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Soil respiration under different forest species in the riparian buffer of the semi-arid region of northwest India

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Soil temperature and soil moisture are the most important environmental factors controlling soil respiration (SR) in ecosystems. However, SR and associated edaphic factors have not been widely studied in semi-arid regions. In this study, SR was measured in a riparian zone and the effect of soil temperature and soil moisture on SR was examined under five forest species of the semi-arid region. The mean daily SR rate was 1.82, 2.08, 2.35, 2.27 and 2.07 g C m⁻² d⁻¹ in *Jatropha curcas*, *Leucaena leucocephala*, *Acacia nilotica*, *Azadirachta indica* and *Prosopis juliflora* sites respectively. It was found that SR was significantly and positively correlated with soil moisture. A univariate model of sub-surface soil moisture could explain 77% of temporal variation in soil CO₂ efflux, irrespective of species and sites. The logarithmic model could best explain the relationship between SR and soil moisture at 10–20 cm of soil depth ($P < 0.001$). There were negative correlations between SR and soil temperature under majority of species. Overall, across all species, soil temperature poorly explained 26% variation in SR as independent variable. For SR rate–temperature relationship, a bell-shaped function gave the best fit in this ecosystem. Under all the species, SR increases with increase in soil temperature up to 33°C (± 2); thereafter it decreases gradually under all species. There was strong evidence that deficit of soil moisture rather than soil temperature was the main regulating factor of SR under the semi-arid ecosystems.

Keywords: Semi-arid region, soil respiration, soil moisture, soil temperature, tree species.

SOIL respiration (SR) is a major process affecting the global carbon cycle and nutrient flux in the terrestrial ecosystem. It is the major pathway for exchange of gases from soil to atmosphere, influencing atmospheric temperature and ultimately contributing to global warming. Soil carbon is returned from the soil to the atmosphere through SR, which represents one of the largest fluxes in the terrestrial C cycle^{1–3}. The main sources of terrestrial flux of CO₂ are decomposing soil organic matter, respiration from heterotrophic soil organisms and autotrophic

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live root respiration. Environmental factors such as soil moisture and temperature influence soil biological activity and CO₂ diffusion, and therefore have a pronounced influence on the seasonal dynamics of SR⁴⁻⁶.

The riparian buffers of the semi-arid region are regarded as zones of soil conservation and comprise the native forest species. Natural or man-made riparian buffers of the semi-arid regions are a vital component of nutrient cycling and carbon balance of a terrestrial ecosystem. Riparian area differs from uplands in soil and hydrologic characteristics, but few studies of SR have been conducted in riparian zones^{7,8}. The riparian buffers of the semi-arid region of India are made up of native vegetation comprising xerophytic shrubs, bushes and trees. Riparian zones are created between terraced table land at the top and ravinous land in the bottom section. They act as a buffer to filter pollutants and sediments coming from upland agriculture; thereby protecting the downstream reservoir/stream⁹. These riparian lands are important pools of the global carbon cycle and nutrient flux. A sizeable area of the semi-arid region is occupied by this buffer zone. In India, the riparian zones of the semi-arid region are mostly occupied by *Prosopis*, *Acacia* and *Azadirachta* species. Recently, large-scale *Jatropha* planting has been adopted by state agencies for land restoration and biofuel generation.

Soil processes in arid and semi-arid lands have received relatively less attention due to relatively small carbon pool and fluxes in these regions^{2,10}. Arid and semi-arid lands occupy about one-third of the earth's surface¹¹, and more areas may come under arid and semi-arid lands in response to climate change¹². Seasonal changes in SR rates are associated with variations in soil temperature and moisture¹³. Such changes are particularly high in arid regions, where moisture may be a factor limiting microbial activity^{14,15}. Information on SR in India is limited; confined to the subtropical and temperate regions of northern India. Information on SR is not available from the semi-arid region of India, which occupy a sizeable portion of the total geographical area of the country. Therefore, the present study was carried out to measure SR under different forest species in the riparian zone of the semi-arid region of northwest India, and to determine the relationships between SR and soil moisture and soil temperature.

The studies were carried out at a typical ravine watershed of the Yamuna River located at the research farm of the Central Soil and Water Conservation Research and Training Institute (CSWCRTI), Agra, India (27°10'N, 78°02'E) during 2007–2008. Elevation of the research farm is 165 m amsl. It occupies an area of 81 ha comprising shallow, medium and deep gullies. The shallow gullies were converted to agriculture fields by levelling and bench terracing in the early 1960s and put under agriculture and block plantations, which act as riparian buffers between table-top agricultural land and ravenous lands at

the bottom section. Some of the terraces were converted to forests by means of plantation and some came up naturally after enclosure. River Yamuna flows on the southern side of the research farm and the other two sides (east and west) are surrounded by typical ravine land. The natural vegetation comprises mixed grasses (dominant – *Cenchrus ciliaris*), xerophytic shrubs and trees (*Acacia nilotica*, *Prosopis juliflora*, *Leucaena leucocephala* and *Azadirachta indica*). Details of the site characteristics are given in Table 1.

The study area is located in a subtropical semi-arid region that receives annual precipitation of 725 mm, with extremes of 1130 and 370 mm (average of 50 years). The year is divisible into four main seasons: summer (April–June), rainy (July–September), autumn (October–November) and winter (December–March). The mean annual maximum and minimum temperature during the experimentation period was 32°C and 17°C respectively, whereas mean monthly maximum and minimum temperature was 39°C and 5°C respectively (Figure 1). The soils are alluvial in origin and are placed under soil order Entisols, subgroup mixed loamy sand hyperthermic Typic Ustifluvent¹⁶. The soils have an ustic moisture regime with warm soil temperature and show no evidence of development of pedogenic horizon. The soils are well-drained, calcareous with 8–18% free CaCO₃ content and saline to alkaline in soil reaction.

Five tree species, viz. *Jatropha curcas*, *L. leucocephala*, *Acacia nilotica*, *A. indica* and *P. juliflora* were selected for the study. Except *J. curcas*, all others are the most prevalent species of the semi-arid region of India. *J. curcas* has been included in the study because of large-scale plantation by several agencies for biofuel generation and wasteland restoration. Five cylindrical chambers (10 cm × 25 cm) were inserted in mineral soil to a depth of 5 cm. Soil respiration was measured *in situ* on a monthly interval basis by alkali absorption method¹³. All green vegetation above the ground was cleared one day before the chambers were fixed for the measurement of SR. This method may underestimate high CO₂ flux rates relative to dynamic chamber methods¹⁷; however, static chamber technique remains the most feasible method for measuring daily fluxes needed to detect *in situ* differences in SR among treatments¹⁸. Carbon dioxide efflux was collected in a vial for reaction with 20 ml 2 M NaOH for 24 h to avoid diurnal changes. We used vials with 25% of the surface area of the cylinders, to optimize the rate of CO₂ absorption¹⁹. Sodium hydroxide solution was precipitated by saturated BaCl₂ solution. Blanks consisted of a sealed chamber of the same volume enclosing a vial of 2 M NaOH. The amount of CO₂ absorbed in 2 M NaOH was determined titrimetrically with 0.5 M HCl solution and using phenolphthalein as a visual indicator. After titrating, CO₂ evolution rates were calculated as follows: CO₂-C (mg) = (B – V) NE, where B is the HCl (ml) needed to titrate the NaOH solution from the control,

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Table 1. Description of soil and land-use characteristics

Tree species	Vegetation cover	Approximate age (yrs)	Surface area (m ²)	Density (trees ha ⁻¹)	Basal area (m ² ha ⁻¹)	Clay	Silt	Sand	Free CaCO ₃
						(%)			
<i>Jatropha curcas</i>	Pure stand	5	ND	250	ND	7.07	11.12	81.81	6.74
<i>Leucaena leucocephala</i>	Pure stand	20	7500	928	21	6.26	15.20	78.54	7.3
<i>Acacia nilotica</i>	Dominant	20	1500	443	8	6.48	11.11	82.42	10.8
<i>Azadirachta indica</i>	Dominant	20	5000	96	6	7.77	14.62	77.61	15.5
<i>Prosopis juliflora</i>	Pure stand	20	7500	176	12	8.30	14.48	77.21	13.8

ND, Not determined.

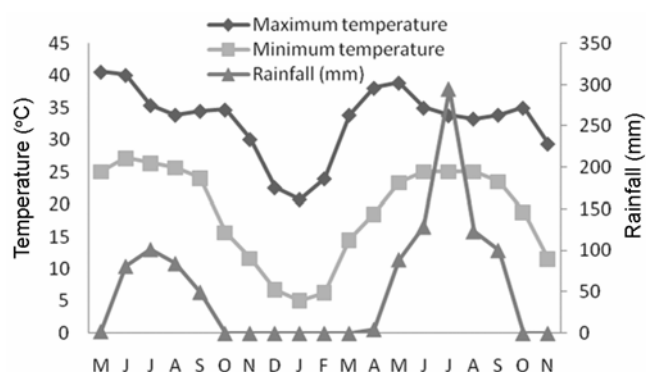


Figure 1. Climatic parameters during the study period.

V the HCl (ml) needed to titrate the NaOH solution in the vials exposed to the soil atmosphere, $N = 1.0$ (HCl molarity) and E the equivalent weight (6 for C; 22 for CO₂)²⁰. All values were converted to g CO₂-C m⁻² d⁻¹. Daily respiration was then multiplied by the number of days in the month to calculate monthly SR. Annual SR was computed as the sum of the monthly rates. The soil temperature at 5 and 10 cm depths was measured by soil thermometer adjacent to the location where SR was measured. Soil moisture content was determined gravimetrically by taking samples from the 0–10 cm and 10–20 cm depths next to the chambers and then weighing them to a constant weight.

The mean residence time (MRT) of soil organic C was estimated under each tree species by dividing the mass of total C present in the top 15 cm of the soil depth by the heterotrophic respiration rate (total SR minus root respiration). As neither root respiration nor heterotrophic respiration was quantified separately, we estimated MRTs for scenarios in which root respiration comprised 30%, 50% or 70% of the total SR^{2,21}. The total carbon content of soil was estimated using chromic acid oxidation method²².

Results were analysed by ANOVA. The data were analysed by MS excel spreadsheet. When effects were significant, treatment means were separated by Student–Newman–Keuls test.

Data on SR under different forest species are shown in Figure 2. Data on SR rate showed a similar pattern among five species, with a single peak occurring during the rainy

season (July–September) and minimum during summer (May–June). Soil respiration began to rise from summer to the rainy season and was intermediate between the rainy and summer seasons. Soil moisture and soil temperature were found to be the most dominant factors controlling SR. In general, the respiration rate increased with increase in soil moisture content. There was a negative relationship between soil moisture and temperature, as maximum soil temperature coincided with the lowest soil moisture content. Soil respiration rate decreased significantly with decrease in soil moisture content. Similarly, extremely low soil temperature significantly affected SR rate under all the species. Respiration rate varied significantly from one season to another.

Mean annual soil temperature at 5 cm depth was 28.1°C, 28.2°C, 28.1°C, 27.7°C and 28.1°C under *Jatropha*, *Leucaena*, *Acacia*, *Azadirachta* and *Prosopis* sites respectively, whereas mean annual soil temperature at 10 cm depth was higher by 0.5°C and 0.4°C in *Jatropha* and *Leucaena* sites and 0.2°C lower under *Acacia*, *Azadirachta* and *Prosopis* sites. In the present study, soil temperature at 5 cm depth ranged from 19.5°C to 46°C in *Jatropha*, 18.8°C to 39.3°C in *Leucaena*, 20.7°C to 36.8°C in *Acacia*, 20.2°C to 38.8°C in *Azadirachta* and 18.9°C to 35.7°C in *Prosopis* sites. During the experimentation period, soil temperature was affected by the canopy closure and age of plantation (Table 1); it was to be lower under *A. nilotica*, *A. indica* and *Prosopis juliflora* sites (20-yr-old and dense canopy) and higher under *Jatropha* (5-yr-old) and *Leucaena* (sparse canopy) sites (Table 1). Significant difference in soil temperature was recorded across the seasons. Soil temperature was higher during the summer months (May–June) and lower during the winter months (November–January). Other than seasonal variations, no other factors were found affecting soil temperature during the experimentation period.

Soil moisture content under the different species was significantly affected by the site characteristics, age of plantation and nature of canopy (Table 1). Mean annual soil moisture content at 0–10 cm depth under *Jatropha*, *Leucaena*, *Acacia*, *Azadirachta* and *Prosopis* sites was 2.9%, 4.0%, 3.7%, 3.5% and 3% respectively. The moisture content under all the tree species was higher during the rainy season (6–15%) in both the years, i.e. 2007 and

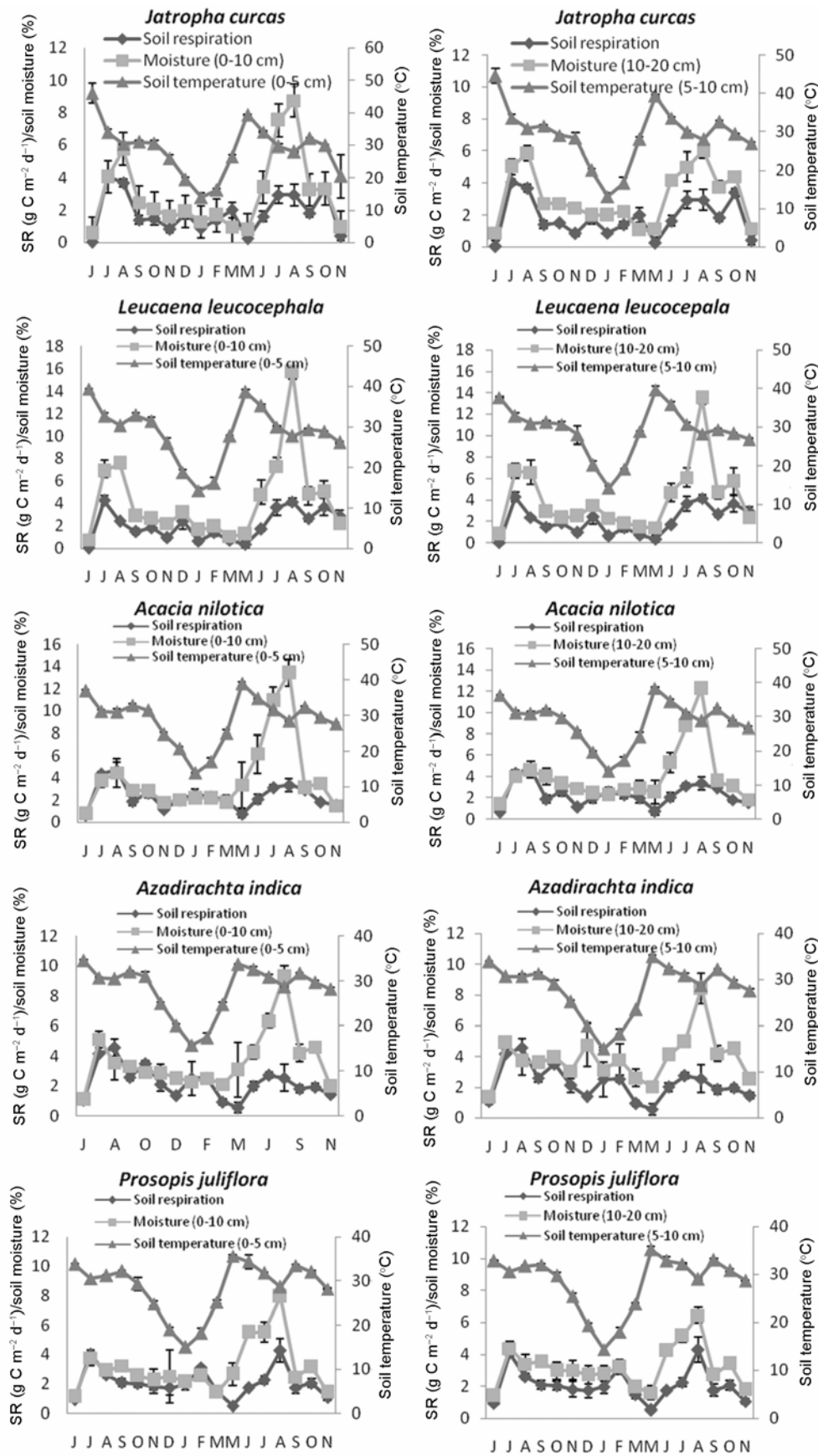


Figure 2. Soil respiration as affected by soil moisture and soil temperature under different forest species.

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Table 2. Nonlinear regression equation and correlation coefficient of soil respiration as a function of soil moisture and soil temperature at two different depths under different forest species

Land use	Parameter	Moisture (%)		Temperature (°C)		Average moisture (%), temperature (°C)	
		Soil depth (cm)	0–10	10–20	0–5	5–10	0–20, 0–10
<i>Jatropha curcas</i>	Equation		$y = 1.201 \ln(x) + 0.772$	$y = 1.477 \ln(x) + 0.296$	$y = -0.005x^2 + 0.338x - 2.916$	$y = -0.006x^2 + 0.360x - 2.877$	$y = 0.455x_1 - 0.0016x_2 + 0.375$
	R^2		$R^2 = 0.64^*$	$R^2 = 0.61^*$	$R^2 = 0.32$	$R^2 = 0.29$	$R^2 = 0.59$
	r		0.71**	0.80**	ns	ns	
<i>Leucaena leucocephala</i>	Equation		$y = 1.375 \ln(x) + 0.477$	$y = 1.540 \ln(x) + 0.24$	$y = -0.014x^2 + 0.744x - 7.077$	$y = -0.014x^2 + 0.744x - 7.077$	$y = 0.302x_1 - 0.0011x_2 + 0.827$
	R^2		$R^2 = 0.73^*$	$R^2 = 0.72^*$	$R^2 = 0.38$	$R^2 = 0.38$	$R^2 = 0.61$
	r		0.77**	0.79**	ns	ns	
<i>Acacia nilotica</i>	Equation		$y = 1.027 \ln(x) + 1.172$	$y = 1.398 \ln(x) + 0.587$	$y = -0.008x^2 + 0.435x - 2.622$	$y = -0.008x^2 + 0.443x - 2.767$	$y = 0.201x_1 - 0.0394x_2 + 2.641$
	R^2		$R^2 = 0.37^{**}$	$R^2 = 0.39^{**}$	$R^2 = 0.16$	$R^2 = 0.14$	$R^2 = 0.27$
	r		0.45***	0.49***	ns	ns	
<i>Azadirachta indica</i>	Equation		$y = 0.949 \ln(x) + 1.141$	$y = 1.343 \ln(x) + 0.552$	$y = -0.005x^2 + 0.254x - 0.815$	$y = -0.005x^2 + 0.254x - 0.815$	$y = 0.243x_1 - 0.0071x_2 + 1.549$
	R^2		$R^2 = 0.18$	$R^2 = 0.26$	$R^2 = 0.015$	$R^2 = 0.015$	$R^2 = 0.14$
	r		0.34***	0.40***	ns	ns	
<i>Prosopis juliflora</i>	Equation		$y = 1.061 \ln(x) + 0.956$	$y = 1.485 \ln(x) + 0.383$	$y = -0.01x^2 + 0.488x - 3.274$	$y = -0.009x^2 + 0.435x - 2.592$	$y = 0.365x_1 - 0.241x_2 + 1.533$
	R^2		$R^2 = 0.31^{**}$	$R^2 = 0.46^*$	$R^2 = 0.15$	$R^2 = 0.10$	$R^2 = 0.38$
	r		0.56**	0.61**	ns	ns	
Across all species (pooled average data of 17 months)	Equation		$y = 1.335 \ln(x) + 0.664$	$y = 1.762 \ln(x) + 0.02$	$y = -0.008x^2 + 0.454x - 3.186$	$y = -0.009x^2 + 0.494x - 3.601$	$y = 0.346x_1 - 0.0218x_2 + 1.480$
	R^2		$R^2 = 0.68^*$	$R^2 = 0.77^*$	$R^2 = 0.29$	$R^2 = 0.29$	$R^2 = 0.61$
	r		0.74**	0.80**	ns	ns	
	N		17	17	17	17	17

*Significant ($P < 0.0001$); **($P < 0.01$); ***($P < 0.05$); ns, not significant.

2008. No significant difference in soil moisture content was recorded in 10–20 cm depth compared to surface soil moisture (0–10 cm). However, soil moisture content at 10–20 cm depth was slightly higher in comparison to 0–10 cm of soil depth. Soil moisture content at 0–10 cm depth ranged from 0.56% to 8.74% in *Jatropha*, 0.77% to 15.67% in *Leucaena*, 0.8% to 13.44% in *Acacia*, 1.13% to 9.35% in *Azadirachta* and 1.12% to 7.93% in *Prosopis* sites. Across all the species, there was significant difference in soil moisture content among the seasons. Soil moisture content under *Acacia* and *Leucaena* was significantly higher than the other forest species.

Some similarities between the CO₂ efflux rate with soil temperature and soil moisture in their seasonal variation was observed under all the forest species. The respiration rate varied significantly from one month to another. It was lowest in May and highest in July. The pattern of SR was found to be similar under different forest species; however, the magnitude varied significantly across different months. During the study period, the daily mean SR rate was 1.82 g C m⁻² d⁻¹ with a range 0.02–4.07 g C m⁻² d⁻¹ in *Jatropha* site; 2.08 g C m⁻² d⁻¹ with a range 0.04–4.27 g C m⁻² d⁻¹ in *Leucaena* site; 2.35 g C m⁻² d⁻¹ with a

range 0.65–5.49 g C m⁻² d⁻¹ in *Acacia* site, 2.27 g C m⁻² d⁻¹ with a range 0.57–4.58 g C m⁻² d⁻¹ in *Azadirachta* sites and 2.07 g C m⁻² d⁻¹ with a range of 0.50–5.34 g C m⁻² d⁻¹ in *Prosopis* sites. Soil respiration together with soil moisture and temperature showed significant seasonal variations in all the sites. In general, SR rate declined during dry summer months (April–June) and increased rapidly with rainfall events (July–September), and moderate fluxes were recorded during other months. The overall SR rate did not vary significantly under different forest species, but significant differences were observed in seasonal trends in each forest site.

Seasonal changes in SR rates were associated with variations in soil temperature and soil moisture (Table 2 and Figure 3). It was positively correlated with the soil moisture at 0–10 cm and 10–20 cm of soil depth. Soil respiration was better correlated with sub-surface (10–20 cm) soil moisture than the surface soil moisture content. Soil moisture as a single independent factor explained greater variability in SR than soil temperature. A logarithmic relationship was observed between soil moisture and SR (monthly average data, $n = 17$). Surface (0–10 cm) soil moisture as a single independent factor

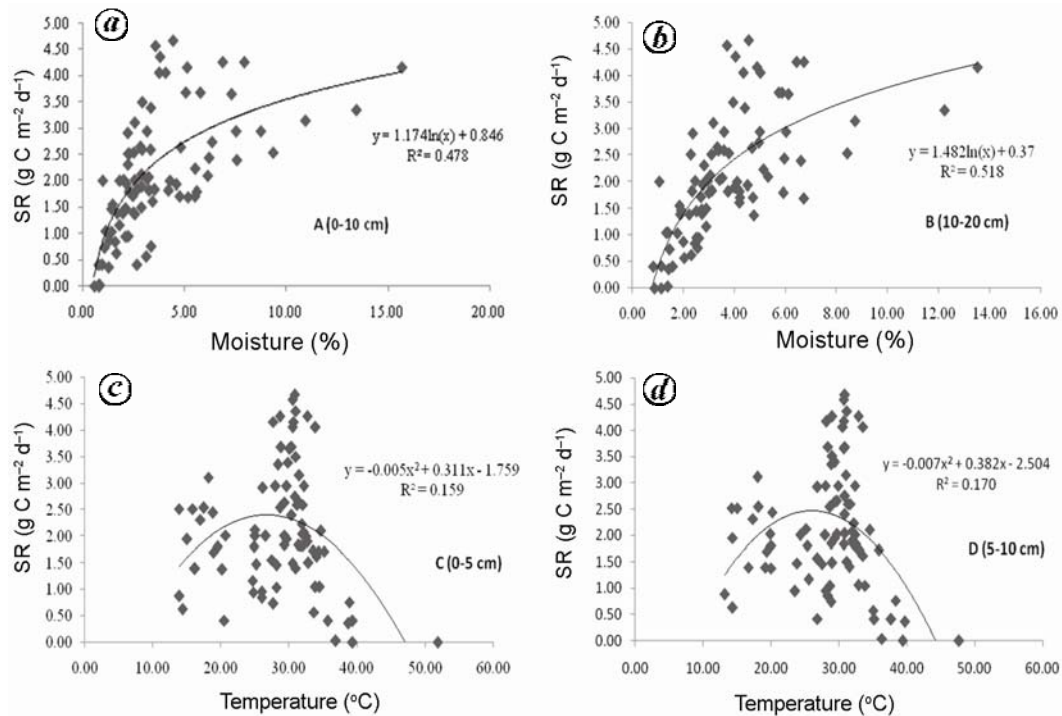


Figure 3. Soil respiration as affected by soil moisture (*a* and *b*) and temperature (*c* and *d*) at two different depths (pooled data; 85 observations).

explained 68%, 76%, 33%, 18% and 40% of the variation in SR in *Jatropha*, *Leucaena*, *Acacia*, *Azadirachta* and *Prosopis* sites respectively, whereas sub-surface (10–20 cm) soil moisture explained 61%, 72%, 39%, 26% and 46% variation in SR under *Jatropha*, *Leucaena*, *Acacia*, *Azadirachta* and *Prosopis* sites respectively (Table 2, $n = 17$). Across the months, the surface (0–10 cm) and sub-surface (10–20 cm) soil moisture regulated SR to the extent of 68% and 77% respectively. Sub-surface soil moisture showed good agreement in variation of SR, when all the data were pooled ($R^2 = 0.51$, $n = 85$, $P < 0.00001$). Soil temperature, was negatively correlated with SR, with an exception occurring at the *A. indica* site. The variation in SR was poorly explained by the changes in soil temperature at 0–5 cm and 5–10 cm soil depth. Soil temperature (0–5 cm and 5–10 cm) as a single independent variable explained only 29–32% under *J. curcas*, 38% under *L. leucocephala*, 14–16% under *A. nilotica*, 1.5% under *A. indica* and 10–15% under *P. juliflora* sites. Overall, across all species, soil temperature explained only 29% variation in SR as an independent variable. The relationship of temperature with SR was best expressed by a bell shaped curve (Figure 3). Under all the species (pooled data, $n = 85$), SR increased with increase of soil temperature up to 33°C, and thereafter decreased gradually under all the species ($R^2 = 0.17$, 0.18 , $n = 85$, $P < 0.0001$, 0.0003). The respiration rate was at its peak around 33°C (± 2) under all the species. The variation in SR was better explained by surface (0–5 cm) soil tem-

perature than the temperature at 5–10 cm of soil depth (Figure 3).

Although SR was explained by variations in soil moisture and soil temperature, it would be better to predict SR by taking a single independent variation of sub-surface soil moisture content, as soil moisture is one of the most important limiting factors affecting SR under the semi-arid ecosystem. Therefore, respiration under the semi-arid ecosystem as prevailing at the experimental site could be predicted using the following equation:

$$y = 1.762 \ln(x) + 0.02 \quad (R^2 = 0.77, P < 0.0001, n = 17), \quad (1)$$

where y is SR rate ($\text{g C m}^{-2} \text{d}^{-1}$) and x the subsurface (10–20 cm) soil moisture (%) content.

Annual SR rate under different forest species ranged from 6.66 to 8.59 $\text{t ha}^{-1} \text{yr}^{-1}$, being lowest in *Jatropha* and highest under the *Acacia* site (Table 3). The total carbon content of soil of different sites ranged from 0.54% to 1.56%. The lower soil respiration rate under *Jatropha* site could be attributed to age (5 yrs) of the plant, where total soil organic carbon content was 0.54%, which was significantly lower than the other forest species. Total organic carbon content of the soil was found to be the highest under *L. leucocephala* site followed by *A. indica* and *P. juliflora*, which were significantly higher than the *A. nilotica* and *J. curcas* sites (Table 3). The annual SR rate was positively correlated with the total

Table 3. Mean residence time of soil organic carbon under different forest species in semi-arid region

Land use	Total carbon (%)	Soil respiration (t C/ha/yr)	Mean residence time (years)		
			30%	50%	70%
<i>Jatropha curcas</i>	0.54 a	6.66 a	2.6	3.6	6.1
<i>Leucaena leucocephala</i>	1.56 b	7.59 a	6.6	9.2	15.3
<i>Acacia nilotica</i>	1.07 b	8.59 a	4.0	5.6	9.3
<i>Azadirachta indica</i>	1.25 b	8.27 a	4.8	6.8	11.3
<i>Prosopis juliflora</i>	1.24 b	7.57 a	5.2	7.3	12.2

Means followed by the same letter are not different at 0.05 probability level using Student–Newman–Keuls test.

The percentage of total soil respiration attributable to root respiration (assumed) was estimated at 30%, 50% and 70% and subtracted from total respiration to estimate heterotrophic respiration.

carbon content of the soil. MRT for surface carbon pool was found to be the lowest under the *Acacia* site (2–6 years) and highest under *Leucaena* site (6.6–15.3 yrs). MRTs for near-surface pools of soil organic C were significantly longer in *Leucaena* (6.6–15.3 yrs) and *Prosopis* (5.2–12.2 yrs) than in *Jatropha* (4.0–9.3 yrs) and *Acacia* (4.0–9.3 yrs; $P = 0.0001$; Table 3).

Soil respiration is affected by soil moisture and soil temperature. The mean daily SR was found in the order: *A. nilotica* > *A. indica* > *L. leucocephala* > *P. juliflora* > *J. curcas*. The high SR rate under *Acacia* species could be attributed to the detritus composition, native soil carbon pool^{23,24} and fine root biomass production^{25,26}. The SR range reported in the present study was similar to that reported in other studies^{23,26–28}. However, it was found to be higher than the respiration rate reported under the vegetation of Shiwalik and Central Himalaya²⁹. The high respiration rate under the present investigation could be due to higher variation in temperature and precipitation prevailing under the present study. No significant difference in SR rate was observed amongst the species; statistically significant differences were evidenced in seasonal trends in all five forest sites. Soil respiration increased from summer to rainy season and decreased from rainy to winter season in all the species, similar to the semi-arid ecosystem. A similar seasonal trend in SR has also been observed by Saraswathi *et al.*³⁰. SR in the semi-arid ecosystems increases with both carbon pool size and annual precipitation, which significantly affects soil moisture content and soil temperature²³. The high respiration rate during rainy season (July–September) could be due to the displacement of air rich in CO₂ from within the soil and from the activity of microbes that oxidize the carbon dissolved in water. However, the main cause could be due to increase in soil organic matter decomposition after a period of drying coupled with rapid proliferation in soil microbial activity.

Soil moisture and soil temperature are the major determinants affecting SR in a majority of the ecosystems. A number of studies have been conducted on the relationship of SR with soil temperature or soil water content^{8,28,31–35}. A clear temperature limitation in winter and water limitation in summer was observed. Similar re-

sults were reported by Tingley *et al.*³⁶. Across all species, a bell-shaped functional relationship between SR rate and soil temperature gave the best fit ($R^2 = 0.18$, $n = 85$, $P < 0.0001$), instead of the widely accepted exponential relationship³⁷. This function has a maximum value at 33°C (± 2) under all the species. As this characteristic also applied to the non water-limited periods, it is probably because of the temporary substrate depletion of the soil caused by enhanced microbial activity. The results of the experiment show that soil moisture is the major factor controlling SR under all the forest species. The dependency of SR rate is best described by soil moisture in all the sites. In the present study as soil moisture and soil temperature were dependent-variables, one affecting the other, i.e. extremes of temperature coincided with lowest soil moisture, hence we propose an empirical relationship of SR with only one independent variable, i.e. soil moisture, which is the most limiting factor in the semi-arid ecosystems. The effect of soil moisture on carbon efflux from the soil was remarkably consistent in all the species, with the regression coefficient consistently high at all the sites. Coupling soil moisture and temperature explained only 14–61% of the temporal variation in SR across all species, whereas univariate models with only one independent variable of soil moisture at 10–20 cm depth explained variance in SR to the extent of 26–80% (Table 2). The R^2 value was found to be high with soil moisture as an independent variable, also correlation coefficient was found to be highest with soil moisture ($P < 0.001$). Most of the other studies have shown different results, where the SR rate is a function of soil temperature^{28,33,34}. This suggests that under semi-arid/arid ecosystem, SR is mostly governed by soil moisture rather than soil temperature. Conant *et al.*²³ also reported that SR under semi-arid ecosystem was largely controlled by soil moisture and size of the soil carbon pool. Jin *et al.*³⁸, also reported spatial heterogeneity of soil respiration in semi-arid (*Ulmus pumila* woodland) region due to variation in soil moisture.

SR increased with increase in soil temperature under all the sites as the season progressed from winter to summer, till it reached 33°C (± 2); thereafter it decreased drastically probably due to lower biological activity owing

to lower availability of soil moisture. SR reached a minimum during the peak summer months (May–June). Rate of SR increased between winter and summer not only because the soils became warm, but also due to optimal moisture availability.

SR is widely believed to follow first-order kinetics, where the rate of SR is directly proportional to the size of the carbon pool^{39,40}. Here also, SR rate was largely related to the total carbon pool. MRT of soil carbon pool ranged from 3 to 15 yrs under different forest species, which was directly proportional to the total carbon content of the soil⁴¹. A longer MRT of soil organic carbon in *L. leucocephala* and *P. juliflora* is indicative of an overall decline in soil organic matter quality. Although all methods for estimating absolute MRTs have limitations, the relative difference in MRTs under different species in Table 3, indicates lower C mineralization in *Leucaena* and *Prosopis* sites, probably implying that the microbial communities in these soils might be less efficient at converting available carbon into microbial biomass.

The present study has showed that SR under the semi-arid ecosystem is largely governed by soil moisture and soil carbon pool size. The inference is completely opposite to the temperate ecosystem, where SR is controlled by soil temperature. Thus changes in rainfall pattern rather than temperature will have a maximum effect on the process of SR under the riparian buffer of the semi-arid ecosystems. The logarithmic model could best explain the relationship between SR and soil moisture at 10–20 cm of soil depth.

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Retraction and reconstruction of Milam Glacier, Kumaon Himalaya, observed with satellite imagery

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The Himalaya is the adobe of one of the world's largest and mostly inaccessible area of glaciers outside the polar regions and provides glacier-stored water to the major Indian river basins. Various studies suggest that many of the Himalayan glaciers have receded in recent decades due to climate forcing. Temporal satellite data analysis shows that the Milam Glacier in Goriganga Basin, Kumaon Himalaya receded 1328 m

laterally and 90 m vertically during 1954–2006. The enhanced satellite imagery helps in establishing the extent of the glacier in inaccessible terrains like the Himalaya.

Keywords: Glaciers, reconstruction, retreat, river basins, satellite imagery.

THE Himalaya is one of the youngest mountain systems on Earth, and has a direct influence on the climate, hydrology and environment of the Indian subcontinent. Glacier inventory carried out by the Geological Survey of India (GSI) depicts the existence of over 9000 glaciers in the Indian administered part of the Himalaya¹. Many of the Himalayan rivers are fed by snow and ice melt run-off from snow fields and glaciers.

Observations showed that the 20th century was a period of glacier retreat in almost all alpine regions of the world with accelerated glacier ice and snow melting in the past two decades^{2–4}. The Intergovernmental Panel on Climate Change (IPCC) considered the mountain glacier as the top priority climatic indicator due to the sensitivity of glaciers to climate⁵. According to the field measurements of the 18 weather stations in western Indian Himalaya screening an increase in seasonal mean, maximum and minimum temperatures by ~2°C, 2.8°C and 1°C from 1984/85 to 2007/08 respectively⁶. Glaciological studies carried out by various researchers in the Himalayas suggest that many of the glaciers are in a state of retreat due to climate forcing^{7–14}. Satellite-based glacial studies of 466 glaciers in Chenab, Parbati and Baspa basins show overall 21% deglaciation from 1962 to 2001 (ref. 15). A similar study carried out in the Chandra river basin, Himachal Pradesh, showed that Samudra Tapu Glacier receded 741 m between 1962 and 2000 (ref. 16). All these studies suggest that most of the Himalayan glaciers have been losing volume and receding in recent decades. Hence it is essential to examine the health of these glaciers and their response to climate forcing for the future water resource assessment.

In the field of glaciology, satellite remote sensing has been proven to be the best tool because many of the glaciers are located at very high altitude, cold weather and rugged terrain conditions, making it a tedious, hazardous and time-consuming task to monitor by conventional field methods^{15–19}. Satellite remote sensing technology facilitates to study the behaviour of ice masses of the Himalaya systematically with a cost to time benefit ratio. Changes in glacier area and terminus position are being used extensively as an indicator of glacier response to climate forcing²⁰. These two parameters are relatively easy to extract from multispectral satellite imagery. In the Himalaya, many glaciers are not capable of dynamically adjusting for the accelerated warming by retreat, and also respond by down-wasting and decoupling of glacier parts^{3,15,21,22}. Considering the receding trend of the

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