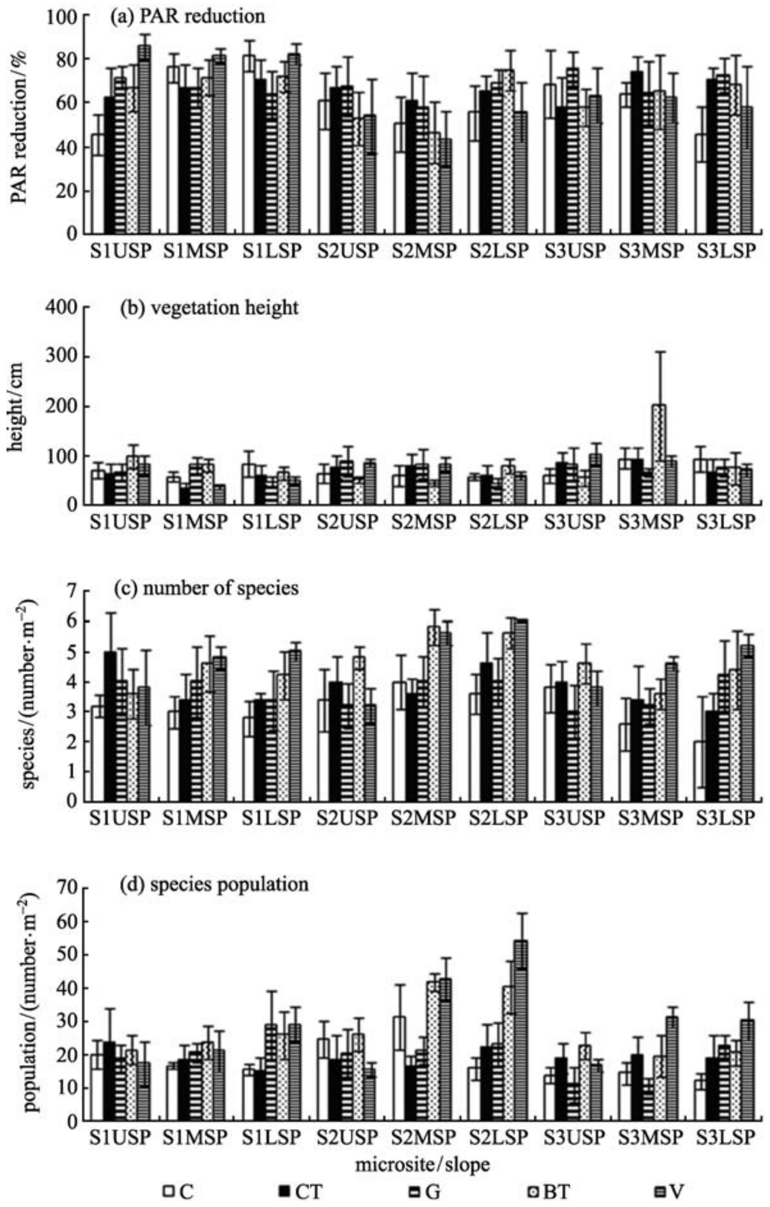

Fig. 3 Changes in photosynthetically active radiation (PAR) and vegetation variables

Note: (a), (b), (c) and (d) are per cent reduction in PAR, vegetation height, species number, and population of herbage, respectively, influenced by microsite, slope gradient and rainwater harvesting treatments in 2007. Values are mean with error bars of ±*SE* of five replications. S1: < 10% slope, S2: 10%–20% slope, and S3: > 20% slope. USP, MSP and LSP are up, middle and lower sampling positions in a plot.

3.6 Herbage yield

Green and dry herbage yields were lowest ($P < 0.01$) at USP and increased by two-fold at LSP within a plot with significant ($P < 0.05$) microsite × treatment interactions (Table 2). Considering slope, both green and dry herbage yields were highest ($P < 0.05$, DMRT) in > 20% slope and lowest in < 10% slope. As compared to the yields at USP, the increase in green and dry herbage yields at LSP were 1.77- and 1.66-fold in < 10% slope, 2.11- and 2.06-fold in 10%–20% slope and 2.14- and 2.17-fold in > 20% slope, respectively. Among RWH treatments, average herbage yield was lowest ($P < 0.05$) in CT plots, which did not differ with the yields in the control and Gradonie plots.

Green (3.37-fold) and dry (3.59-fold) herbage yields were highest ($P < 0.05$) in VD plots. Second best treatment was BT (1.65- and 1.74-fold yields, respectively). Significant ($P < 0.05$) slope × treatment interaction indicated highest herbage yields in BT plots in < 10% slope and in VD plots in 10%–20% and > 20% slopes. Herbage dry yield was positively related with vegetation height ($r = 0.401$, $P < 0.01$) and population ($r = 0.248$, $P < 0.05$).

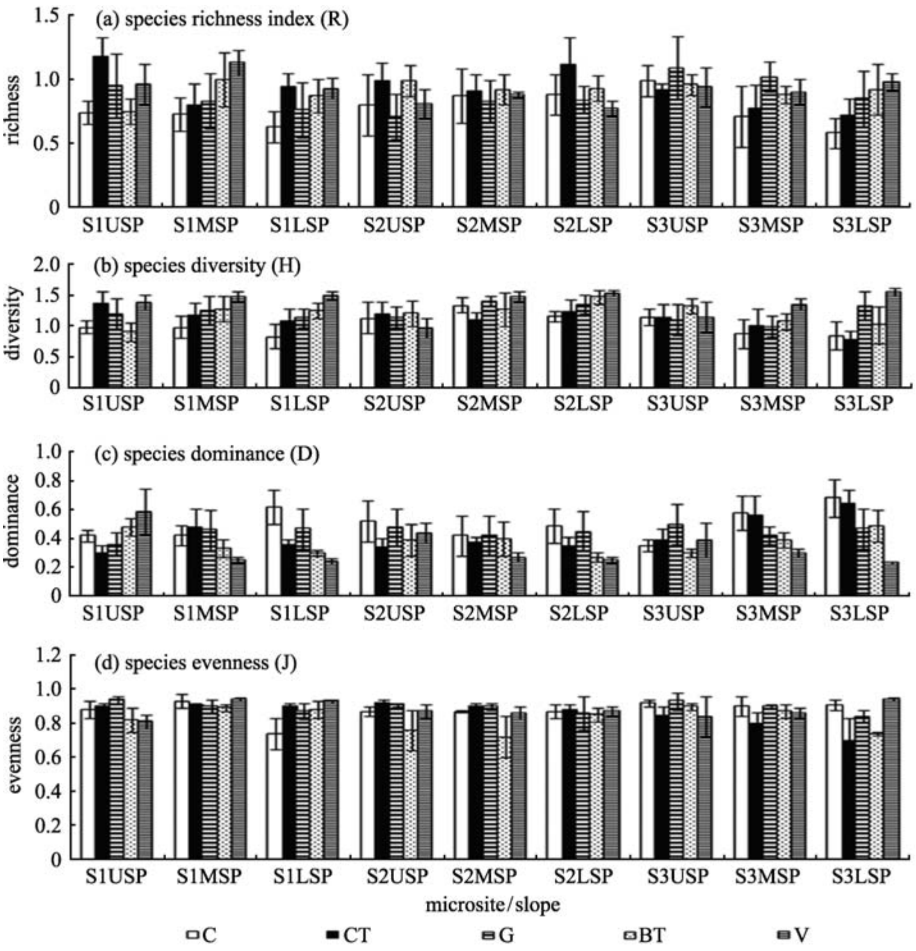

Fig. 4 Changes in herbage diversity variables under the influence of microsite, slope gradient and rainwater harvesting treatments in 2007
Note: (a), (b), (c) and (d) are species richness, species diversity, species dominance, and species evenness, respectively. Values are mean with error bars of ±*SE* of five replications. S1: < 10% slope, S2: 10%–20% slope, and S3: > 20% slope. USP, MSP and LSP are up, middle and lower sampling positions in a plot.

3.7 Regression relations

We did not find significant ($P > 0.05$) relation between dry herbage with soil nutrients at different microsites. But NO_3-N and NH_4-N, soil sand content and soil water content in June and August in 2007 showed a positive ($P < 0.05$) relation with diversity variables and yields, except dry yield and species dominance with SWC in December and NH_4-N concentration, respectively (Table 3).

Dry herbage yield increased with species number, their population and SOC and NO_3-N concentration (Fig. 5). It was non-linearly ($P < 0.05$) related with species number, dominance, diversity and richness at USP. Dry herbage yield decreased ($P > 0.05$ at USP) with an increase in species richness at all microsites, but after showing a decreasing trend at USP, dry herbage yield increased with diversity at LSP (Fig. 5). Dry herbage increased with vegetation height by power ($R^2 = 0.357$, $P < 0.01$) relation and with SWC in December ($R^2 = 0.094$, $P < 0.01$) by sigmoid relation.

4 Discussion

4.1 Slope gradient and vegetation diversity

Though variations in quantity and intensity of rainfall influenced SWC (Fig. 2b-d), the decrease in SWC from August to June was due to downward drainage, soil water usage by the growing vegetation and surface evaporation caused by solar radiation and increased air temperature. Relatively greater decrease in soil water at USP than at LSP or MSP during August to December was due to down-slope movement and/or soil water usage by the growing vegetation. Rastetter et al. (2004) examined the effects of down-slope movement of water and nutrients, and their simulation model indicated 30% higher net carbon storage

Table 2 Green and dry herbage yields influenced by natural slope, rainwater harvesting treatments and microsites within plots in Aravalli hills and repeated measure ANOVA of the data

slope	RWH treat.	green herbage/($g \cdot m^{-2}$)			dry herbage/($g \cdot m^{-2}$)		
		USP	MSP	LSP	USP	MSP	LSP
S_1	control	464.0±147.2	652.4±250.0	900.0±262.1	250.2±102.1	275.2±97.8	438.9±109.4
	C. trench	379.9±128.9	298.4±114.2	679.5±272.2	172.6±64.9	153.4±62.7	320.7±134.9
	Gradonie	649.3±263.0	664.9±278.0	1021.4±489.1	319.6±133.2	323.4±131.4	511.1±229.9
	B. trench	846.8±79.5	1243.7±432.3	1131.5±417.4	423.5±42.5	697.3±267.8	559.5±220.9
	V-ditch	695.0±340.6	1044.8±389.7	1631.4±361.6	408.2±211.9	485.7±183.7	786.4±180.3
S_2	Control	497.3±156.1	405.2±176.3	456.4±287.2	223.7±65.8	201.9±87.6	230.0±147.3
	C. trench	522.8±72.8	446.4±105.9	495.7±174.1	244.4±35.2	216.9±50.6	243.1±83.8
	Gradonie	649.3±249.7	606.6±255.4	599.1±240.4	326.6±122.9	295.3±128.8	303.8±123.3
	B. trench	397.3±76.9	824.3±324.4	1204.8±207.3	210.6±41.1	401.4±155.5	596.1±99.2
	V-ditch	804.1±125.0	2798.8±226.8	3293.7±103.9	515.1±142.4	1407.9±133.6	1751.5±144.2
S_3	Control	260.0±113.3	669.1±242.2	871.9±319.8	137.6±51.4	350.6±126.8	414.8±158.2
	C. trench	631.4±149.8	633.7±249.8	714.0±231.9	296.3±79.9	345.6±123.5	355.9±114.9
	Gradonie	860.5±381.1	244.9±43.9	817.9±548.7	449.8±205.2	111.5±21.3	403.5±265.3
	B. trench	311.0±106.8	1567.5±670.1	991.40±303.2	142.1±50.7	812.0±353.9	538.8±171.4
	V-ditch	997.1±319.8	3032.7±335.5	3153.2±271.3	488.9±145.3	1644.5±184.3	1567.8±166.3

repeated-measure ANOVA		green herbage		dry herbage	
		MSE	*F* value	MSE	*F* value
tests of within-subjects effects					
microsite	2	7053967.18	25.560**	1714250.43	20.974**
microsite × slope	4	315018.556	1.141NS	126463.964	1.547NS
microsite × treatment	8	2585600.57	9.369**	618728.223	7.570**
tests of between-subjects effects					
slope	2	993791.143	1.525NS	312303.070	1.848NS
treatment	4	15347056.2	23.544**	4328217.60	25.617**
slope × treatment	8	1816451.37	2.787*	537440.327	3.181*

Note: Values are means±*SE* of five replications. USP, MSP and LSP are up, middle and lower sampling positions (micro-sites) in a plot. MS: mean square. Values significant at **: $P < 0.01$, *: $P < 0.05$ and NS: not significant ($P > 0.05$).

at the base of the 100-m transect than at the top due to the movement of nutrient downhill. Thus, increased SWC from USP to LSP was due to an obvious soil water gradient existing since longer time resulting in differentiation of microsites. But application of RWH and its effects in reducing water flow and prolonging time of water movement increased the differences in SWC between USP and LSP (as RWH structure in downside of USP) at the end of December (Fig. 2). Microsite differentiation due to slope gradient influencing soil water-nutrient gradient was also observed by López et al. (2003). Similar trends in species number, population, diversity, light interception (PAR reduction) and soil water content indicated a positive relation between resource availability and diversity at a microsite level. Baer et al. (2003) observed a positive relationship between ANPP and intercepted light with a strong correlation between light availability and diversity. However, an increasing trend of vegetation height (R^2 = 0.100, $F = 8.10$, $P = 0.006$, $n = 73$) and herbage yield with slope (particularly in $> 20\%$ slope) might be due to selection effects caused by dominance of species with tall habit, i.e., *Themada quadrivelvis* and *Apluda mutica*. But relatively greater height at MSP particularly in $> 20\%$ slope suggested positive effects of RWH in soil water and fertility improvement and, thus, vegetation growth (Fig. 3b). Positive relations of SWC with soil EC and available PO_4-P and negative relations with NH_4-N ($r = -0.353$, $P < 0.01$) at MSP in September and December 2007 were indicative of mineral accumulation through runoff collection, their mineralization and utilization in vegetation growth. During his calculation of nutrient budgets, Koerselman et al. (1990) also suggested that nutrients accumulated in former period can facilitate plant growth in the next year after re-mineralization.

However, non-existence of the above trend in SWC at slope level was probably due to variations in and interaction of soil texture, vegetation cover and species identity, which exerted interactive controls over SWC similar to the observation of English et al. (2005). But reduced water retention due to greater sand content and

Table 3 Regression relations of soil water and soil physico-chemical properties with herbage diversity and productivity

dependent variables	independent variables	relations	regression constants			ANOVA			
			a	b_1	b_2	*F* value	*P* value	R^2	*SE*
NH_4-N	richness	cubic*	53.5411	−138.15	154.418	3.99	0.011	0.144	5.8109
NH_4-N	No. species	cubic**	42.6618	−25.204	6.9797	3.67	0.016	0.134	5.8457
NH_4-N	diversity	expo.	10.6782	0.3577	–	7.94	0.006	0.101	0.3637
NH_4-N	dominance	quadratic	28.8699	−49.011	43.3712	3.99	0.023	0.100	5.9193
NO_3-N	Richness	sigmoidal	1.7315	−0.2410	–	5.32	0.024	0.070	0.5635
NO_3-N	No. species	power	2.6385	0.3557	–	5.54	0.034	0.059	0.5634
NO_3-N	evenness	inverse	0.9141	3.4022	–	4.89	0.030	0.064	2.2331
Sand	No. species	expo.	9.2225	0.0769	–	6.521	0.013	0.082	0.3522
Sand	diversity	comp.	8.4140	1.4149	–	8.27	0.005	0.104	0.3458
Sand	dominance	quadratic	22.0401	−35.365	29.9207	3.60	0.032	0.091	4.6259
SWC (JN)	richness	inverse	1.0021	0.2725	–	5.18	0.026	0.068	0.6387
SWC(AG)	evenness	sigmoidal	3.4514	−0.6008	–	8.73	0.004	0.109	0.2952
DY (USP)	dominance	linear	78.6922	544.775	–	18.99	0.000	0.206	233.709
DY (USP)	diversity	inverse	132.858	140.802	–	10.68	0.002	0.136	206.967
DY (USP)	richness	power	200.104	−0.5654	–	6.66	0.012	0.085	256.261
DY (LSP)	diversity	linear	73.2586	418.334	–	5.61	0.021	0.080	551.246
DY	population	linear	270.259	9.0192	–	4.78	0.032	0.061	372.483
DY (USP)	No. species	inverse	110.654	576.723	–	20.77	0.000	0.225	231.479
DY	SWC (Dec)	sigmoidal	6.0787	−0.5120	–	7.61	0.007	0.094	0.7736
DY	SOC	sigmoidal	7.6638	−1.4891	–	21.34	0.000	0.226	0.7151

Note: Most of the cases, degrees of freedom are 71 and 73, whereas it was 68 in dry yields related with diversity and richness. *b_3= −52.113, ** = −0.5711. DY stands for dry herbage yield.

run-off loss (unpublished data) from 10%–20% slope than in the $> 20\%$ and $< 10\%$ slopes due to skeletal soil was also responsible for low SWC in 10%–20% slope. Singh et al. (1998) also observed differences in SWC between the slopes due to variability in soil texture and clay content. Increased green and dry herbage yields from $< 10\%$ to $> 20\%$ slope were probably due to RWH that improved soil water and nutrient availability substantiated by clay content. Presence of pebbles reduced surface runoff prolonging time for water absorption in soil enhancing SWC and herbage yield in $> 20\%$ slope (Fig. 2, Table 2). Svoray et al. (2004) and Danalatos et al. (2007) recorded higher herbaceous production influenced by soil rockiness or rock fragments. Interestingly, 10%–20% slope showed that the highest species number, population ($P < 0.05$), species richness and diversity were probably associated with sand content, skeletal soil and relatively greater availability of NO_3-N and NH_4-N (Fig. 4). Despite the low SWC enhancing a higher herbage yield in 10%–20% than in $< 10\%$ slope, it was due to more diverse vegetation, higher soil water usage (82.7% water usage) facilitated by relatively greater soil fertility and regular rain during the growing season. This showed a positive relation between available nitrogen and species number/ herbage diversity (Table 3). Evolutionary computer model of Warren et al. (2009) demonstrated that given the opportunity, species-rich communities may be evolved under high fertility conditions. The finding was also supported by low soil pH and SOC in 10%–20% as a result of mineralization or decomposition of accumulated litters/SOC increasing soil fertility. Decline in soil pH, soil organic matter and its mineralization has also been recorded by Berendse et al. (1998) in coastal dune of Netherlands. But the highest ($P < 0.05$) SWC, pH and PO_4-P availability in $< 10\%$ slope was due to absorption and retention of equally distributed water and nutrients in the gentle slope plots. Tsui et al. (2004) also observed higher pH, exchangeable Ca and Mg and lower organic carbon, and available N and K in the footslope because slope factors are involved in the transport and accumulation of solutes. Relatively greater diversity and vegetation populations in $< 10\%$ slope as compared to those in $> 20\%$ slope (Fig. 3 and Fig. 4) might influence infiltration by reducing run-off and nutrient losses, which is similar to the observation of Yong et al. (2006), who recorded a decrease in nutrient loss because of increased infiltration influenced by soil texture, porosity, water content and vegetation coverage, reduced runoff flow velocity and transferring form of nutrients in soil.

4.2 Rainwater harvesting and vegetation diversity

Relatively greater SWC at USP than at MSP in CT and G treatments enhanced herbage yield in upward rather than immediate downward as in the case of BT and VD

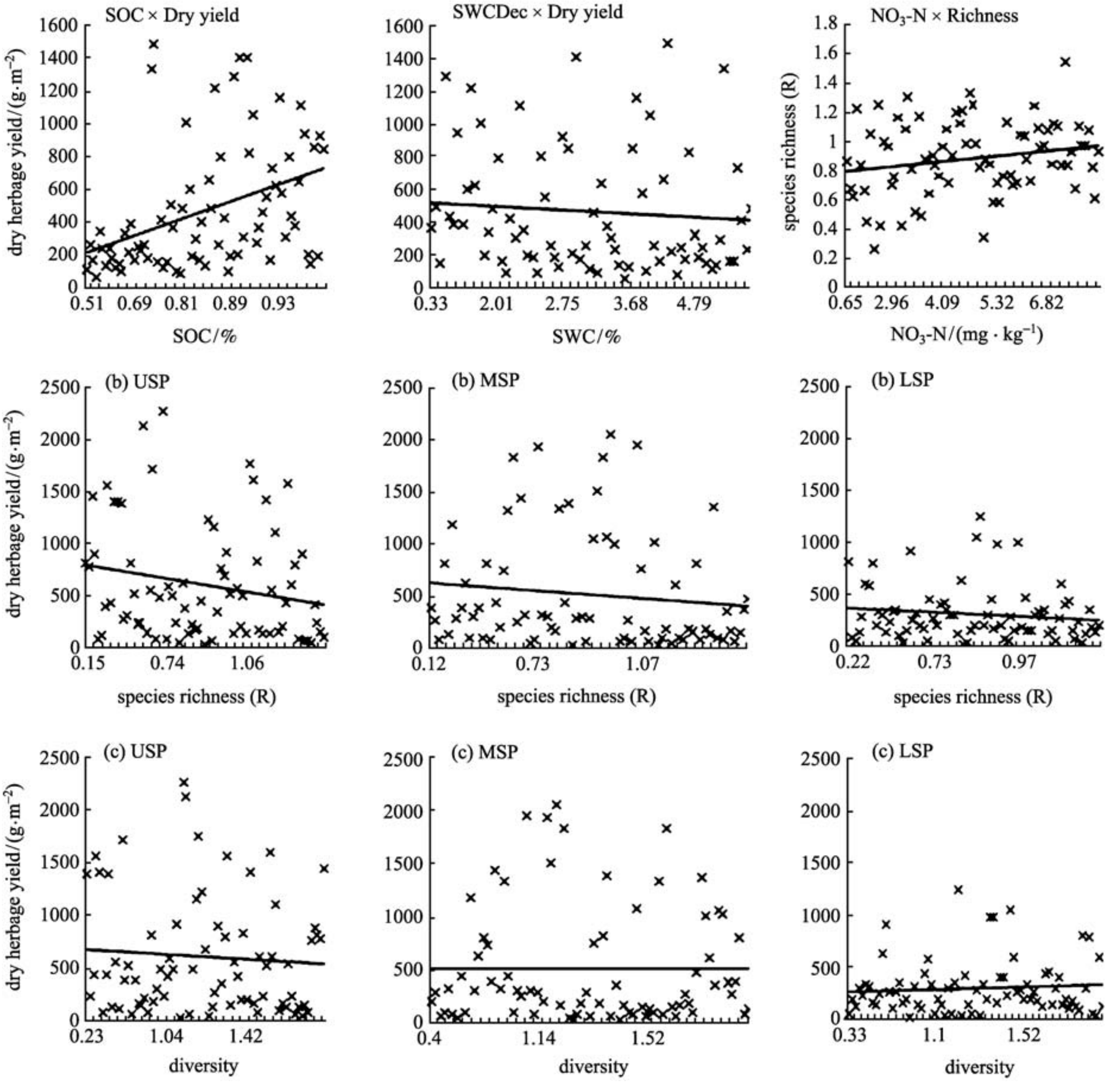

Fig. 5 Relations between soil resources, herbage diversity and yields under the influence of microsite, slope gradients and rainwater harvesting treatments

Note: The indent of the right panels is similar to that in left panels. Only a linear trend has been shown.USP, MSP and LSP are up, middle and lower sampling positions in a plot.

structures. Thus, CT and G structures improved soil water status upward also, but it was limited to monsoon season only. Downward movement of stored water in RWH structures resulted in greater SWC downside particularly in CT and BT treatments in June (Fig. 2b). The highest ($P < 0.05$) SWC in G plots only in August indicated a positive relation with rainfall, suggesting that this structure was beneficial only when rainfall was high and regular. Uniform distribution of rainfall and run-off collection in box trenches improved SWC in BT plots in most of the observations resulting in taller vegetation. Species richness, diversity and herbage yield showed negative relations with SWC in VD plots during the growing period, suggesting efficient utilization of soil water by more diverse vegetation, the regeneration of which was probably influenced by soil fertility, i.e., SOC, NO_3-N and NH_4-N availability (Table 1), indicating a cause-effect relation between herbage species and soil resources as observed by Liu et al. (2008) along the slope. It was supported by increased SWC in VD plots in December because grass harvesting/vegetation senescence reduced soil water usage. This increase in SWC was facilitated by vegetation height, which reduced PAR reaching to ground surface and, thus, evaporation loss. Positive relations of SWC, NH_4-N and NO_3-N with species diversity, species richness, dominance and evenness suggested that diversity increased with soil resources. Thus, the tallest vegetation in BT plots was probably facilitated by relatively greater concentration of NO_3-N. This showed that diversity variables varied with soil fertility and micro-environment, i.e., microsites and RWH structures. Ventura et al. (2006) recorded changes in the sign of the relationship between soil fertility and species richness, which varied according to the nutrient and the micro-environment. The highest pH and EC and lowest concentration of SOC and PO_4-P in CT due to salt-induced mineralization under more water storage than that in the G and VD plots affected vegetation diversity.

4.3 Vegetation diversity and productivity relations

Increased herbage yields with number of species, population and diversity indicated a positive relation (Fig. 5) between yield and diversity ($R^2 = 0.079$, $P = 0.021$, $n = 65$ at LSP), but a negative relation of herbage yield with species richness ($r = -0.244$, $P = 0.035$, $n = 75$) showed a compositional rather than richness effect in increasing herbage yield in the present study (Table 3). The relationship between species richness and productivity is unimodal (hump-shaped), though a more comprehensive survey of the ecological literature uncovered approximately 200 relationships, of which 30%, 26%,12% and 32% were unimodal, positive linear, negative linear, and non-significant, respectively (Waide et al., 1999). However, a positive relation of herbage yields with diversity and nutrient availability in VD plots indicated fertility-reinforced diversity and productivity. Fornara and Tilman (2009) found seven variables simultaneously controlling productivity, i.e., initial total soil nitrogen, diversity-dependent increases in soil N, soil N mineralization rates, soil nitrate (NO_3^-) utilization, increases in plant N-use efficiency at greater plant diversity, legume presence, and higher species numbers. Changes in relations between diversity and herbage yield from a negative ($r = -0.249$, $P = 0.037$) at USP to a positive ($r = 0.282$, $P = 0.021$) at LSP through a non-significant relation ($r = 0.072$, $P > 0.05$) at MSP showed the influence of resource availability on herbage yield (Fig. 5). Non-linear increase of species diversity, species richness, dominance and evenness with NH_4-N and NO_3-N concentrations suggested that the effects of diversity on productivity increased with fertility (Table 3). Aude et al. (2003) observed that more species normal in semi-natural habitats were found on organic farms than on non-organic farms, indicating the importance of soil fertility on diversity and species composition.

5 Conclusions

Downward increase in soil water content, species diversity and herbage yields indicated a resource gradient with variation in microsites. More important is a positive relation of soil water availability with herbage diversity and yield, particularly at a microlevel, and RWH influenced them positively. Though a reverse trend was observed for herbage yield and SWC between < 10% and 10%–20% slopes, regular rain and greater usage of soil water in 10%–20% slope suggested the importance of efficient utilization of soil resources by a diverse community, which was influenced by soil texture and fertility. VD structure was the best with the highest herbage yield, which was the combined effect of species richness, composition and soil fertility. The effect of species composition was relatively greater than that of richness in increasing herbage yield. These results showed the effect of slope gradient and soil texture on herbage regeneration, diversity and productivity. But existing soil fertility and application of RWH structures positively influenced these to a greater extent by mobilizing soil water and nutrients. Significantly greater effects of V-ditches on herbage composition and yield suggested its positive influence on improving herbaceous vegetation and, consequently, a long-term effect of diversity in restoring ecosystem productivity.

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