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Soil CO_2 efflux among four coniferous forest types of Kashmir Himalaya, India

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Abstract Soil CO_2 efflux was measured in four different coniferous forest types (*Cedrus deodara* (CD), *Pinus wallichiana* (PW), mixed coniferous (MC), and *Abies pindrow* (AP)) for a period of 2 years (April 2012 to December 2013). The monthly soil CO_2 efflux ranged from 0.8 to 4.1 μmoles CO_2 m^{-2} s^{-1} in 2012 and 1.01 to 5.48 μmoles CO_2 m^{-2} s^{-1} in 2013. The soil CO_2 efflux rate was highest in PW forest type in both the years, while it was lowest in MC and CD forest types during 2012 and 2013, respectively. Soil temperature (T_S) at a depth of 10 cm ranged from 3.8 to 19.4 °C in 2012 and 3.5 to 19.1 °C in 2013 in all the four forest types. Soil moisture (M_S) ranged from 19.8 to 58.6 % in 2012 and 18.5 to 58.6 % in 2013. Soil CO_2 efflux rate was found to be significantly higher in summer than the other seasons and least during winter. Soil CO_2 efflux showed a significant positive relationship with T_S (R^2 = 0.52 to 0.74), SOC % (R^2 = 0.67), pH (R^2 = 0.68), and shrub biomass (R^2 = 0.51), whereas, only a weak positive relationship was found with soil moisture (R^2 = 0.16 to 0.41), tree density (R^2 = 0.25), tree basal area (R^2 = 0.01), tree biomass (R^2 = 0.07), herb biomass (R^2 = 0.01), and forest floor litter (R^2 = 0.02). Thus, the study indicates that soil CO_2 efflux in high mountainous areas is greatly influenced by seasons, soil temperature, and other environmental factors.

Keywords Coniferous forests · Soil respiration · Soil temperature · Understory biomass · Western Himalaya

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Introduction

Soil CO_2 efflux is known to account for approximately 70 % of ecosystem respiration in temperate forest ecosystems (Law et al. 1999). Thus, changes in soil CO_2 efflux can strongly influence net ecosystem exchange (Valentini et al. 2000). As the largest source of atmospheric CO_2, soil CO_2 emission from terrestrial ecosystems is estimated to be 98 ± 12 Pg $year^{-1}$, with an annual increase of 0.1 Pg (Bond-Lamberty and Thomson 2010). The amount of C emitted through soil respiration is 10 times more than that released through fossil fuel combustion and cement manufacturing (IPCC 2007; Peters et al. 2012). Despite the vital role of soil CO_2 efflux in global C budget, there is still a limited understanding of CO_2 efflux due to its high complexity and variability of environmental factors. Even a small change in soil CO_2 efflux can result in significant changes in atmospheric CO_2 concentration and heat balance (Schlesinger and Andrews 2000). Due to its crucial role in global warming, soil CO_2 efflux has become an important issue in climate change ecology (Yi et al. 2007). It is very important to study soil CO_2 efflux from the soils of temperate forests to better understand the forests' response to global C cycling (Davidson et al. 1998; Kang et al. 2003; Wang et al. 2010).

Soil CO_2 efflux shows large variations in different ecosystems (Rayment and Jarvis 2000; Khomik et al. 2006) due to the synergistic effect of both biotic and abiotic factors (Gaumont-Guay et al. 2006). In many forest ecosystems, soil temperature (T_S) and soil moisture (M_S) are the two most important determinants of soil CO_2 efflux (Li et al. 2008; Zhang et al. 2010). Some studies have proved that changes in soil CO_2 efflux varied seasonally and were dominantly related to T_S (Fang and Moncrieff 2001). T_S and M_S often covary in field conditions, and it had been difficult to separate their effects (Borken et al. 2006).

Although there are numerous studies on soil CO_2 efflux from various parts of the world (Tufekcioglu and Kucuk 2004), there are not too many studies from Indian forests, especially from Western Himalayas. Only few studies have been conducted on seasonal and annual soil CO_2 efflux from Indian Himalaya (Joshi et al. 1991, Thokchom and Yadava 2014). Therefore, the present study was undertaken with the following objectives: (1) to determine the seasonal soil CO_2 efflux in four different coniferous forest types and (2) to understand the relationship between soil CO_2 efflux and other environmental factors.

Materials and methods

Study area

The present study was carried out in the temperate forests of Kashmir Himalayas of district Anantnag, Jammu & Kashmir, India (Fig. 1). Anantnag is located in southern Kashmir between 33° 45′–34° 15′ N and 74° 02′–75° 32′ E, and it occupies 3984 km^2 of the state, of which 36.09 % (1438 km^2) is forested (FSI, 2011). This temperate region receives moderate to high snowfall from December to February. The average annual precipitation in this area ranges from 844 to 1213 mm, while the mean monthly temperature varies from 8.3 to 26 °C (Fig. 2). The vegetation of this area is temperate, with conifers as chief components. There is a great altitudinal variation among the forest types. The low-lying (1550–2000 m) temperate forests in the area are mainly composed of broad-leaved species such as *Populus deltoides*, *Juglans regia*, *Salix* species, *Ulmus villosa*, etc. whereas, the mid-altitude (2000–2800 m) forests are composed of conifers like *Pinus wallichiana*, *Cedrus deodara*, *Abies pindrow*, and *Picea smithiana*. In high altitudes (2800–3250 m), *Betula utilis* stands are dominant and constitute the timber line. Measurements were taken in four natural coniferous forest types: *Cedrus deodara* (CD), *Pinus wallichiana* (PW), mixed coniferous (MC), and *Abies pindrow* (AP), with three replicate plots (50 m × 50 m) in each forest type (Fig. 1). This study was restricted to only the four coniferous forest types because low elevation broad-leaved forest types are close to human settlements and are frequently disturbed with grazing and other anthropogenic activities which would affect the experiment. On the other hand, high elevation broad-leaved forest type (*Betula utilis* stand) is not easily accessible due to extreme climatic conditions and is covered with snow for around 6 months. The four coniferous forest types are located between 2106 and 2373 m. The laid-out plots in each forest type were with similar abiotic conditions and high homogeneity of species composition. Study area characteristics such as density, basal area, biomass of above-ground and understory vegetation, forest floor litter, soil organic carbon, pH, and soil bulk density were determined (Table 1).

Field measurements

Soil CO_2 efflux was measured from April 2012 to December 2013. It could not be measured from January to March due to heavy snow cover on the soil surface in all the forest types. Soil CO_2 efflux was measured by alkali absorption method (Gupta and Singh 1977), using open-ended plastic jars of 13 × 23 cm, that were inserted into the soil at a depth of 5 cm. Five replicates of experimental plastic jars with one set of three control plastic jars with airtight lids were randomly placed in each plot for 24 h before measuring soil respiration. Before placing each plastic jar, the herbaceous vegetation falling within the jar was clipped. A 100 ml beaker containing 50 ml of 0.25 N NaOH solution was placed in a thin wire tripod stand that held the beaker above the ground by about 2 cm. The alkali was titrated against 0.25 N HCl using phenolphthalein as the indicator after an absorption period of 24 h to avoid diurnal variations (Harris and van

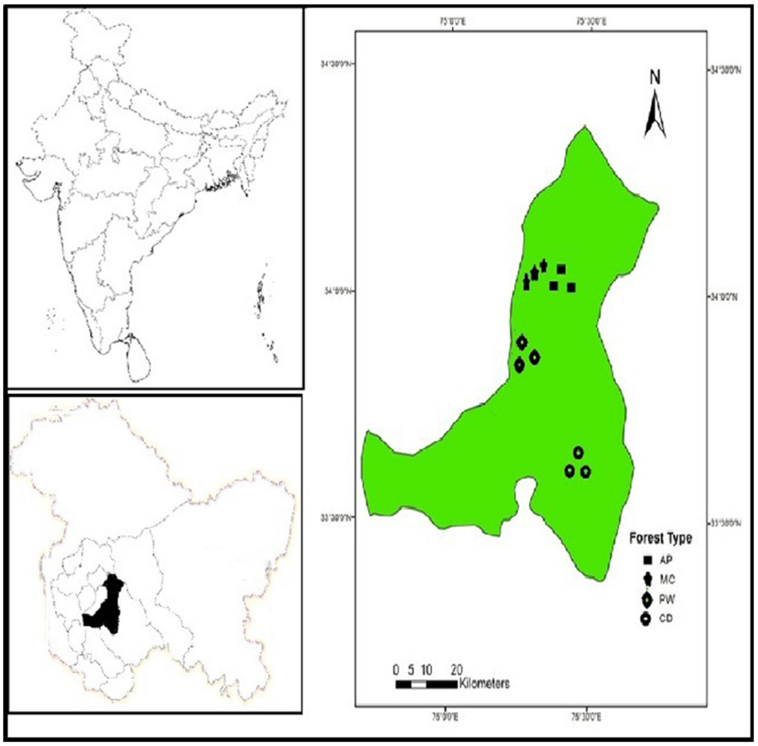

Fig. 1 Location of the study site plots of four coniferous forest types in temperate forests of Kashmir Himalaya, India

Bavel 1957). The CO_2 evolved during the experiment was calculated using the formula proposed by Anderson and Ingram (1993):

$$mg\,CO_2 = V \times N \times 22$$

whereas, V represents titration of the blank minus sample titration and N is the normality of HCl. The units of the values obtained (mg CO_2 m^{-2} day^{-1}) are then converted to μmoles CO_2 m^{-2} s^{-1} (Lin et al. 2008).

Soil temperature was measured at a depth of 0–10 cm adjacent to each soil CO_2 efflux beaker in the morning (10.30–11 a.m.) using a digital soil thermometer. For the estimation of soil moisture, soil samples were taken from 0 to 10 cm depth adjacent to each CO_2 efflux beaker, oven-dried at 105 ± 5 °C, and the moisture content was measured by gravimetric method.

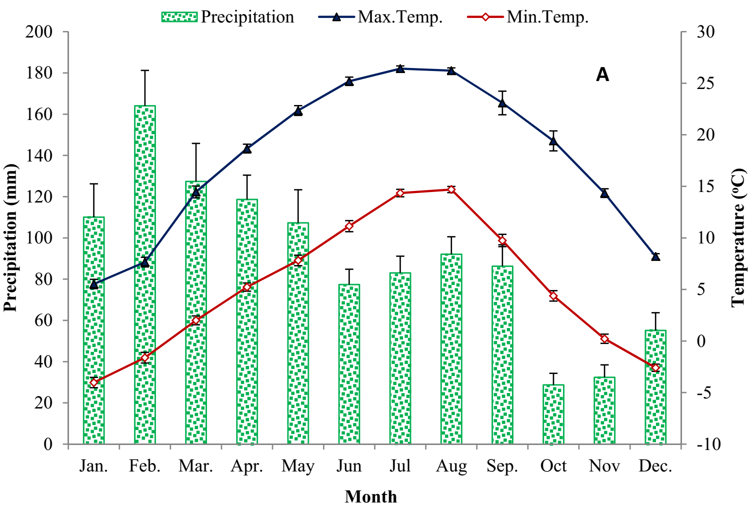

Fig. 2 Mean monthly maximum and minimum temperature and rainfall (including snow) pattern of 12 years of data (2002–2013) in the study area (Source: Indian Meteorological Department, Srinagar)

Table 1 Study area characteristics of four coniferous forest types (*Cedrus deodara* (CD), *Pinus wallichiana* (PW), mixed coniferous (MC), and *Abies pindrow* (AP)) of Kashmir Himalaya, India

Parameter	CD	PW	MC	AP
Elevation (m)	2106	2172	2270	2373
Latitude	33° 58	34° 00	34° 00	34° 02
Longitude	75° 19	75° 17	75° 19	75° 21
Mean annual precipitation (mm)	1289	1289	1289	1289
Dominant understory species	*Berberis orthobotrys*, *Stipa sibirica*, *Fragaria nubicola*, *Viola odorata*	*Viburnum grandiflorum*, *Stipa sibirica*, *Fragaria nubicola*	*Viburnum grandiflorum*, *Fragaria nubicola*, *Clinopodium vulgare*	*Viburnum grandiflorum*, *Stipa sibirica*, *Fragaria nubicola*, *Viola odorata*
Tree density (No. ha^{-1})	207 ± 17	239 ± 13	234 ± 37	242 ± 10
Tree basal area (m^2 ha^{-1})	52.9 ± 2.1	54.1 ± 2.6	52.1 ± 7.2	55.7 ± 4.3
Tree biomass (Mg ha^{-1})	248.8 ± 37.8	265.7 ± 26.5	238.6 ± 37.2	258.6 ± 26.7
Shrub density (No. ha^{-1})	12,392 ± 1013	77,349 ± 2183	15,280 ± 1322	14,543 ± 1487
Shrub basal area (m^2 ha^{-1})	2.12 ± 0.5	3.0 ± 0.9	0.96 ± 0.2	1.9 ± 0.3
Shrub biomass (g m^{-2})	374 ± 118	863 ± 530	235 ± 73	331 ± 105
Herbaceous biomass (g m^{-2})	28.5 ± 3.9	25.8 ± 2.4	29.1 ± 3.3	43.9 ± 7.2
Forest floor litter (g m^{-2})	364.9 ± 54.6	466.5 ± 45.4	439 ± 55.4	194.1 ± 33.0
Soil organic carbon (Mg C ha^{-1}) 0–30 cm	62.2 ± 1.7	65.9 ± 2.1	62.5 ± 1.0	60.7 ± 1.5
pH	5.8	6.1	5.9	6.1
Bulk density (g cm^{-3}) 0–10 cm	0.59 ± 0.03	0.44 ± 0.01	0.49 ± 0.04	0.55 ± 0.02

In each forest type, fifteen aggregated undisturbed soil cores were taken from each depth (0–10, 10–20, and 20–30 cm) by soil core sampler with an internal diameter of 5 cm to measure bulk density. The soil samples were weighed immediately and transported to the laboratory where they were oven-dried at 105 ± 5 °C for 72 h and reweighed. The soils containing rocky and coarse fragments were separated by a 2-mm sieve and weighed again. The bulk density of the soil core was calculated using the formula described by Pearson et al. (2005).

$$\text{Bulk density}\left(\text{g/m}^3\right) = \frac{\text{Oven dry mass }\left(\text{g/m}^3\right)}{\text{Core volume }(\text{m}^3)\text{–(Mass of coarse fragments (g)}/2.65\,(\text{g/cm}^3)\text{)}}$$

where 2.65 is a constant for the density of rock fragments (g cm^{-3}).

Another set of fifteen aggregated soil samples were collected by soil core sampler, and soil organic carbon (SOC) was determined by rapid titration method (Walkley and Black 1934). Soil pH was measured with a potentiometric pH meter in a 1:2.5 soil/water suspension.

Statistical analyses

One-way ANOVA was used to test the differences between mean soil CO_2 efflux, soil temperature, and soil moisture among the four forest types, and Turkey's HSD test was applied whenever the ANOVA was significant. The level of significance for the analyses was set at $P < 0.05$. Linear correlation/regression analyses were used to examine the relationship of soil CO_2 efflux with soil temperature, soil moisture, pH, forest floor litter, tree density, biomass, bulk density, and SOC. SPSS 20.0 software was used for all statistical analyses.

Results

Monthly and seasonal variation in soil CO_2 efflux

Soil CO_2 efflux varied significantly among all the forest types ($P < 0.001$) in both the years (Table 2). The monthly soil CO_2 efflux ranged from 0.80 to 4.14 μmoles CO_2 m^{-2} s^{-1} in 2012, whereas, in 2013, it ranged from 1.01 to 5.48 μmoles CO_2 m^{-2} s^{-1}. Soil CO_2 efflux was observed to be significantly ($P < 0.001$) greater in June 2012 and 2013 (4.14 and 5.48 μmoles CO_2 m^{-2} s^{-1}) than the other months in all the forest types. Among the forest types, PW forest type had the highest rate of soil CO_2 efflux in 2012 in all the months except September. Similar trend was observed in April, October, and November when AP was highest.

Soil CO_2 efflux showed a strong seasonal pattern in all the forest types (Table 3). The peak was during summer (mean 3.57 ± 0.34 μmoles CO_2 m^{-2} s^{-1}; range 2.89–4.61 μmoles CO_2 m^{-2} s^{-1} in 2013 and mean 3.10 ± 0.18 μmoles CO_2 m^{-2} s^{-1}; range 2.78–3.67 μmoles CO_2 m^{-2} s^{-1} in 2012), followed by spring (mean 2.73 ± 0.81 μmoles CO_2 m^{-2} s^{-1}; range 2.03–3.28 μmoles CO_2 m^{-2} s^{-1} in 2012 and mean 2.11 ± 0.27 μmoles CO_2 m^{-2} s^{-1}; range 1.98–2.33 μmoles CO_2 m^{-2} s^{-1} in 2013), was moderate during autumn (mean 2.16 ± 0.47 μmoles CO_2 m^{-2} s^{-1}; range 1.66–2.55 μmoles CO_2 m^{-2} s^{-1} in 2012 and mean 1.68 ± 0.37 μmoles CO_2 m^{-2} s^{-1}; range 1.61–1.84 μmoles CO_2 m^{-2} s^{-1} in 2013) and lowest during winter (mean 1.06 ± 0.03 μmoles CO_2 m^{-2} s^{-1}; range 0.96–1.22 μmoles CO_2 m^{-2} s^{-1} in 2012 and mean 0.92 ± 0.01 μmoles CO_2 m^{-2} s^{-1}; range 0.76–1.10 μmoles CO_2 m^{-2} s^{-1} in 2013). Soil CO_2 efflux showed significant differences seasonally among the forest types in both the years.

Soil temperature (T_S) and soil moisture content (M_S)

Mean monthly T_S and M_S showed significant differences among the forest types ($P < 0.001$) in the 2 years of study (Tables 4 and 5). Soil temperature ranged from 3.8 to 19.4 °C in 2012 and from 3.5 to 19.1 °C in 2013. The maximum T_S was observed in CD (19.4 and 19.1 °C) forest type during August in both the years.

Soil moisture ranged from 19.3 to 58.6 % in 2012 and from 18.5 to 58.6 % in 2013. The highest monthly M_S was observed in PW (2012) and AP (2013) forest types in June (Table 5).

Soil temperature showed a strong seasonal pattern across all the forest types and was maximum

Table 2 Mean soil CO_2 efflux (μmoles CO_2 m^{-2} s^{-1}) in four coniferous forest types (*Cedrus deodara* (CD), *Pinus wallichiana* (PW), mixed coniferous (MC), and *Abies pindrow* (AP)) of Kashmir Himalaya, India

	Year 2012 Soil CO_2 efflux (μmoles CO_2 m^{-2} s^{-1})					Year 2013 Soil CO_2 efflux (μmoles CO_2 m^{-2} s^{-1})				
Month	CD	PW	MC	AP	*P* value	CD	PW	MC	AP	*P* value
April	1.82^{b}	2.18^{a}	1.98^{b}	1.83^{b}	0.001	1.69^{c}	2.14^{b}	2.14^{b}	2.38^{a}	0.000
May	2.33^{b}	2.71^{a}	2.39^{b}	2.45^{b}	0.000	2.56^{c}	4.75^{b}	3.58^{a}	3.65^{b}	0.000
June	3.10^{c}	4.14^{a}	3.12^{c}	3.56^{b}	0.000	3.35^{d}	5.48^{b}	4.25^{a}	3.68^{c}	0.000
July	3.01^{c}	3.83^{a}	2.88^{d}	3.18^{b}	0.000	3.02^{d}	4.58^{b}	3.84^{a}	3.38^{c}	0.000
August	2.79^{c}	3.58^{a}	2.76^{c}	3.08^{b}	0.000	2.72^{c}	4.48^{b}	3.09^{a}	3.16^{b}	0.000
September	2.25^{b}	2.17^{b}	2.00^{b}	2.59^{a}	0.001	2.16^{d}	3.63^{c}	2.57^{a}	3.05^{b}	0.000
October	1.49^{c}	1.96^{a}	1.42^{c}	1.82^{b}	0.000	1.64^{d}	2.52^{c}	2.03^{b}	2.76^{a}	0.000
November	1.34^{bc}	1.55^{a}	1.23^{c}	1.39^{b}	0.000	1.42^{b}	1.87^{b}	1.55^{a}	1.99^{a}	0.000
December	0.98^{b}	1.16^{a}	0.92^{b}	0.80^{c}	0.000	1.01^{b}	1.28^{b}	1.06^{a}	1.12^{b}	0.000

Values within the row followed by the same letter are not statistically different at 0.05 significance level

during summer (15.2–19.4 °C, Table 4) followed by spring, autumn, and winter. On the other hand, soil moisture (%) showed a different trend, which was generally higher in spring than the other seasons (Table 5).

Relationship between soil CO_2 efflux and environmental variables

Soil CO_2 efflux showed significant positive correlations with soil temperature (R^2 = 0.52–0.74), SOC %

Table 3 Seasonal variation in soil CO_2 efflux (R_S), soil temperature (T_S), and soil moisture (M_S) in four coniferous forest types (*Cedrus deodara* (CD), *Pinus wallichiana* (PW), mixed coniferous (MC), and *Abies pindrow* (AP)) of Kashmir Himalaya, India (Mean ± SE)

Forest type	Season	Year 2012			Year 2013		
		Soil CO_2 efflux (μmoles CO_2 m^{-2} s^{-1})	Soil temperature (°C)	Soil moisture (%)	Soil CO_2 efflux (μmoles CO_2 m^{-2} s^{-1})	Soil temperature (°C)	Soil moisture (%)
CD	Spring	2.03 ± 0.46	10.8 ± 2.4	37.8 ± 2.0	1.98 ± 0.28	11.1 ± 3.8	32.3 ± 2.6
	Summer	2.89 ± 0.26	18.0 ± 1.5	31.4 ± 3.7	2.82 ± 0.14	18.4 ± 0.9	31.7 ± 5.3
	Autumn	1.66 ± 0.32	13.4 ± 4.5	26.3 ± 3.3	1.61 ± 0.41	12.1 ± 5.2	23.3 ± 4.1
	Winter	0.96 ± 0.04	4.0 ± 0.1	19.9 ± 3.5	0.93 ± 0.04	3.5 ± 0.1	18.5 ± 0.8
PW	Spring	2.73 ± 0.75	10.4 ± 2.5	36.6 ± 8.0	2.33 ± 0.28	11.0 ± 3.1	36.7 ± 6.3
	Summer	3.55 ± 0.49	17.1 ± 1.4	42.9 ± 12.1	3.67 ± 0.24	17.8 ± 0.4	33.9 ± 5.5
	Autumn	1.95 ± 0.42	13.1 ± 5.3	35.4 ± 4.0	1.80 ± 0.27	12.3 ± 5.3	24.7 ± 4.9
	Winter	1.01 ± 0.03	4.5 ± 0.1	21.4 ± 1.1	1.10 ± 0.02	4.1 ± 0.1	21.5 ± 0.9
MC	Spring	3.28 ± 0.36	10.0 ± 3.7	38.5 ± 2.2	2.08 ± 0.22	10.8 ± 3.4	42.5 ± 2.8
	Summer	4.61 ± 0.46	17.7 ± 1.1	32.1 ± 4.7	2.78 ± 0.16	17.9 ± 0.7	36.1 ± 5.5
	Autumn	2.55 ± 0.74	13.1 ± 5.2	24.0 ± 4.7	1.47 ± 0.34	12.4 ± 4.5	25.9 ± 4.4
	Winter	1.22 ± 0.05	3.8 ± 0.1	23.1 ± 1.3	0.88 ± 0.02	4.0 ± 0.1	19.8 ± 0.8
AP	Spring	2.87 ± 0.67	9.5 ± 3.7	39.1 ± 1.6	2.04 ± 0.33	10.8 ± 3.1	36.6 ± 8.0
	Summer	3.25 ± 0.22	17.9 ± 0.7	35.6 ± 4.0	3.12 ± 0.21	18.0 ± 1.6	42.9 ± 12.1
	Autumn	2.48 ± 0.45	13.7 ± 4.7	27.6 ± 4.1	1.84 ± 0.51	11.9 ± 5.8	35.4 ± 4.0
	Winter	1.07 ± 0.04	3.9 ± 0.1	29.7 ± 3.8	0.76 ± 0.02	3.5 ± 0.1	21.4 ± 1.1

Table 4 Mean soil temperature (°C) in four coniferous forest types (*Cedrus deodara* (CD), *Pinus wallichiana* (PW), mixed coniferous (MC), and *Abies pindrow* (AP)) of Kashmir Himalaya, India

Soil temperature (°C) Year 2012						Soil temperature (°C) Year 2013				
Month	CD	PW	MC	AP	*P* value	CD	PW	MC	AP	*P* value
April	8.5[a]	8.1[a]	6.6[b]	6.1[c]	0.000	7.6[b]	8.1[a]	7.7[b]	7.9[ab]	0.006
May	12.9[b]	12.6[b]	13.4[a]	12.8[b]	0.001	14.5[a]	13.8[b]	13.9[b]	13.6[b]	0.000
June	16.0[b]	15.2[c]	16.1[b]	16.9[a]	0.000	17.1[a]	17.3[a]	17[a]	15.9[b]	0.000
July	18.6[a]	18.1[b]	18.3[ab]	18.2[b]	0.005	18.8[a]	17.8[c]	18.2[b]	19.1[a]	0.000
August	19.4[a]	18.0[c]	18.4[b]	18.6[b]	0.000	19.1[a]	18.2[c]	18.5[b]	19[a]	0.000
September	17.1[b]	17.5[a]	17.5[a]	17.0[b]	0.006	16.5[a]	16.0[b]	16.1[b]	16.5[a]	0.006
October	15.6[b]	15.6[b]	15.4[b]	16.5[a]	0.001	14.4[c]	15.5[a]	14.6[bc]	15.1[ab]	0.001
November	7.5[a]	6.2[b]	6.3[b]	7.4[a]	0.000	5.3[b]	5.4[b]	6.5[a]	4.2[c]	0.000
December	4.4[a]	4.5[a]	3.8[b]	3.9[b]	0.000	3.5[b]	4.1[a]	4[a]	3.5[b]	0.000

Values within the row followed by the same letter are not statistically different at 0.05 significance level

(R^2 = 0.67), pH (R^2 = 0.68), and shrub biomass (R^2 = 0.51) but only weak positive relationships with soil moisture (R^2 = 0.16–0.41), tree density (R^2 = 0.25), tree basal area (R^2 = 0.01), tree biomass (R^2 = 0.07), herb biomass (R^2 = 0.01), and forest floor litter (R^2 = 0.02). Nevertheless, soil CO_2 efflux showed a negative relationship with bulk density (R^2 = 0.75) (Fig. 3a–c).

Discussion

Soil CO_2 efflux rates showed both monthly and seasonal variations in all the forest types. It was maximum during June and minimum during December, which may be due to similar seasonal climatic conditions in all the forest types (Thokchom and Yadava 2014). The highest CO_2 efflux was observed in PW followed by AP, MC, and CD forest types, which may be attributed to greater microbial activity, litter quality and quantity, shrub biomass, tree density, pH values, and higher SOC (%) than the other forest types. High rates of soil CO_2 efflux were observed during June, July, and August (both the years) in all the forest types as this is the peak growing season of plants, especially herbs which tend to increase the contribution of root respiration and associated microbial activities (Chen et al. 2010; Wang et al. 2014). Low rates of soil CO_2 efflux in November and

Table 5 Mean soil moisture (%) in four coniferous forest types (*Cedrus deodara* (CD), *Pinus wallichiana* (PW), mixed coniferous (MC), and *Abies pindrow* (AP)) of Kashmir Himalaya, India

Soil moisture (%) Year 2012						Soil moisture (%) Year 2013				
Month	CD	PW	MC	AP	*P* value	CD	PW	MC	AP	*P* value
April	36.7[b]	43.8[a]	40.2[ab]	39.8[ab]	0.140	33.5[b]	42.3[a]	44.8[a]	43.8[a]	0.000
May	38.8[a]	29.4[b]	36.7[a]	38.4[a]	0.000	31.2[b]	30.9[b]	40[a]	29.4[b]	0.000
June	34.2[b]	58.6[a]	37.6[b]	39.6[b]	0.000	38.2[b]	40.9[b]	43[b]	58.6[a]	0.000
July	27.6[b]	32.5[ab]	30.7[ab]	34.5[a]	0.039	30.6[b]	31.5[ab]	34[a]	32.5[ab]	0.059
August	32.3[ab]	37.6[a]	28.0[b]	32.6[ab]	0.008	26.3[d]	29[c]	31.4[b]	37.6[a]	0.000
September	28.4[b]	37.2[a]	26.6[b]	29.2[b]	0.011	22.4[c]	23.2[c]	28[b]	37.2[a]	0.000
October	25.1[ab]	30.3[a]	19.3[c]	23.3[bc]	0.002	19.1[b]	20[b]	20.3[b]	30.3[a]	0.000
November	25.3[b]	38.7[a]	26.1[b]	30.1[ab]	0.005	28.3[b]	30.9[b]	29.4[b]	38.7[a]	0.000
December	19.8[b]	21.4[b]	23.1[ab]	29.7[a]	0.010	18.5[b]	21.5[a]	19.8[ab]	21.4[a]	0.009

Values within the row followed by the same letter are not statistically different at 0.05 significance level

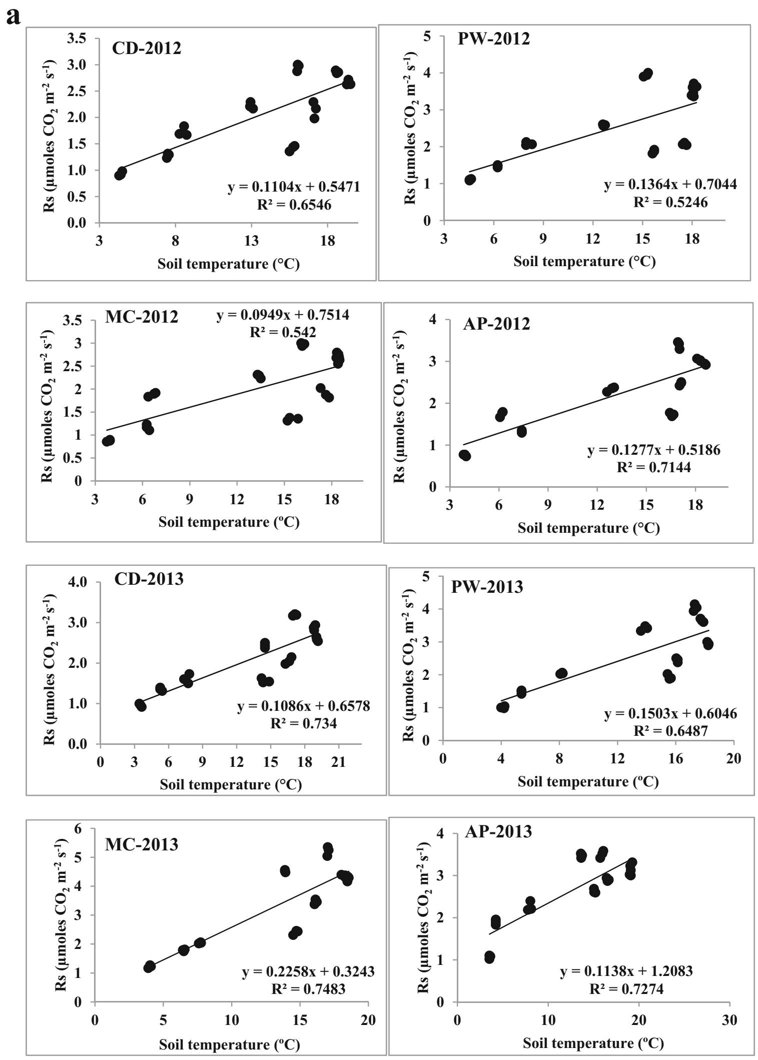

Fig. 3 **a** Relationship between soil CO_2 efflux (Rs) and soil temperature (°C) at a depth of 10 cm in four different coniferous forest types of Kashmir Himalaya, India. **b** Relationship between soil CO_2 efflux (Rs) and soil moisture (%) at a depth of 10 cm in four different coniferous forest types of Kashmir Himalaya, India. **c** Relationship between soil CO_2 efflux (Rs) and environmental parameters in four different coniferous forest types of Kashmir Himalaya, India

December in all the forest types may be attributed to variations in the incoming solar radiation and temperature lagging day-length, which results in low microbial activities and low T_S (Lloyd and Taylor 1994; Han et al. 2012). Other environmental parameters such as M_S, SOC, pH, tree density, and shrub biomass could also influence soil CO_2 efflux either directly or indirectly to a certain extent (Sundarapandian and Dar 2013). Luo et al. (2012) have also reported a positive influence of soil moisture, SOC, pH, and bulk density on soil CO_2 efflux in different primary successional stages in Gongga Mountain, China. Low rates of soil CO_2 efflux in early and late months could be due to differences in T_S and M_S (Li et al. 2008). In general, soils with high SOC content have more potential for CO_2 efflux. The SOC content is highest in PW, and therefore, this forest type has the greatest soil CO_2 efflux. Zheng et al. (2009) have also stated that higher the SOC, higher would be soil CO_2 efflux.

The results of soil CO_2 efflux in the present study were comparable to the range obtained in other temperate forests (152 g C m^{-2} $year^{-1}$ (Rayment and Jarvis 2000) to 1478 g C m^{-2} $year^{-1}$ (Wang et al. 2010)) and closer to the range between 2.43 and 6.03 µmoles b

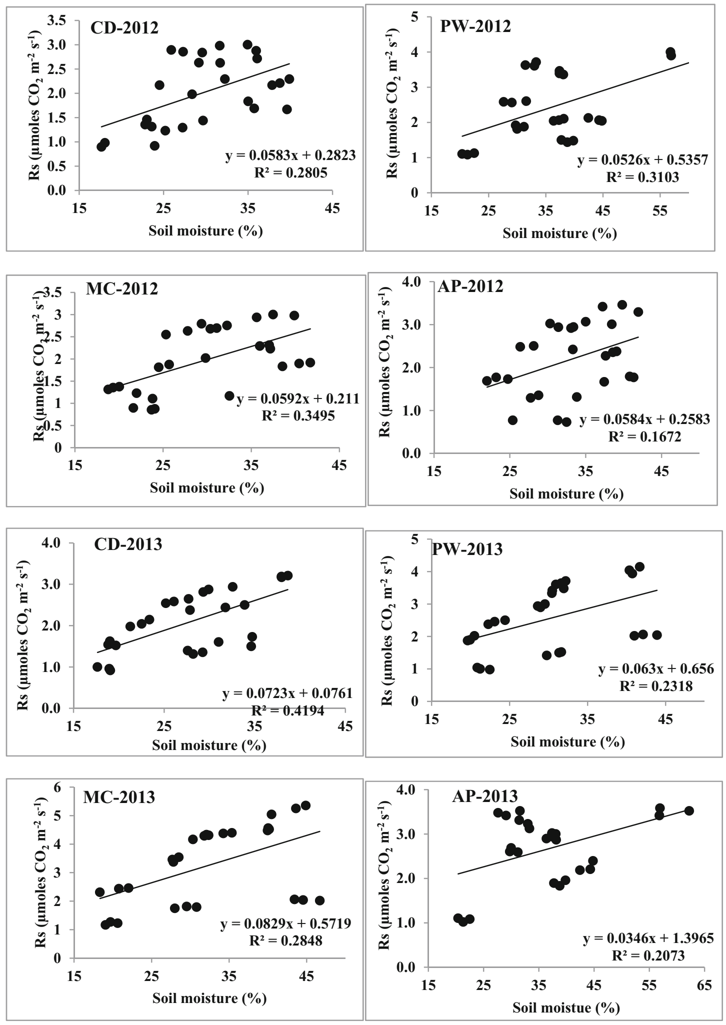

Fig. 3 (continued)

CO_2 m^{-2} s^{-1} in a young ponderosa pine plantation in California (Qi and Xu 2001). Similarly, Li et al. (2008) also obtained a range of 2.50 to 5.19 µmoles CO_2 m^{-2} s^{-1} in 11 different vegetation types on a Chinese mountain. However, the values recorded by Curiel-Yuste et al. (2003) ranged from 0.3 to 2.3 µmoles CO_2 m^{-2} s^{-1} in a temperate maritime pine plantation in California. In a temperate forest in Korea, Kang et al. (2003) reported a maximum of 7.3 µmoles CO_2 m^{-2} s^{-1} of soil CO_2 efflux during summer. Vincent et al. (2006) observed a wide range of soil CO_2 efflux from about 1 to 10 µmoles CO_2 m^{-2} s^{-1} from nine forest plots in France.

Seasonal soil CO_2 efflux rates showed noteworthy variations in all the forest types. Highest soil CO_2 efflux was observed in summer, followed by spring, autumn, and winter. Similarly, Mo et al. (2005) have reported that daily soil CO_2 efflux rates were moderate in late spring (1.8–2.9 g C m^{-2} day^{-1}), which then increased rapidly and peaked during summer (4.6–6.0 g C m^{-2} day^{-1}) and then declined in autumn (1.5–2.5 g C m^{-2} day^{-1}) in a cool temperate deciduous forest in Japan. Lee et al. (2010) have also observed high respiration rates in summer (710–1170 mg CO_2 m^{-2} h^{-1}), which slowed down during spring (270–460 mg CO_2 m^{-2} h^{-1}) and was least in autumn (120–160 mg CO_2 m^{-2} h^{-1}) in temperate evergreen forests of central Korea. In temperate ecosystems, T_S is the dominant factor influencing soil CO_2 efflux (Lloyd and Taylor 1994). In the present study, Ts was maximum during summer and along with moderate moisture content, there is an

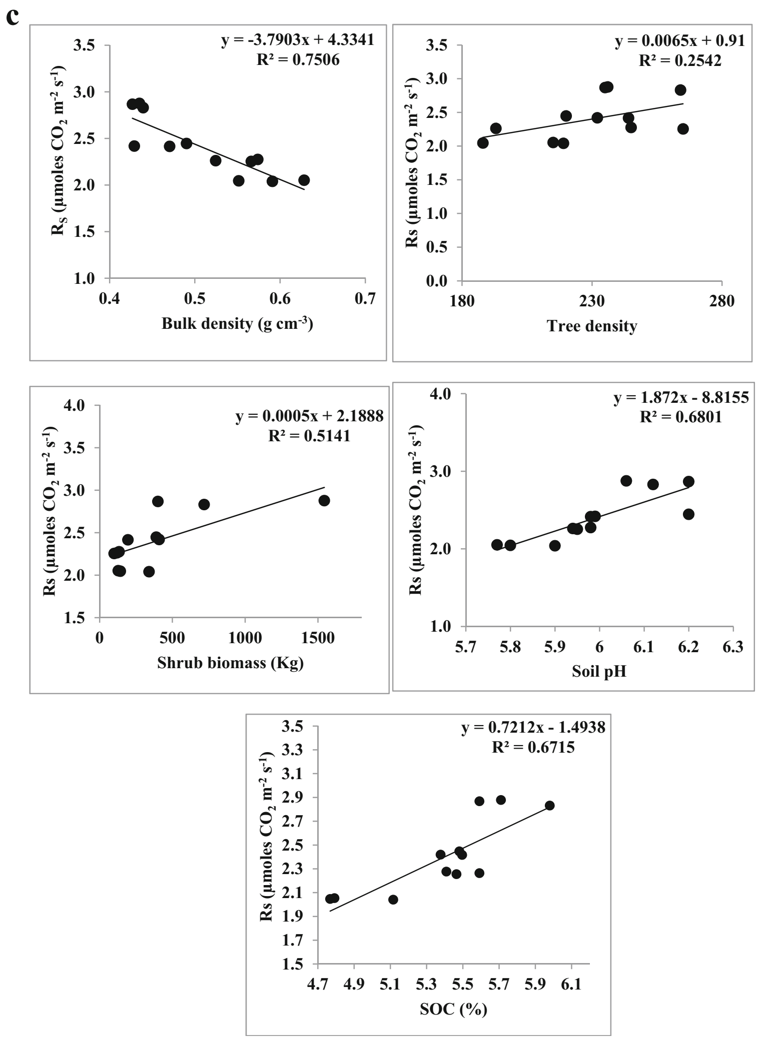

Fig. 3 (continued)

enhanced activity of microorganisms in the decomposition of organic matter, which could have resulted in higher soil CO_2 efflux in this season in all the forest types. Ground vegetation finishes its growth in late autumn, during which temperatures also decrease drastically resulting in less microbial activity and therefore slow decomposition of organic matter resulting in low soil CO_2 efflux (Raich and Potter 1995). Temperate forests are more sensitive to soil temperature than tropical and subtropical ecosystems. Low temperature is the major limiting factor in ecosystems of cold regions, where the soil microbial activity and root growth is slowed down, leading to slow soil CO_2 efflux. The present study also showed that the response of soil CO_2 efflux to T_S differed significantly. This is because T_S is the main dominant factor of soil CO_2 efflux in temperate forest ecosystems (Li et al. 2008), which varies monthly as well as seasonally. These variations in soil temperature in these forest types may be attributed to solar light intensity, day length, duration of growing period, and moisture content as observed by Li et al. (2008). T_S and M_S are important drivers of spatial and temporal variations of soil CO_2 efflux by affecting the productivity and decomposition rate of soil organic matter of terrestrial ecosystems (Qi and Xu 2001; Li et al. 2008; Devi and Yadava 2009; Chen et al. 2013). T_S showed a significant positive correlation with soil CO_2 efflux, which indicates the dependence of soil CO_2 efflux on T_S. Several workers have also reported similar results (Lloyd and Taylor 1994; Li et al. 2008; Wang et al. 2014). Our results have revealed that T_S is the main environmental variable controlling short-term variations in soil CO_2 efflux and this is confirmed with the findings of other studies (Lloyd and Taylor 1994; Zheng et al. 2009; Wang et al. 2010).

After T_S, M_S is another main factor that greatly influences soil CO_2 efflux (Akburak and Makineci 2013). Wu et al. (2006) reported that when T_S is >15 °C and M_S is medium, soil CO_2 efflux is at its maximum. Likewise, in the present study, highest soil CO_2 efflux was observed in summer when T_S was >15 °C and M_S was medium (30.8 %) and in contrast, lowest CO_2 efflux was observed in winter when T_S was <5 °C and M_S was high (38.3 %). High soil CO_2 efflux rates during summer may be due to rapid decomposition of organic matter by active microorganisms at high temperatures, and low soil CO_2 efflux rates during winter could be the result of low temperatures which reduce the microbial growth that leads to low decomposition rates or due to water saturation. The influence of M_S on CO_2 efflux may also be associated with forest structure, soil substrate, and forest floor litter. Mo et al. (2005) and Lee et al. (2006) have also observed similar results. Soil CO_2 efflux has been found to decrease when soil water content is low during drought (Mo et al. 2005). M_S is found to negatively influence soil respiration when it is too high (due to less aeration and low CO_2 diffusivity) or too low (due to desiccation) (Janssens and Pilegaard 2003). Davidson et al. (1998) have stated that both T_S and M_S regulate soil CO_2 efflux, either independently or synergistically.

CO_2 efflux in an ecosystem is also partly dependent on carbon stocks of litter and soil, as these influence both autotrophic and heterotrophic respiration, although they are given a lesser priority than T_S and M_S (Wang et al. 2010; Zhou et al. 2013). Zhou et al. (2013) stated that combined carbon stocks of litter and top soil explain 48 % of the spatial variation of CO_2 efflux in temperate forests. In our study, a weak positive relationship was obtained between soil CO_2 efflux and forest floor litter. Various environmental parameters such as T_S, shrub biomass, pH, and SOC have shown a strong positive correlation with soil CO_2 efflux. Similar results were reported from other temperate forests as well (Wang et al. 2006; Wang et al. 2010; Zhou et al. 2013; Wang et al. 2014). The negative relationship between bulk density and soil CO_2 efflux shows the need for the presence of pore spaces for microbial activity (Elliot et al. 1980; Tewari et al. 1982; Wang et al. 2014). Gough and Seiler (2004) have reported that soil respiration has a linear relationship with mineral soil carbon and root surface area under *Pinus taeda* plantation, and the most effective factor on respiration was T_S. Wang et al. (2010) have reported that soil CO_2 efflux is negatively correlated with SOC and positively correlated with pH. Thus, the present study reveals that besides T_S and M_S, other environmental factors such as SOC, pH, and vegetation also play key roles in affecting soil CO_2 efflux.

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Conflict of interest The authors declare that they have no competing interests.

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