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Variation in soil organic matter accumulation and metabolic activity along an elevation gradient in the Santa Rosa Mountains of Southern California, USA

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Abstract: Variations in soil organic matter accumulation across an elevation can be used to explain the control of substrate supply and variability on soil metabolic activity. We investigated geographic changes in soil organic matter and metabolic rates along an elevation gradient (289–2,489 m) in the Santa Rosa Mountains, California, USA from subalpine and montane pine forests through chaparral to desert. From base (289 m) to summit (2,489 m), 24 sites were established for collecting soil samples under canopies and inter-canopy spaces, at 0–5 and 5–15 cm soil depths increments. Soil organic matter (SOM) content was determined using weight loss on ignition at 550°C and soil CO_2 efflux (R) was measured at day 5 (R_5) and day 20 (R_{20}) of incubation. Changes in SOM content along the elevation gradient showed a significant relationship ($P<0.05$) but R_5 and R_{20} were not related to either elevation or SOM content. However, the ratio of R and SOM (R_5/SOM) showed a strong relationship across the mountains at both soil depths. R_5/SOM, as an indicator of carbon use efficiency, may be applicable to other semi-arid transects at larger scale modeling of soil metabolic processes.

Keywords: elevation gradient; soil organic matter; CO_2 efflux; metabolic activity

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Studying the relationship between soil organic matter (SOM) content and metabolic activity (R) across an elevation gradient, representing ecologically diverse landscapes, provides opportunity to model large scale spatial heterogeneity in metabolic response (Xu et al., 2010; Kunkel et al., 2011). With large variabilities of dryland ecosystems occurring across a broad range of scales, it is important to understand how geomorphological (e.g. elevation) and ecological (e.g. plant distributions) factors interact and control R (Jenerette et al., 2012). Variation in SOM along the elevation gradient is effect of climate, organic matter input and decomposition rate (Hanawalt and Whittaker, 1976; Trumbore et al., 1996; Austin, 2002; Rasmussen et al., 2006). As plant cover type changes across an elevation gradient, we expected significant differences of soil R between the space just beneath the canopy due to high organic matter accumulation than in the space between the canopies or the bare space due to low organic matter accumulation (Burke et al., 1999; Barron-Gafford et al., 2011). Moreover, the characteristics of points and patches under canopies and inter-canopy spaces significantly change with elevation and illustrate the variability of soil R under the same climate and plant cover (Aandereud et al., 2011; Jenerette and Chatterjee, 2012).

Hanawalt and Whittaker (1976), Smith et al. (2002) and Kunkel et al. (2011) observed a significant and positive relationship between distribution of SOM content and elevation gradient. However, prediction of soil R response across an elevation gradient is difficult due to a range of factors such as, organic matter

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(OM) quality and quantity and soil moisture availability (Schlesinger, 1990; Davidson and Janssens, 2006; Jenerette and Chatterjee, 2012). For example, in a precipitation gradient in Hawaii, net primary production reached a peak at intermediate levels of rainfall and then declined but decomposition increased throughout the gradient (Austin, 2002). In contrast, data from a series of elevation gradients in California identified an inverse relationship between soil R and elevation (Rasmussen et al., 2006). A better understanding of soil respiration across spatial gradients will help identify the interaction between ecosystem functioning and climate, where parent material, relief and time are controlled.

In this study, we evaluated SOM and R along an elevation gradient (289–2,489 m) of Santa Rosa Mountains in southern California. The main objective of this experiment was to determine the variation in SOM and R with the elevation gradient in this region. We also determined differences in SOM and R between soils underneath plant canopies and in the interspaces and at near surface and deeper within the profile. Experimental manipulation of soils across two dominant landscapes of variation (plant-interplant and elevation) provided an opportunity to better understand variation and regulation of soil R in this dryland region (Jenerette and Shen, 2012).

1 Materials and methods

We selected 24 sites along an elevation (289–2,489 m) gradient on Santa Rosa Mountains near Palm Springs (33°49′26″N, 116°31′49″W) of Riverside County in southern California, approximately 177 km away from Los Angeles (Fig. 1; Table 1). The transect was over 16 km long and passed through desert scrub, pinyon juniper woodland, chaparral and coniferous forest (Hanawalt and Whittaker, 1976; Kelly and Goulden 2008; Chatterjee and Jenerette, 2011a). The overall climate of this transect is arid and semiarid, with predominant winter season precipitation although monsoon derived summer storms occasionally. Mean annual temperature decreases by 0.73°C, whereas the precipitation increases by 5 cm with each 100-m rise in elevation (Kelly and Goulden, 2008).

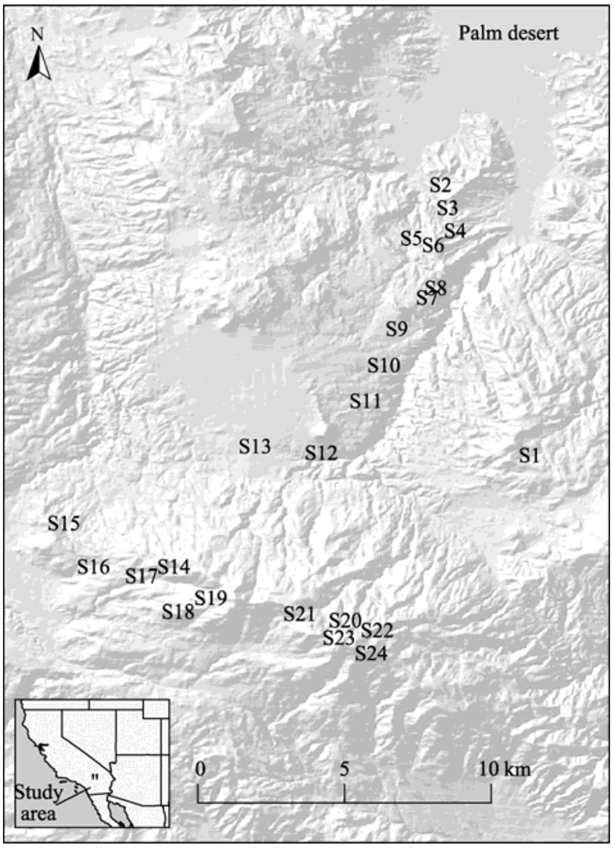

Fig. 1 Soil sampling locations

Out of 24 sites, seven sites, S1, S8, S14, S16, S17, S18 and S24, were extensively sampled at 2 m intervals along three 100-m transects at 10 m apart with depth increment of 0–5 and 5–15 cm and sampling points were classified for either canopy or interspace. From seven sites, total 2,142 soil samples (51 (samples/transect)×3 transects×2 depths×7 sites) were collected. For the rest of 17 sites, representative soils were sampled from (1) underneath the dominant plant canopy and (2) in the interspace between plants within 0–5 and 5–15 cm depths, for a total of 4 soil samples at each site, resulting in 68 soil samples from 17 sites.

Collected soil samples were air dried and sieved (2 mm) for analysis. Processed soil samples were analyzed for water holding capacity by measuring gravimetric water content of saturated soil at field capacity level and soil organic matter (SOM) content by weight loss following ignition at 550°C for 4 h in a muffle furnace. Processed 50-gram soil samples were incubated in small glass jars for 20 days at 25°C and soil moisture content was maintained at 40% water holding capacity (Chatterjee and Jenerette, 2011b). Soil CO_2

Table 1 Geographic locations, vegetation, climatic condition and soil properties of the extensively sampled sites

Site	Elevation (m)	Altitude (N)	Latitude (E)	Dominant vegetation	Mean temperature (°C)	Mean precipitation (mm)	Soil texture	Soil pH	SOM (%)	No. of soil samples
S1	289	33°34'55"	116°22'16"	Desert scrub (*Larrea tridentata*)	23.6	150	Sand	7.9	1.6	306
S8	825	33°38'00"	116°24'00"	Desert scrub (*Agave parryi, Encelia farinosa*)	20.5	440	Sandy loam	7.2	2.5	306
S14	1,300	33°32'52"	116°29'00"	Desert shrub/tree (*Quercus cornelius-mulleri, Juniperus californica, Pinus monophylla*)	17.9	690	Loamy sand	6.9	2.2	306
S16	1,592	33°32'52"	116°30'18"	Evergreen chapparal shrub (*Artemesia tridentata*)	21.0	840	Loamy sand	6.6	4.9	306
S17	1,829	33°32'42"	116°29'25"	Evergreen chapparal shrub (*Adenostoma fasciculatum, Arctostaphylos pringlei*)	20.0	970	Sandy loam	6.7	3.8	306
S18	2,155	33°32'02"	116°28'44"	Evergreen broadleaf tree (*Quercus chrysolepis*)	17.0	1,140	Sandy loam	6.6	3.8	306
S24	2,489	33°31'16"	116°25'11"	Evergreen needle-leaf tree (*Pinus jeffreyi*)	15.0	1,320	Sandy loam	6.1	8.8	306

Note: SOM, soil organic matter.

efflux (R) was measured as the change in headspace CO_2 concentration over a 90-s sampling period using an infrared gas analyzer (LI-7000 Licor Biosciences, Lincoln, NE). Soil R was measured at day 5 (R_5) and day 20 (R_{20}) after initiation of the incubation. We used the Statistical Analysis System (SAS, Version 9.2) to perform regression analyses among SOM, R_5 and R_{20}.

2 Results and discussions

Our study indicated that SOM content significantly (P<0.001) increased with elevation at both soil depths (Fig. 2). The increase of SOM content with elevation is likely the result of greater input of OM with a relatively constant rate of C loss through SOM decomposition (Garten and Hanson, 2006). Across the elevation gradient, SOM content increased from 1.77% at S1, the base of the transect (289 m), to 9.11% at the summit (S24). Hanawalt and Whittaker (1976) also recorded an increase in SOM content from 1.38% at upper Bajada desert scrub system (244 m) to 6.98% at subalpine woodland (2,960 m) in San Jacinto Mountains, California.

At S1, SOM under canopy was 2.40%, whereas the interspace SOM content was 1.68%, resulting in a difference of 0.72% within 0–5 cm depth; the SOM content was 1.68% under canopy and 1.33% under interspace, generating a difference of 0.35% within 5–15 cm depth. The differences in SOM distribution between under canopies and inter-canopy spaces decreased with soil depth. At S24, SOM under cano piesand inter-canopy spaces were 9.86% and 7.59%, respectively within 0–5 cm depth bringing about a SOM difference of 2.27%; within 5–15 cm depth, the SOM under canopy was 10.8% and under inter-canopy space was 8.14%, indicating a difference of 2.70%. Differences in surface organic matter and initial flux between under canopy and inter-canopy space within a site may be linked to more accumulations of litter under canopy. Smith et al. (2002) reported soil carbon concentration significantly increased with elevation with greater increase associated with soils under bunchgrass canopy than crypotogamic crust of interspace in a shrub-steppe ecosystem located in eastern Washington of USA.

Soil R_5 and R_{20} did not show any significant relation (P>0.05) with elevation gradient at both soil depths. At S1, soil R_5 under canopy and inter-canopy space were 0.154 and 0.067 μmol/(g•d), respectively within 0–5 cm soil depth; whereas the same values within 5–15 cm depth were 0.059 and 0.030 μmol/(g•d), respectively (Fig. 3). At S1, R_5 increased almost double from interspace to canopy at both soil depths. At S24, R_5 (0.039 μmol/(g•d)) was same for both under canopy and inter-canopy space within 0–5 cm depth; whereas the R_5 within 5–15 cm depth were 0.030 and 0.022 μmol/(g•d) for under canopy and inter-canopy space, respectively. At S24, R_5 did not show much differences between under canopy and inter-canopy space or 0–5 and 5–15 cm depths. Soil R_5 and R_{20} values were higher at the lower elevation sites although SOM content showed an opposite trend.

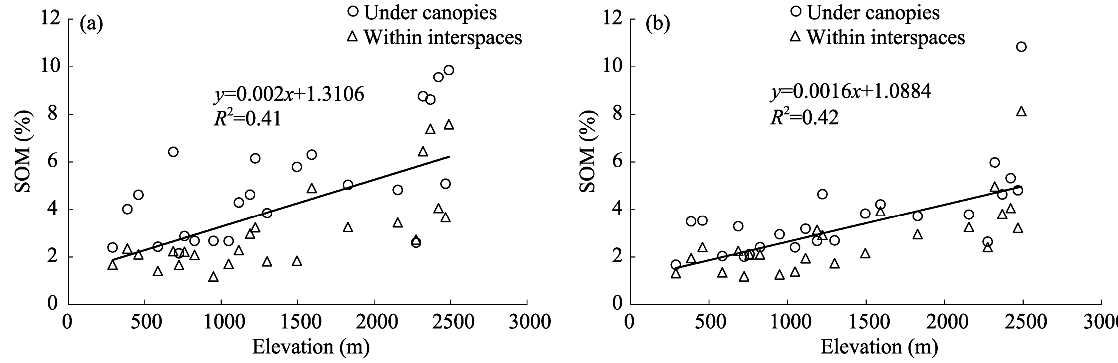

Fig. 2 Changes in SOM of under canopies and inter-canopy spaces soil within (a) 0–5 cm and (b) 5–15 cm soil depths across the elevation gradient in the Santa Rosa Mountain of Southern California

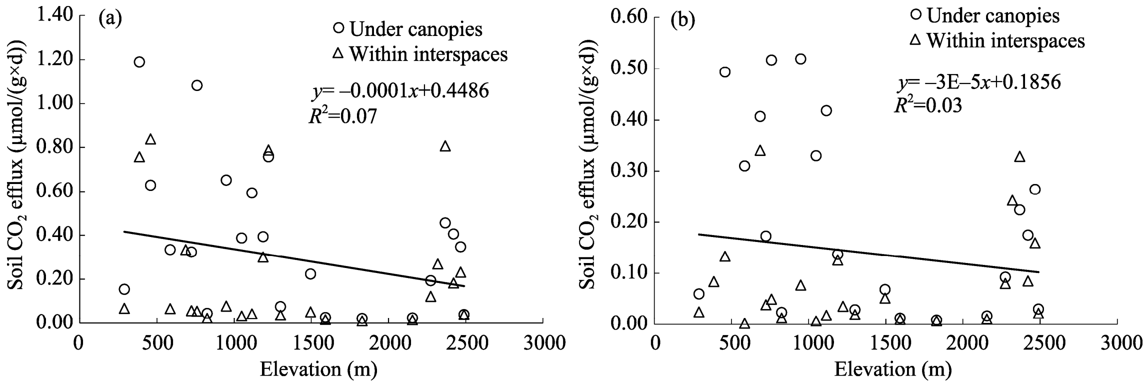

Fig. 3 Changes in soil CO_2 efflux on 5th day of incubation (R_5) within (a) 0–5 cm and (b) 5–15 cm soil depths across the elevation gradient in the Santa Rosa Mountains of Southern California

At S1, R_{20} rates were 0.063 and 0.036 µmol/(g•d) under canopy and inter-canopy space, respectively within 0–5 cm depth; the R_{20} under canopies and inter-canopy spaces within 5–15 cm depth were 0.024 and 0.014 µmol/(g•d), respectively. Even after 20 days of incubation, canopy R was 75% and 71% higher than interspace R at 0–5 and 5–15 cm depths, respectively. At S24, R_{20} were 0.026 and 0.023 µmol/(g•d) within 0–5 cm, 0.019 and 0.014 µmol/(g•d) within 5–15 cm soil depth under canopies and inter-canopy spaces, respectively. It was evident that there was no significant difference in under canopies and inter-canopy spaces or 0–5 and 5–15 cm depths. Presence of surface duff layer reduced the water and dissolved organic matter transport down the profile, whereas interspace soils with no duff or little litter are generally drier and have the lower rates of soil respiration than wetter canopy soil (Conant et al., 2000). Canopy-interspace variation has a potential influence on microclimate through soil processes and soil characteristics including the accumulation of surface organic matter particularly in arid to semi-arid environments (Schlesinger, 1990, Austin et al., 2004, Chatterjee and Jenerette, 2011b).

Relationship between soil R_5 and SOM content also did not show any significance (P>0.05) at both depths. Field observations on the same transect also supported soil metabolic pulses exhibited strong scale dependencies in contrast to general expectations of increasing metabolic pulses with higher SOM (Jenerette and Chatterjee, 2012). This result indicates soil metabolic response did not correspond to SOM content. Trumbore et al. (1996) concluded that increase in C inventory from low to mid elevation due to high C inputs accompanied with slow decomposition along an elevation gradient in the Sierra Nevada, California. Elevation gradient represents simultaneous changes in climate (temperature and moisture), vegetation type, soil properties and nutrient availability (Garten et al., 1999). The interaction of all these factors might have cancelled out the effect of combined variations in the rates of carbon input and decay on soil respiration reaction along the elevation gradient.

However, ratio of soil R_5 to SOM content, an indicator of C respiration efficiency of soil, showed a significant relationship with changes in elevation at both soil depths (Fig. 4). Jenerette and Chatterjee (2012) found that soil metabolic pulse during the summer period and SOM were correlated positively within sites and negatively between sites on the same transect; at low elevations, the proportion of labile SOM was a much larger fraction than at higher elevations. Regulations of labile fractions to SOM distributions will increasingly influence long-term biogeochemical dynamics at large spatial scale (Austin et al., 2004).

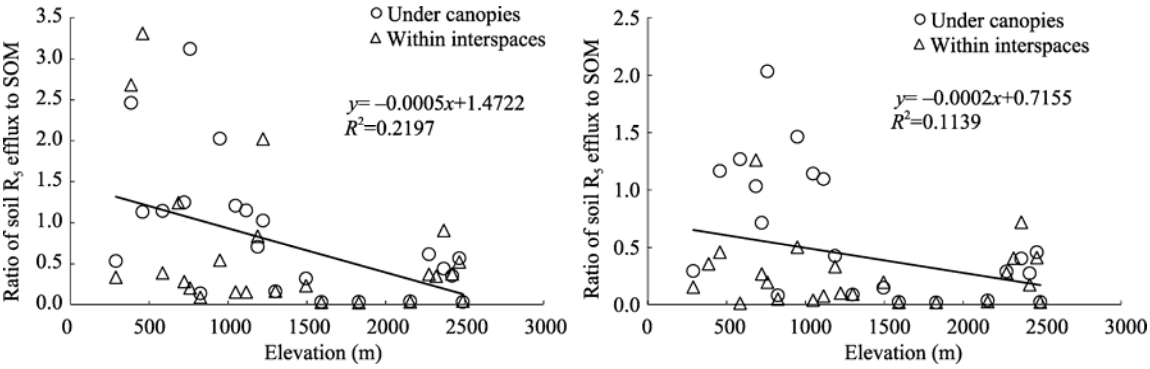

Fig. 4 Changes in ratio of soil CO_2 efflux on 5th day of incubation (R_5) to SOM content with elevation (m) within (a) 0–5 cm and (b) 5–15 cm soil depths across the elevation gradient in the Santa Rosa Mountains of Southern California

3 Conclusion

Our findings conclude that, first, we show here that SOM content can be predicted along an elevation gradient from a simple linear relationship. However, soil respiration is much more variable and cannot be predicted solely by elevation or SOM content. Second, shifts in SOM, R_5 and R_{20} patterns (1) over under canopies and inter-canopy spaces and (2) in between surface (0–5 cm) and sub-surface (5–15 cm) layers increased along the elevation gradient. Third, ratio of R_5 to SOM can be potentially used as a variable to predict the soil metabolic responses across the elevation gradient and highlights the potential interactive effects of carbon quality and quantity on soil respiration.

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