



Climatic and topographic controls on soil organic matter storage and dynamics in the Indian Himalaya: Potential carbon cycle–climate change feedbacks



Todd L. Longbottom^{a,b}, Amy Townsend-Small^{a,c,*}, Lewis A. Owen^a, Madhav K. Murari^a

^a Department of Geology, University of Cincinnati, Cincinnati, OH, USA

^b Department of Geology, Baylor University, Waco, TX, USA

^c Department of Geography, University of Cincinnati, Cincinnati, OH, USA

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ABSTRACT

Soil organic carbon (SOC) affects soil fertility and agricultural production, and SOC storage can also mitigate increasing atmospheric CO₂ concentrations on decadal timescales or longer. SOC storage is dependent on climatic conditions, and changes in temperature and precipitation associated with climate change can influence soil processes leading to feedback mechanisms that help control atmospheric CO₂ concentrations. Soils in tropical and subtropical mountain systems may be particularly sensitive to climate change, but SOC storage in high tropical and subtropical mountain regions is poorly quantified. To begin to evaluate the importance of C storage in soils in high mountain regions, regional SOC abundance was examined across the Himalaya of northern India. Soil samples were collected from the Kulu Lesser Himalaya, Lahul Himalaya, and Zanskar along an altitudinal and precipitation gradient of ~1900 to ~5000 m above sea level and ~100 to ~900 mm yr⁻¹, respectively, and analyzed for SOC inventory as well as $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$. The average annual SOC accumulation rates (between 1.9 g m⁻² yr⁻¹ and 47.3 g m⁻² yr⁻¹) and corresponding SOC turnover times (between ~50 and 3300 years) were highly variable. The results show that SOC stocks in the Indian Himalaya are more sensitive to moisture availability than temperature, as average annual precipitation was a greater influence on SOC than altitude. Stable carbon isotope data indicate that C3 vegetation has been consistently dominant in the region for the last ~7000 years. Rates of SOC accumulation and turnover are influenced greatly by variations in climate, vegetation, and topography. We conclude that increased precipitation may lead to increased SOC storage in the region, unless soils are exposed to greater erosion rates during intense storms.

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1. Introduction

Soil is the largest pool of terrestrial organic carbon (C) in the global C cycle, and C burial and storage can help mitigate increasing atmospheric CO₂ (Sitaula et al., 2004; Zhang et al., 2008). Anthropogenic modifications to the global soil organic carbon (SOC) pool such as agriculture/tilling (Knops and Tilman, 2000; Powlson et al., 2012), grazing pressure (Frank et al., 1995; Han et al., 2008), and differing land-use management practices (Cerri et al., 2007; Liu et al., 2011; Nayak et al., 2012; Yimer et al., 2007) can all profoundly affect SOC and nutrient dynamics from local to global scales. Of particular interest is the response of SOC to changing climate, as increased temperature and precipitation may increase SOC mineralization and erosion, respectively, leading to greater terrestrial CO₂ emissions and a positive feedback to climate change (Hopkins et al., 2012; Kirschbaum, 2000; Lal, 2003). Current estimates of SOC storage are plagued with uncertainties due to the paucity of

studies, particularly due to low sample numbers, high spatial variability, and the need for a standard sampling protocol (Grüneberg et al., 2010; Kimble et al., 2001; Sheikh et al., 2009). Understanding the pools, fluxes, and drivers of C cycling in upland areas is especially important, as high-altitude soils promote drainage and movement of soil particles to lower-lying areas (Shaffer and Ma, 2001), and can be a substantial component of riverine organic C transported to coastal margins, particularly in the subtropics and tropics (Townsend-Small et al., 2005, 2008).

SOC storage is largely dependent on regional climatic conditions: temperature and precipitation control the input of live biomass to soils and the rate at which it cycles through the terrestrial SOC pool, and precipitation is the primary driver of erosion rates on non-geologic timescales (Bird et al., 2001). In general, rates of C turnover decrease with an observable increase in temperature and rainfall (Trumbore et al., 1996), and SOC stocks decrease with an increase in temperature (Jenny, 1980; Post et al., 1982). One way to examine the relationship between SOC and changes in climate is to examine soils along environmental gradients of precipitation and temperature. SOC decreased with increased drought-stress along an aridity gradient in China (Yang et al., 2011), while SOC increased along an increasing

* Corresponding author at: Department of Geology, 500 Geology-Physics Building, University of Cincinnati, Cincinnati, OH 45221, USA. Tel.: +1 513 556 3762.

E-mail address: amy.townsend-small@uc.edu (A. Townsend-Small).

precipitation gradient in Negev Desert, Israel (Shem-Tov et al., 1999). In Rajasthan in NW India south of the Himalaya comprising essentially the Thar Desert, Singh et al. (2007) explained higher SOC in Alfisols, Vertisols and Inceptisols (compared with Aridisols) as a result of higher rainfall inputs. Additionally, changes in SOC storage have been identified with changes in altitude in the Garhwal Himalaya (Martin et al., 2010; Sheikh et al., 2009).

Stable C isotope and radiocarbon analyses are a valuable supplement to studies of soil organic matter dynamics. ^{13}C content is an indicator of plant type precursor, particularly useful for differentiating between C3 ($\delta^{13}\text{C} \sim -25\%$) and C4 ($\delta^{13}\text{C} \sim -11\%$) plants, which can be related to climate as well as to agricultural extent (Lajtha and Marshall, 1994). Stable C isotopes may be useful in inferring degradation extent of soils (Lehmann et al., 2002; Nadelhoffer and Fry, 1988). Radiocarbon has a half-life of 5730 ± 40 years and, as such, is used for dating and turnover time estimates (Trumbore and Harden, 1997). Both isotopes can be used as tracers of organic matter source, particularly in mountainous environments where inputs from higher elevations may be a source of organic C (Townsend-Small et al., 2005, 2007).

Impacts of climate change in the Himalayan region are of grave concern, as it has the highest concentration of high mountains and glaciers in the tropics and subtropics. The region is the source of the Ganges and Indus Rivers, which are among the largest sources of sediment and associated terrestrial organic matter to the global oceans due to high erosion rates, particularly during seasonal monsoon rains (Ahmad et al., 1998; Ali and De Boer, 2007). Significant and rapid changes in precipitation and temperature are expected in the coming decades in the Himalaya, potentially leading to large-scale destabilization of soil organic matter. Changes to climate and the atmosphere (temperature, precipitation, CO_2 concentration) will likely affect net primary production (NPP), which balances the carbon losses of soils and rates of turnover/decomposition of SOC (Falloon et al., 2007; Townsend et al., 1995). Organic matter in soils may be vulnerable, as previous work defining SOC stock in the Himalaya have shown high SOC densities in forest soils, and deciduous forests (the dominant forest type in India) have a carbon stock of 2.64 Pg C in the top 1 m of soil (Chhabra et al., 2003).

A significant precipitation gradient has previously been established for portions of Northern India, revealing a difference in annual precipitation in the northern and southern ranges, which spans from 200 to 1000 mm/yr (Hedrick et al., 2011). The purpose of this study was to characterize the distribution and dynamics of soil organic carbon and nitrogen stocks in northern India along a climatic gradient. We measured $\Delta^{14}\text{C}$, $\delta^{13}\text{C}$, and SOC stock along a gradient of precipitation and temperature/altitude to address whether warming and increasing precipitation will affect SOC storage in soils in the Himalaya.

2. Materials and methods

2.1. Regional setting

The Indian Himalaya occupies an area of 590,000 km^2 , comprising ~27.8% forests, ~36.2% pasture, ~9.2% agriculture and ~1.2% orchards

(Sidhu et al., 1997). Sample sites were chosen in the states of Himachal Pradesh, Jammu, and Kashmir, partly along the 'Manali-Leh highway' in northern India, in September 2011 (Table 1; Fig. 1). Several significant mountain ranges/geographic regions span the region trending approximately east–west. From south to north, these include the Lesser Himalaya (Kulu Himalaya), Greater Himalaya (Lahul Himalaya), Zaskar and Ladakh, which rise to progressively higher elevations northwards. These regions are influenced by two major climatic systems, the mid-latitude westerlies and the Indian monsoon that brings precipitation to the region during the winter and summer, respectively.

The southernmost sites (sites 1–4) were sampled in the Kulu Lesser Himalaya near the town of Manali, Himachal Pradesh. Sites 1–3 were located in the northern section of the Kulu valley in close proximity to the Beas River, a major tributary of the Indus River. These regions are characterized by a temperate climate, with high variation in inter-annual rainfall (637–819 mm yr^{-1}), and mean maximum and minimum temperature of 24 °C and 7 °C, respectively (Sah and Mazari, 1998). Site 4 was located on the northern side of the Rohtang Pass, a significant physical and bioclimatic barrier within the Pir Panjal range, which separates the Kulu and Lahul valleys.

Sites 5 and 6 were in the Lahul Himalaya. The Lahul Himalaya comprises two distinct mountain ranges, the Pir Panjal and the Greater Himalaya, which trend NW–SE. The climate of the Lahul is varied according to altitude, receiving total annual rainfall ranging from 454 to 636 mm yr^{-1} , with a mean annual temperature of ~8.5 °C (Fig. 1). Low annual rainfall and atmospheric pressure limit the distribution of natural vegetation at high altitudes, which transitions from mixed deciduous forests at lower altitudes, to coniferous forests to alpine between elevations of 3350 and 4850 m above sea level (asl), to sparse vegetation above 4850 m asl (Owen et al., 1996; Sehgal, 1973). Site 7 was sampled on the Baralacha La (La is the local name for pass), which separates Lahul from Zaskar to the north. Finally, sites 8 and 9 were sampled in the Zaskar region, an area composed of a series of mountain valleys and ranges in high-altitude alpine desert behind the rainshadow of the Greater Himalaya. The Zaskar River primarily drains Zaskar to flow into the Indus River. Zaskar is bounded to the north by Ladakh, which is traversed by the Indus and Shyok rivers, and the Ladakh range. A 30-year record of climate measurements at Leh in Ladakh reveal an annual precipitation of ~115 mm yr^{-1} (Osmaston, 1994; Taylor and Mitchell, 2000), similar to our finding of 87–270 mm yr^{-1} from TRMM data in this study (Table 1). The majority of yearly precipitation falls during monsoon season (July–September; Taylor and Mitchell, 2000).

The region has been extensively glaciated throughout the Quaternary (Owen, 2011). In Lahul, glaciers extended down the main Chandra valley during the Last Glacial (Owen et al., 2001). Glaciation became progressively more restricted northwards into Ladakh, where glaciers during the Last Glacial Maximum extended only a few kilometers beyond the present ice margin. However, in Ladakh, glaciation was much more extensive in earlier glacial cycles with glaciers advancing into the Indus valley (Dortch et al., 2013; Owen, 2011; Owen et al., 2006) and glacial evidence exists for advances prior to ~400 ka.

Table 1
Site numbers, latitude/longitude, elevation, rainfall regime, descriptions of sample sites in this study, and major taxonomic classifications of examined samples.

Site no.	Latitude N	Longitude E	Elevation (m asl)	Rainfall (mm/yr)	Name	Soil type (order, suborder)
1	32°18.975'	77°08.705'	2940	636–819	Solang Valley	Inceptisols, Cryepts
2	32°14.303'	77°11.332'	1891	636–819	Manali	Inceptisols, Cryepts
3	32°18.988'	77°14.59'	2543	636–819	S. of Rohtang Pass	Inceptisols, Cryepts
4	32°23.173'	77°94.724'	3460	636–819	N. of Rohtang Pass	Inceptisols, Cryepts
5	32°38.299'	77°10.951'	3285	453–636	Jispa, Lahul	Inceptisols, Cryepts
6	32°45.414'	77°15.323'	3810	453–636	Patseo	Inceptisols, Cryepts
7	32°45.284'	77°25.326'	4885	270–453	Baralacha La	Gelisols, Turbels
8	33°13.338'	78°18.921'	4424	87–270	Puga Valley	Gelisols, Orthels
9	32°57.408'	78°16.018'	4553	87–270	Tso Moriri	Gelisols, Orthels

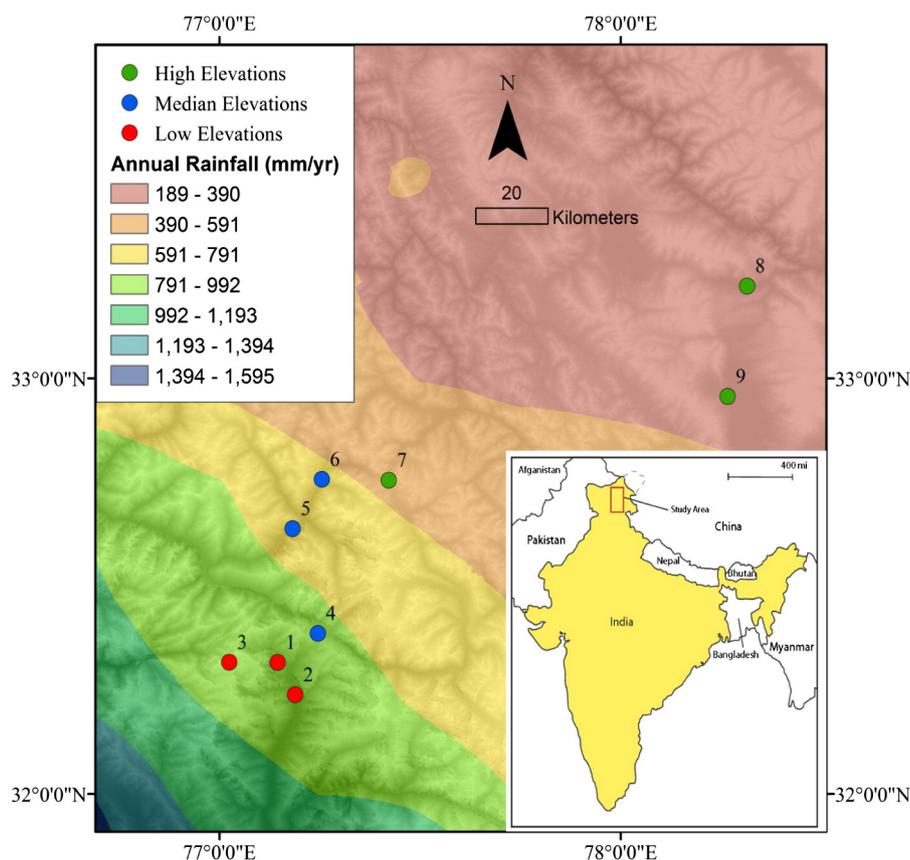


Fig. 1. Digital elevation model showing distribution of sample sites overlain by NASA TRMM satellite precipitation data (in mm/yr) for years 1998–2012. Digital elevation data was provided by NASA's Shuttle Radar Topographic Mission (SRTM) 90 m global dataset and the CGIAR-CSI GeoPortal (Jarvis et al., 2008).

2.2. Site selection, soil sampling, and laboratory analyses

The study sites were selected to examine the relationship between altitude, climate and regional SOC abundance in northern India. Soil samples were collected from the O, A, and B horizons in Inceptisols and Gelisols, using the terminology of (NRCS 1999), at 9 unique sites along the transect of interest. Sites were chosen by first establishing annual rainfall regimes using gridded monthly precipitation data obtained from the National Aeronautics and Space Administration's (NASA) Tropical Rainfall Measuring Mission satellite (TRMM), revealing a difference in annual precipitation in northern and southern ranges spanning from 190 to 1000 mm yr⁻¹ (Fig. 1). The precipitation data used in this study were acquired using the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure ("Giovanni") as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC). A total of four precipitation regimes were defined using the ArcGIS geostatistical analyst (ordinary kriging interpolation method), and soil cores from 5 to 6 soil profiles were taken at each sampling site.

At each site we sampled at a central point and 4 to 5 additional points, each positioned roughly 5 m apart. Coordinates and altitudes were recorded for each site using a handheld GPS unit. All samples were collected in September of 2011 using an AMS soil recovery probe with plastic liners to a maximum depth of ~30 cm. The maximum sampling depth was chosen as a result of limited soil development in the sites, ease of sample transport/acquisition, and the high SOC densities noticed in the first horizon. Prior to sampling, the surface of each site was cleared of leaf litter, plants, and humus to limit the amount of SOC contributed by these materials. Land use across the sample sites is characterized as primarily grazing/undeveloped. Landscape position for sample sites 2, and 4–9 were valley bottoms while sample sites 1 and 3 were sampled on hillslopes.

Individual cores were sectioned into 5 cm increments to characterize the SOC concentrations with depth. The samples were oven-dried at 60 °C for 48 h, hand-crushed, and sieved to separate fine (<2 mm) and coarse (>2 mm) fractions. The fractions were weighed to determine bulk density, and then ground in a mechanical ball mill grinder. Soil bulk density was calculated for each 5 cm-increment of known volume as:

$$BD = (\text{total dry mass} - \text{rock mass}) / (\text{total volume} - \text{rock volume}). \quad (1)$$

SOC concentration was determined after combustion in a CE Elantech Flash 2000 Elemental Analyzer at the University of Cincinnati. SOC stocks in units of kg C m⁻² were calculated by multiplying thickness, bulk density, and SOC concentration for each sample increment. All samples were pretreated using 2 N HCl to dissolve carbonates.

Representative cores exhibiting ideal and expected SOC stock at depth were chosen from sites 3, 4, 5, 6, 7, and 8 for $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$ analysis of SOM. Prior to isotope analysis, acidified samples were thoroughly rinsed to obtain a pH of ~7, and then dried. Graphite targets were prepared using a modified sealed tube zinc reduction method for CO₂ to graphite conversion (Xu et al., 2007) and $\Delta^{14}\text{C}$ values were measured via accelerator mass spectrometry (AMS) at the University of California, Irvine. Sample preparation backgrounds have been subtracted based on measurements of ¹⁴C-free coal. All $\Delta^{14}\text{C}$ results have been corrected for isotopic fractionation using the conventions of Stuiver and Polach (1977). Stable carbon isotope ratios were measured from a CO₂ aliquot collected during the combustion process using a Gas Bench coupled with a Finnigan Delta-plus isotope ratio mass spectrometer (IRMS) at the University of California, Irvine. $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$ values are expressed in per mil notation relative to the Oxalic Acid and Pee-Dee Belemnite standards, respectively.

2.3. SOC accumulation/turnover modeling

We used our radiocarbon and organic C concentration data to quantify rates of SOC accumulation and decomposition in our study area, based on the methods of Trumbore and Harden (1997) and Harden et al. (1997). The net change in SOC storage (dC/dt), or annual SOC inputs (I) minus decomposition (kC) for a particular year, is given by:

$$dC/dt = I - kC(t) \quad (2)$$

After solving this equation, assuming initial C concentration is zero:

$$C(t) = (I/k) * (1 - \exp(-kt)) \quad (3)$$

where $SOC(t)$ is SOC inventory (kg C m^{-2}) in year t , I is annual SOC inputs ($\text{kg C m}^{-2} \text{ yr}^{-1}$), and k is the decomposition rate constant (yr^{-1}). To ultimately determine constants I and k , the cumulative C stocks [$C(t)$] for chosen profiles were plotted versus conventional radiocarbon age (converted to calendar ages), or years before sampling (t). Calendar year calibration was accomplished using the CALIB 5.0 program, and the IntCal04 terrestrial radiocarbon calibration dataset for the northern hemisphere (Reimer et al., 2004; Stuiver and Reimer, 1993). The data were then fit with Eq. (3) to derive long-term estimates for I & k , while turnover times were obtained from taking the inverse of these k values (Harden et al., 1997; O'Donnell et al., 2011; Trumbore and Harden, 1997). As a result of the alteration of $\Delta^{14}\text{C}$ - CO_2 levels from above-ground nuclear weapons tests throughout the 1950s and 1960s, several samples had a $\Delta^{14}\text{C}$ value above 0, and are approximated as "modern" (Rehemeyer et al., 2005). For the purpose of long term SOC turnover derivation, depth increments denoted as modern were assigned an age of 0 years BP, in order to standardize all estimates.

3. Results

3.1. SOC, $\delta^{13}\text{C}$, and $\Delta^{14}\text{C}$ in soil cores

SOC stock generally decreased with increasing depth in the soil profile (Fig. 2). An exception to this trend is sample site 5, which revealed extremely low SOC stock in the O and A horizons. The $\delta^{13}\text{C}$ values of SOM consistently ranged from -20 to -28‰ across all sample sites and depths, with $\delta^{13}\text{C}$ increasingly enriched at depth (Fig. 3A). ^{14}C ages are approximately modern in surface soils, and became progressively older with depth (Fig. 3B). In general, older soils were more enriched in ^{13}C (Fig. 3C).

3.2. Transect elevation & annual precipitation

The overall relationship between SOC stock and elevation was complex, as the greatest SOC stocks were noticed at median elevations (~ 3000 to 3800 m asl) with the exception of site 5 (Fig. 4). Comparatively, lower elevations (1900 to 2500 m asl) had less SOC. The highest elevations (above 4000 m asl) had the lowest SOC stocks. SOC stocks in the top 15 cm across all sample sites showed no significant trend with elevation ($r^2 = 0.1092$; Fig. 5A). Finally, there was no relationship between elevation and SOM $\delta^{13}\text{C}$ ($r^2 = 0.0472$; Fig. 5B) or $\Delta^{14}\text{C}$ ($r^2 = 0.0099$; Fig. 5C). SOC stock was positively correlated with annual precipitation ($r^2 = 0.6822$, $p < 0.02$; Fig. 6A). SOM $\delta^{13}\text{C}$ and $\Delta^{14}\text{C}$ values were not correlated with annual precipitation (Fig. 6B, C).

3.3. Organic carbon accumulation and turnover

SOC accumulation and turnover rates varied throughout the sites (Table 2; Fig. 7; Fig. 8). There was no discernible trend between C turnover time and precipitation/elevation. The highest average annual accumulation rates were retrieved for sites 4, 6, and 8 ($12.9 \pm 2.14 \times 10^{-4} \text{ g C m}^{-2} \text{ yr}^{-1}$, $34.3 \pm 2.6 \times 10^{-5} \text{ g C m}^{-2} \text{ yr}^{-1}$, and $47.3 \pm$

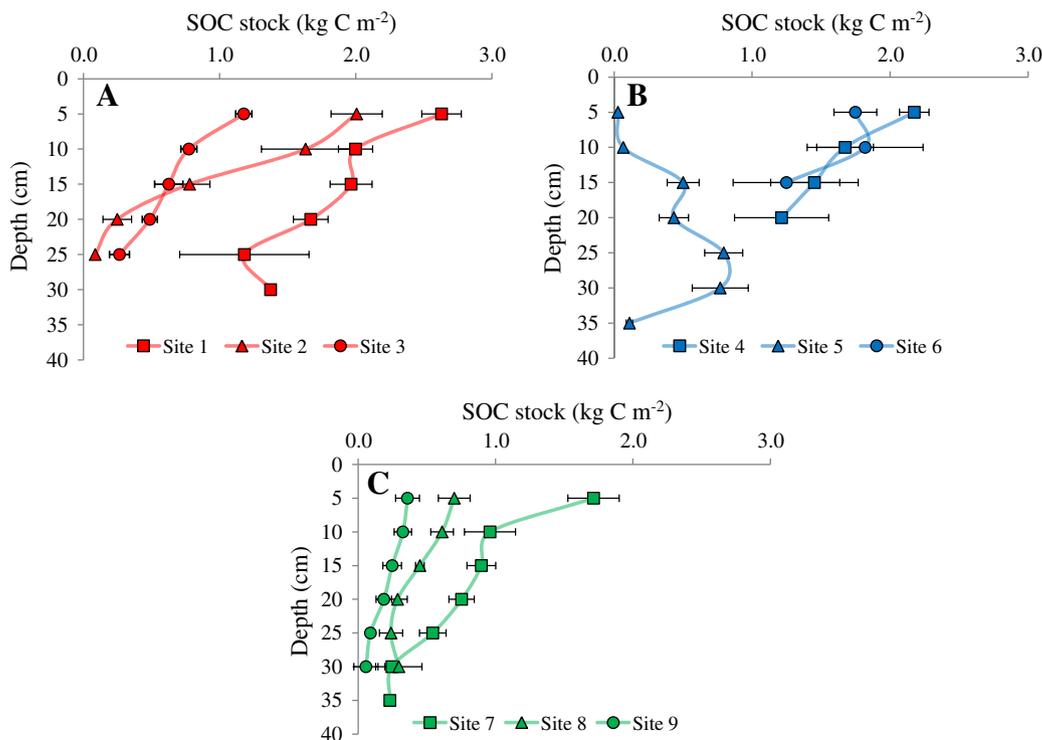


Fig. 2. SOC stock (kg C m^{-2}) at depth for all sample sites. Plots are grouped by elevation for a) 1900–2500 m asl, b) 3000–3800 m asl, and c) ≥ 4000 m asl.

Table 2

SOC stock (kg C m^{-2}), average annual C accumulation ($\text{kg C m}^{-2} \text{yr}^{-1}$), decomposition rate constant (yr^{-1}), and C turnover time (yr) values for all nine sites listed by sample site. Values for SOC stock represent an average of the top 15 cm. ND – not determined.

Site no.	SOC stock (kg C m^{-2})	I ($\text{kg C m}^{-2} \text{yr}^{-1}$)	k (yr^{-1})	C turnover time (yr)
3	2.6	$0.0041 \pm 3.62\text{e}-05$	$0.0013 \pm 1.36\text{e}-05$	~769
4	5.3	$0.0129 \pm 2.14\text{e}-07$	$0.0011 \pm 1.08\text{e}-07$	~909
5	0.6	ND	ND	ND
6	4.8	$0.0343 \pm 2.63\text{e}-08$	$0.0055 \pm 4.46\text{e}-09$	~181
7	3.6	$0.0019 \pm 6.64\text{e}-06$	$0.0003 \pm 1.75\text{e}-06$	~3333
8	1.8	$0.0473 \pm 2.17\text{e}-05$	$0.0225 \pm 1.03\text{e}-05$	~44

$0.02 \text{ g C m}^{-2} \text{yr}^{-1}$, respectively). Conversely, sites 3 and 7 had comparatively lower C accumulation rates ($4.1 \pm 0.04 \text{ g C m}^{-2} \text{yr}^{-1}$, $1.9 \pm 6.6 \times 10^{-3} \text{ g C m}^{-2} \text{yr}^{-1}$). Turnover times were somewhat short for sites 6 and 8 (181 years and 44 years, respectively), longer in sites 3 and 4 in the south (769 years, 909 years), and extremely long for site 7 atop the Baralacha La (3300 years). Average annual C accumulation and turnover were not calculated for sites 1, 2, and 9 as these samples were not analyzed for radiocarbon content. Estimations for I and k were not determined for site 5 because Eq. (3) could not be adequately fit to the unusual vertical distribution of SOC and associated radiocarbon ages.

4. Discussion

We have shown evidence for a SOC gradient corresponding with topographic-controlled precipitation barriers, and that SOC stocks in the Indian Himalaya are most sensitive to precipitation as opposed to physical factors such as altitude or temperature (Figs. 1 and 6). This has profound implications for the future, as increasing precipitation in arid regions may increase SOC sequestration due to increasing precipitation growth. In contrast, soils in the Himalaya are also made more vulnerable to erosion in an increased precipitation scenario, such as that observed in the 2000 and 2002 abnormal monsoon years (Bookhagen

et al., 2005; Krishnan et al., 2003), and recent anomalously heavy rain events in 2010 and 2013 (Lau and Kim, 2012).

4.1. Carbon stock, $\delta^{13}\text{C}$, & $\Delta^{14}\text{C}$ in soils

SOC stock declines with an increase in depth, a trend that is consistent across the observed climatic and geomorphic gradients, with the exception of sample site 5. Due to the proximity of site 5 to the Bhaga River, it appears that the contemporary floodplain was sampled, and that soil composition at this site was heavily controlled by recent high-volume flooding events. Furthermore, the profile exhibits a “reversed” characteristic where SOC stock greatly increases with depth, supporting the notion that site 5 was recently buried by alluvium. This is supported by physical attributes of soil at site 5, as the substrate was primarily sand and gravel with a high bulk density ($<1 \text{ g cm}^{-3}$).

$\delta^{13}\text{C}$ of SOM is consistent with dominant C3 vegetation at all of the study sites and horizons ($\delta^{13}\text{C}$ between -21 and -26%) (Lajtha and Marshall, 1994). Due to the apparent consistency in vegetation through time, $\delta^{13}\text{C}$ could not be used to determine carbon turnover. Variation of ^{14}C and ^{13}C , with older soils exhibiting more enriched ^{13}C values, is perhaps indicative of prolonged degradation of SOC in situ (Fig. 3C). The average $\delta^{13}\text{C}$ of surface soils (0–15 cm) increased with increasing altitude (Fig. 5B), likely due to higher $\delta^{13}\text{C}$ of plants at high altitudes, where

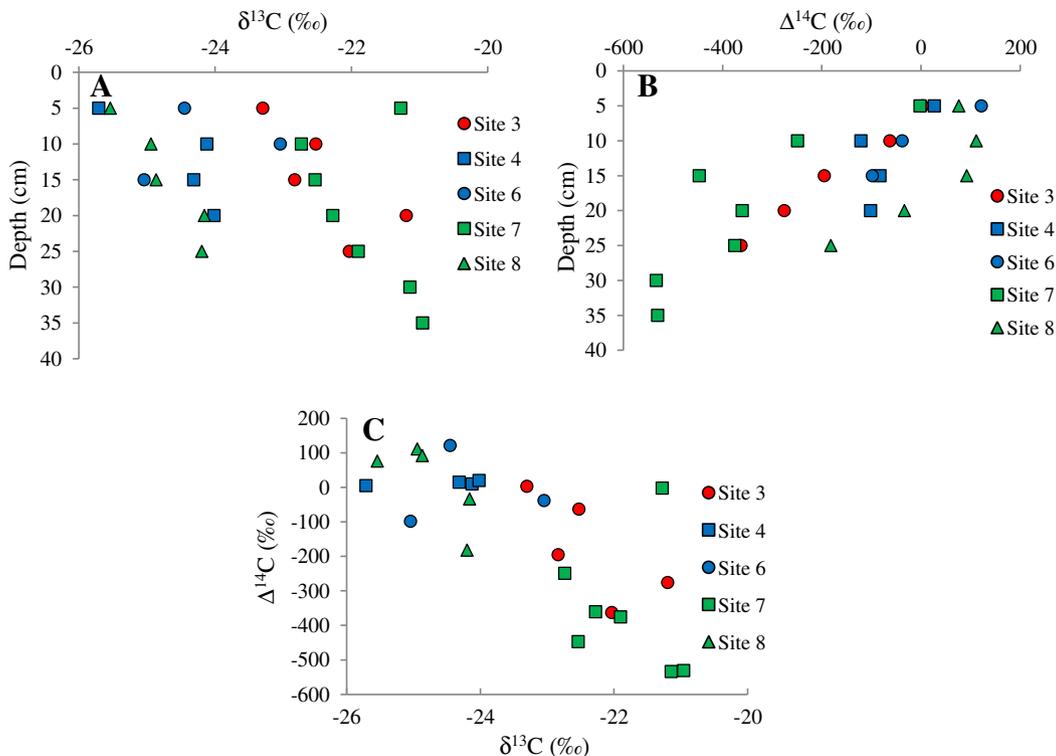


Fig. 3. Variation of carbon isotopes for study sites 3, 4, and 6–8, a) $\delta^{13}\text{C}$ for SOC for selected samples versus depth, (b) radiocarbon content of SOM versus depth and (c) $\delta^{13}\text{C}$ of SOC presented versus radiocarbon content ($\Delta^{14}\text{C}$) for the same samples.

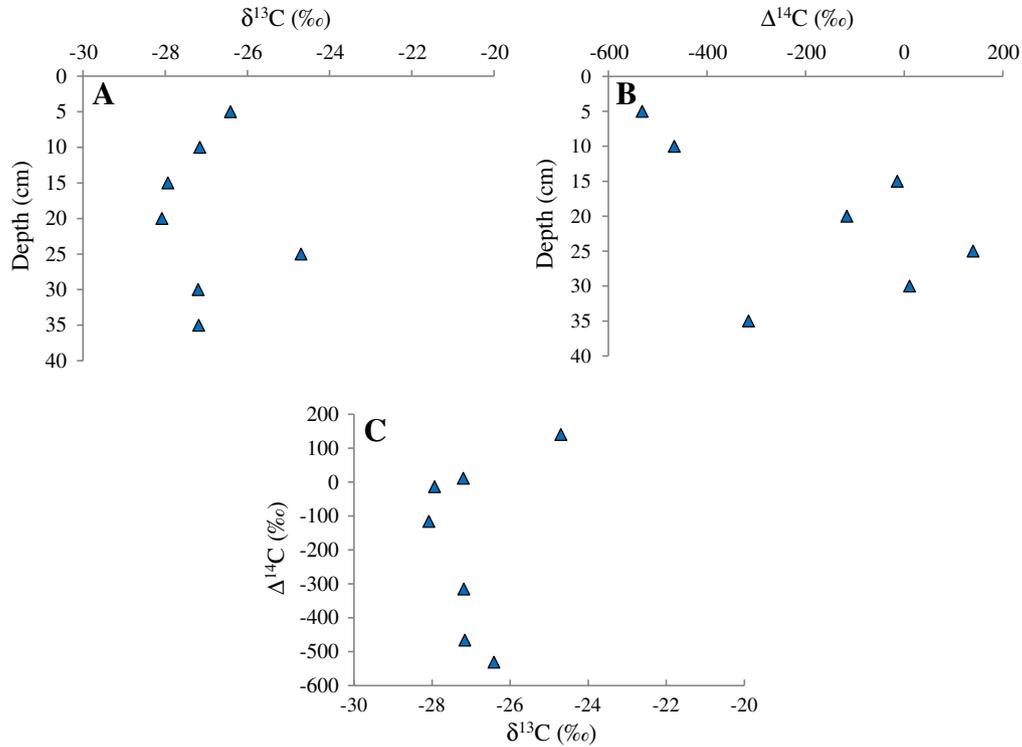


Fig. 4. Variation of carbon isotopes for study site 5. (a) $\delta^{13}\text{C}$ for SOC for selected samples versus depth, (b) radiocarbon content of SOM versus depth and (c) $\delta^{13}\text{C}$ of SOC presented versus radiocarbon content ($\Delta^{14}\text{C}$) for the same samples.

lower atmospheric pressure decreases isotope fractionation by photosynthesis (Townsend-Small et al., 2005). Surface soils were dominated by bomb-enriched radiocarbon, while older horizons became

progressively depleted in ¹⁴C with increases in profile depth (Fig. 3B), with the exception of site 5, which yet again, likely represents a reversed or buried soil stratigraphy (Fig. 4).

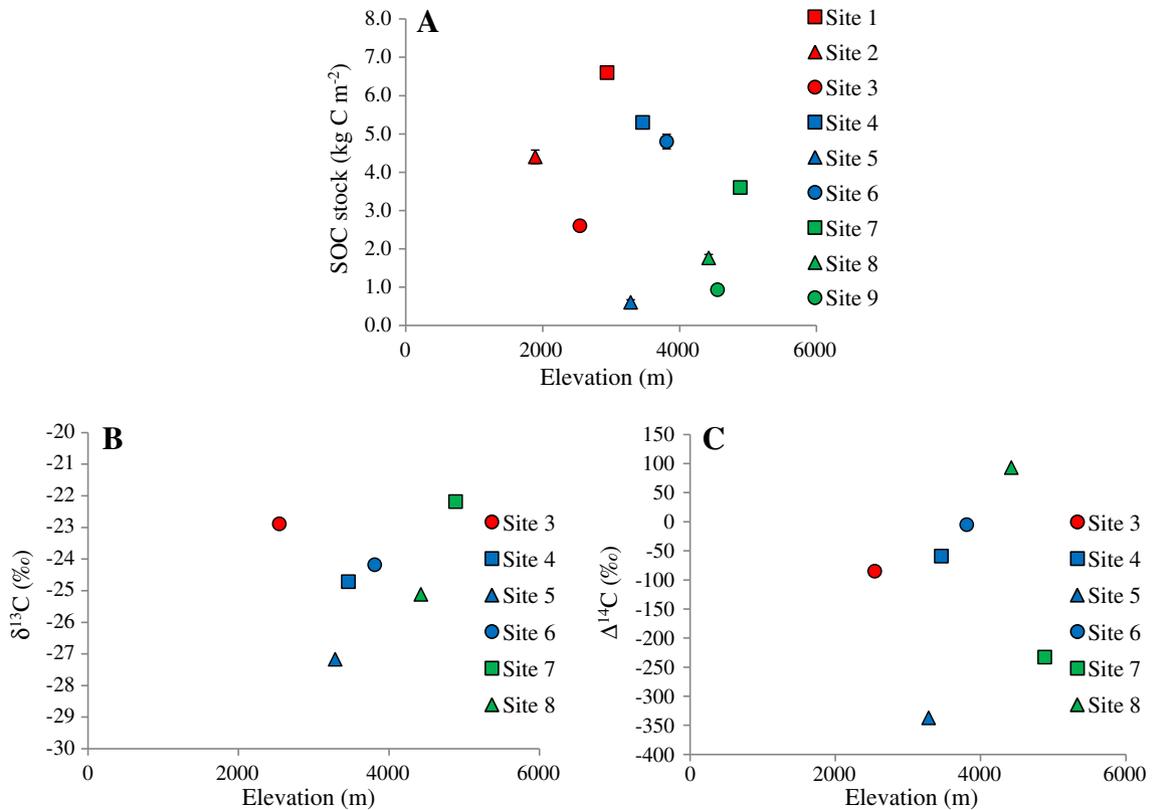


Fig. 5. Variation of SOC and carbon isotopes with altitude for sites 3–8. a) Average SOC stock, (b) average $\delta^{13}\text{C}$ and (c) average $\Delta^{14}\text{C}$. All values are normalized to a soil depth of 15 cm.

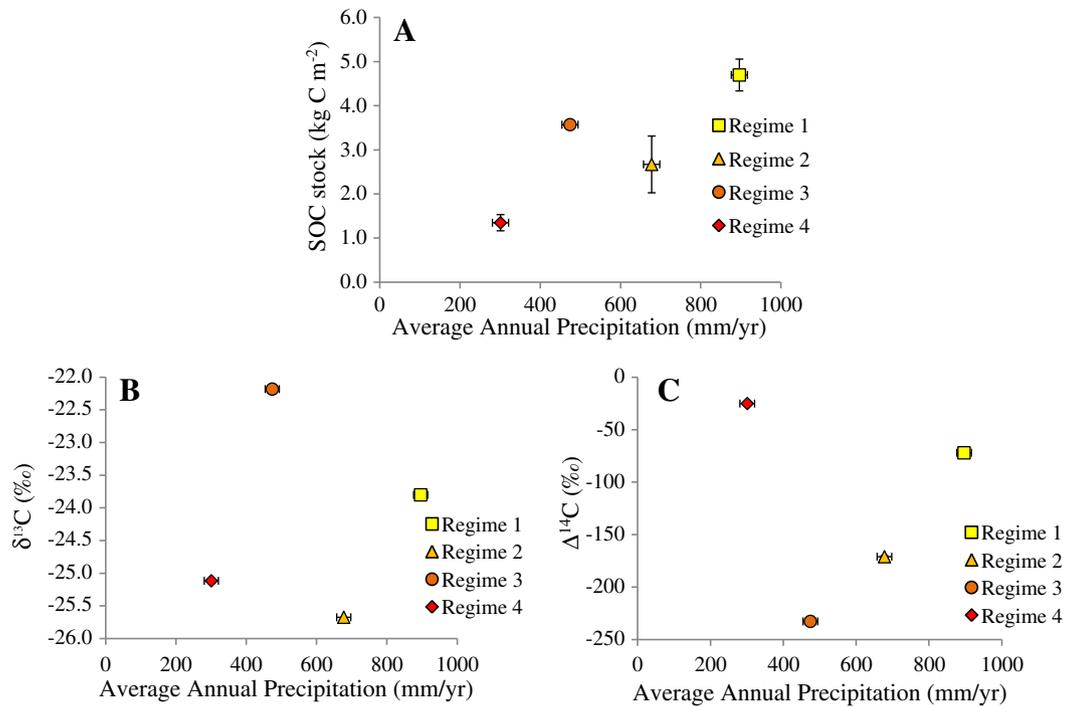


Fig. 6. Variation of SOC and carbon isotopes with mean annual precipitation for four precipitation regimes. a) Average SOC stock, b) average $\delta^{13}\text{C}$, and c) average $\Delta^{14}\text{C}$. All values are normalized to a soil depth of 15 cm. Error bars represent standard error and are generally smaller than the symbol with the exception of region 2.

4.2. SOC stock – comparison to other areas in India and the Indian Himalaya

SOC stocks were normalized to a depth of 15 cm for the purpose of comparison with previously published data for India (Chhabra et al., 2003; Martin et al., 2010; Sheikh et al., 2009; Singh et al., 2007, 2011). Areas that revealed the highest average SOC stocks proved somewhat surprising: sites 1, 4, and 6 had the highest SOC inventories with 6.6 kg C m^{-2} , 5.3 kg C m^{-2} , and 4.8 kg C m^{-2} , respectively. The geographic distribution of these sites implies that SOC inventory is not related linearly to elevation (Fig. 5). Instead, sites 1, 4, and 6 may represent ideal conditions of temperature and precipitation to sequester C in soils. Sites 2, 3, and 7 showed median SOC inventories of 4.4 kg C m^{-2} , 2.6 kg C m^{-2} , and 3.6 kg C m^{-2} , respectively. Finally, the lowest SOC stocks were observed in sites 5, 8, and 9. The low SOC stocks in sites 8 and 9 in the Zaskar range were expected, as the small amount of annual precipitation (regime 4, Fig. 1) coupled with sparse vegetation in Zaskar likely inhibits C sequestration in soils. Low SOC stocks at site 5 are likely due to recent burial, where most of the first horizon (~15 cm) is composed of alluvium.

Singh et al. (2007) studied SOC stock in Rajasthan where, like Zaskar, erosion, periodic drought, low productivity, and dwindling water resources have limited the amount of SOC in these arid and semiarid soils. Regional estimations of SOC stock were reported as ~1230 Tg for Rajasthan, which is possibly the closest previous approximation for regional SOC stock for the Manali-Leh highway (Singh et al., 2007). Meanwhile, SOC stocks for the first 25 cm under Entisols was $0.0055 \text{ kg C m}^{-2}$, $0.00256 \text{ kg C m}^{-2}$ under Aridisols, $0.00106 \text{ kg C m}^{-2}$ under Inceptisols, $0.00169 \text{ kg C m}^{-2}$ under Vertisols, and $0.00168 \text{ kg C m}^{-2}$ under Alfisols (Singh et al., 2007). Singh et al. (2011) evaluated SOC stock and its relation to climate in the western Himalaya (Himachal Pradesh), reporting SOC stock results for sub-tropical forests (6.2 kg C m^{-2} from 0 to 30 cm), horticulture/agriculture land use types (3.3 kg C m^{-2} and 2.7 kg C m^{-2} from 0 to 30 cm), temperate (10.4 kg C m^{-2} for 0 to 30 cm), lower alpine ($10.0\text{--}10.9 \text{ kg C m}^{-2}$ for 0 to 30 cm), and

upper alpine forests (7.9 kg C m^{-2} for 0 to 30 cm); results that corroborate well with our data for the Lesser and Greater Himalaya (~0.5–7.0 kg C m^{-2} for 0 to 15 cm; Fig. 5A).

A comparison of soils in nearby regions shows that our study region has lower C stocks in soils than elsewhere in the Himalaya and the Indian subcontinent. Sheikh et al. (2009) established SOC stocks for differing forest types in the Garwhal Himalaya to the southeast of our study site. The largest SOC stock was in *Quercus leucotrichopohra* forest soils, ranging from 15 to 17 kg C m^{-2} , while *Pinus roxburghii* forest soils ranged from 11 to 13 kg C m^{-2} (Sheikh et al., 2009). Such values are significantly higher than those reported in the current study for the Manali-Leh highway. Furthermore, Martin et al. (2010) evaluated SOC storage for differing physiographic units in Garwhal, noting large variation in SOC ($2.3\text{--}34.5 \text{ kg C m}^{-2}$) from 0 to 15 cm between hilltops, slopes, valleys, and piedmont plains. Chhabra et al. (2003) compiled a database of published SOC measurements across a suite on Indian forest ecosystems using estimated mean SOC densities and forest area derived from satellite data, reporting 3.40 kg C m^{-2} in tropical dry deciduous forests and 8.36 kg C m^{-2} in littoral/swamp forests from 0 to 50 cm depth. In addition, estimates for tropical dry deciduous forests (6.34 kg C m^{-2}) and montane temperate forests ($14.69 \text{ kg C m}^{-2}$) were measured for 1 m soil depth (Chhabra et al., 2003).

4.3. SOC stock – comparison to tundra and desert soils

On the basis of precipitation and strong seasonality, some sites in this study (specifically sites 4, 6, and 7) are analogous to soils of the high-latitude Arctic tundra. Northern soils are of particular interest and importance due to their potential to be either a substantial global C source or sink (Oechel et al., 1993). Colder temperatures characteristic of the Arctic can serve to limit the rate of both aerobic and anaerobic decomposition of SOM in soils, augmenting SOM preservation (White et al., 2004). For this reason, Arctic soils are particularly at risk for increased SOM decomposition through climate change, primarily increasing temperature (White et al., 2004), which could increase bacterial

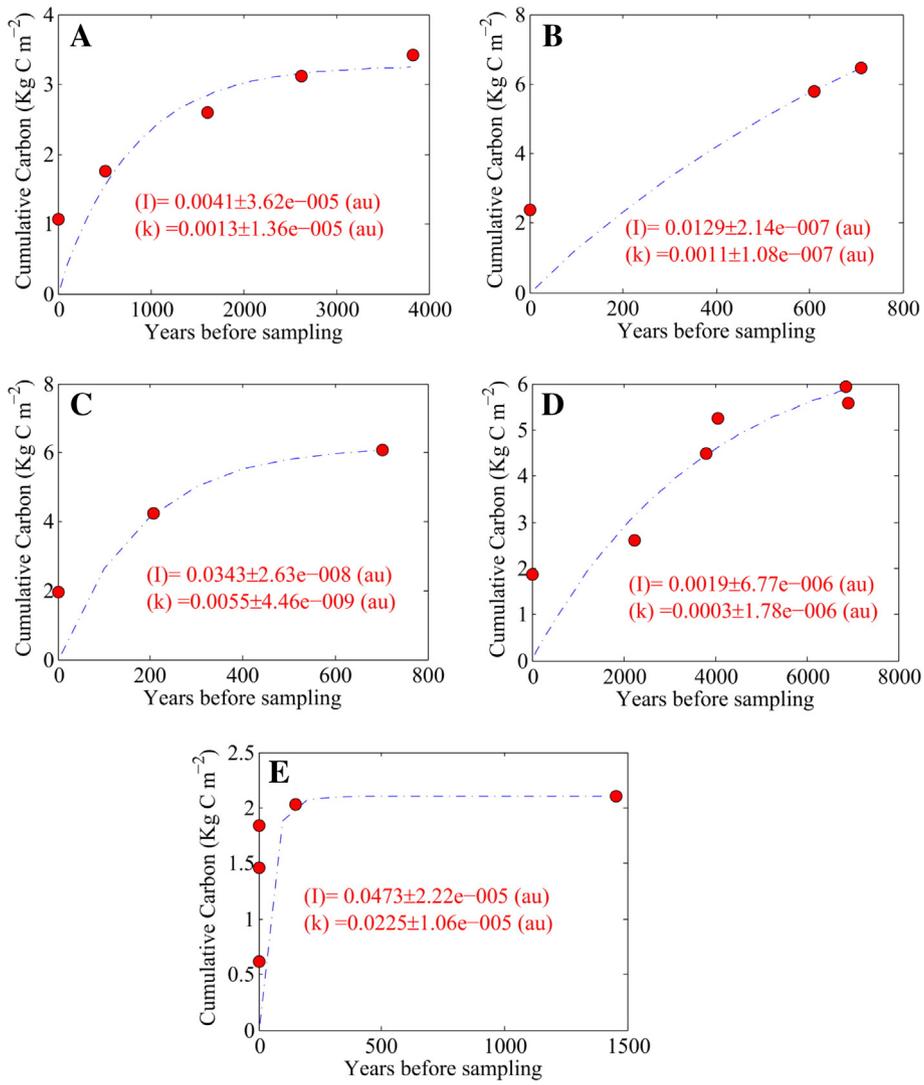


Fig. 7. Derivation of carbon accumulation rates (*I*), and decomposition rate constants (*k*), using Eq. (3) fit to a plot of cumulative carbon inventory versus years before sampling (radiocarbon age, years BP). Curve fits for a) site 3, b) site 4, c) site 6, d) site 7, and e) site 8.

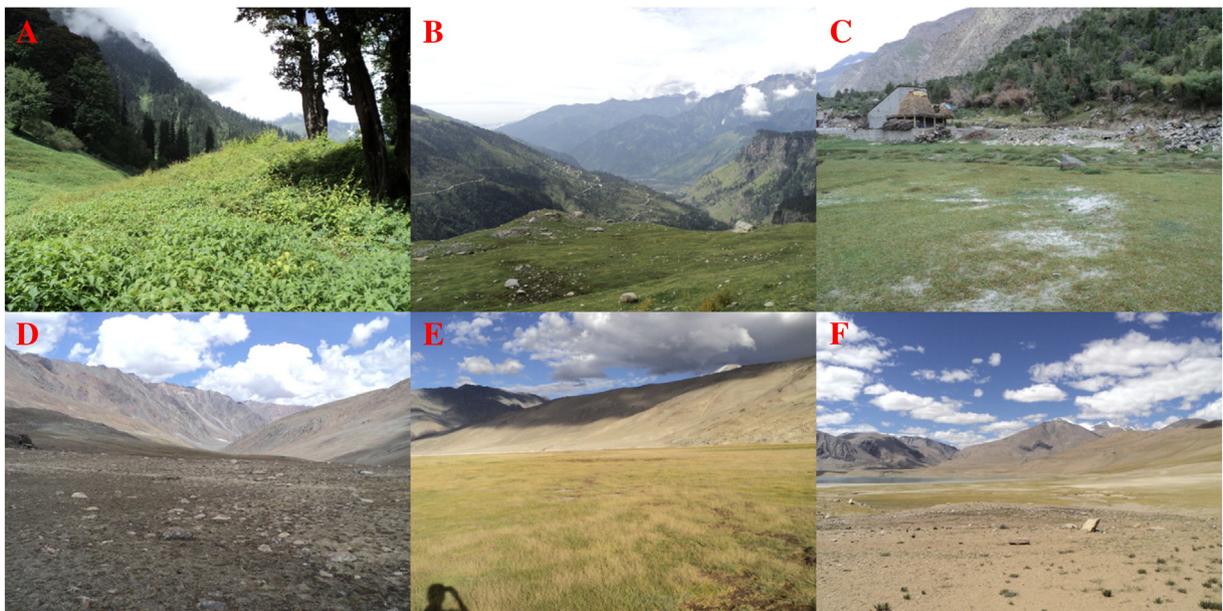


Fig. 8. Views illustrating the diversity in ecosystem type throughout a N-S transect across the study region. a) Site 1 – Solang Nala, b) Site 3 – S. Rohtang Pass, c) Site 5 – Jispa, d) Site 7 – Baralacha La, e) Site 8 – Puga Valley, and f) Site 9 – Tso Moriri.

growth rate (Rinnan et al., 2007) and change species composition and plant productivity (Jonasson et al., 1999).

Studies of SOC storage in the Arctic region has shown very high C concentration in the active layer, with about 21.7 kg C m^{-2} in the pan-Arctic region (Ping et al., 2008). SOC storage from 0 to 15 cm for sites 4, 6, and 7 in the current study fall within this range, and have carbon turnover times on the scale of centuries. Sites 4 and 6 have relatively large accumulation rates, suggesting extended periods of net C sequestration in soils. Conversely, site 7 has the lowest calculated C accumulation rate, but has a corresponding turnover time of greater than 3000 years. The Baralacha La (site 7) is of unique interest from these findings, as low vegetation cover does not favor C accumulation. Instead, due to the very high elevation of the pass, it could be concluded that both respiration and accumulation have occurred at very slow rates simultaneously, also thought to be the cause of high standing stocks of organic C in Arctic soils. Townsend et al. (1995) argued that an increase in altitude, and hence a decrease in temperature, limits microbial activity/decomposition rates and increases SOC stock in higher-altitude environments.

Previous studies have examined the relationship between elevation/precipitation and SOC stock along altitudinal and climatic gradients. Dieleman et al. (2013) measured SOC stock along a 3000 m altitudinal gradient in New Guinea, finding that SOC stock responded linearly with increasing altitude, while similar gradients in Hawaii, Taiwan, Ethiopia, and the southern Appalachian Mountains mirror these findings (Dieleman et al., 2013; Garten and Hanson, 2006; Lemenih and Itanna, 2004; Tsui et al., 2013). Similarly, SOC stocks increase with increasing precipitation (Dieleman et al., 2013; Lemenih and Itanna, 2004; Shem-Tov et al., 1999). However, across the physical/climatic barriers of interest it is not possible to decouple the various influences on SOC stock. Physical and climatic variables of interest likely covary with observed SOC stock and turnover calculations.

SOC inventory in sites 8 and 9 in the Zaskar range are more akin to arid soils due to their low SOC inventories, coupled with the lowest annual precipitation rates among all of the regions in question. Kunkel et al. (2011) report an average value of 2.1 kg C m^{-2} for 0 to 30 cm in a semi-arid mountainous watershed in Idaho. In addition, Mills and Cowling (2010) reported stocks ranging from 1.63 to 4.72 kg C m^{-2} in the top 25 cm in subtropical thickets in semiarid South Africa. Values obtained for SOC stock for sites 8 (1.8 kg C m^{-2}) and 9 (0.9 kg C m^{-2}) in the current study are consistent with these published values. Meanwhile, the derived SOC accumulation rate for site 8 was unexpectedly high ($47.3 \pm 0.02 \text{ g C m}^{-2} \text{ yr}^{-1}$) and the SOC turnover time for this soil profile was also the shortest (~ 44 years), suggesting an increase in C accumulation rate in recent decades, perhaps due to increasing rainfall in the region (see further discussion below). The approximately modern ages retrieved for the first 15 cm of sample site 8 could also be explained by enhanced illuviation, where surface-derived organics have been displaced in the soil profile through the action of percolating rainwater.

4.3.1. Evidence for 2010 flood as related to monsoon activity, and implications for climate change feedbacks

We have shown that recent high-precipitation events may have already affected SOC stock in this region. Most notably, ages calculated from the first 10 cm of site 5 seem to be a function of parent material, closely resembling ages of ~ 7000 calibrated years BP (Table 2) retrieved from site 7 (Baralacha La, Lahul Himalaya) upvalley, and potentially validating the notion of a recent high-discharge flood event in the immediate area. In contrast to other sites, the SOM below the recently-deposited alluvium at a depth of ~ 25 cm was determined to be modern. Although estimates for C accumulation and turnover could not be determined for the chronosequence for site 5, the results for the site are an important indicator of the effects of anthropogenic climatic change on C cycling in mountainous regions. Aside from the risk of increased soil respiration through a shift in annual temperature and precipitation,

the risk of an increase in frequency of flooding events could enhance soil erosion if the Asian monsoon is steadily augmented in magnitude and duration. Similarly, increasing precipitation in the region may result in acceleration of biomass accumulation as well as SOC turnover. Recent abnormal monsoon years have resulted in rainfall breaching orographic boundaries, triggering a two-fold increase in sediment transport in arid localities of the northwestern Himalaya (Bookhagen et al., 2005). SOC mobilized during river floods has a high likelihood of being respired as CO_2 during stream metabolism (e.g., Cole et al., 2007; Johnson et al., 2008). Furthermore, construction of impoundments for hydroelectric power and flood control in India may lead to CH_4 emissions derived from imported organic matter (Bastviken et al., 2011; Tranvik et al., 2009).

Soil erosion is a significant degradative process in the Himalaya, reducing the productivity of plants and reducing the SOC pool through transportation and deposition (Sitaula et al., 2004). Extreme rainfall events have previously been identified as triggers of large-scale landslides in the Himalaya and Transhimalaya, rapidly destabilizing and removing slope-material (Dortch et al., 2009). Such conclusions are of concern to the majority of the sites evaluated in this study, as semiarid slopes promote high runoff and are not stabilized by organic content and dense vegetation. Previously arid and semi-arid regions in the northwest Himalaya were identified as 'geomorphic threshold areas,' where steep, and sparsely vegetated hillslopes are particularly vulnerable, and exhibit enhanced erosional processes following significant rainfall events (Bookhagen et al., 2005). The need for climatic/meteorological monitoring in this region is crucial, as precipitation may increase in volume and intensity in the future, with important consequences for human health and safety.

Monsoon rainfall is a primary driver of flooding in the Indus basin (Ali and De Boer, 2007), and erosion rates on millennial timescales in both the Lesser and Greater Himalaya are largely dependent, in volume and pattern, by the relative intensity of the monsoon (Clift et al., 2008). The intensity of the south Asian monsoon has increased in south peninsular India since 1970 (Naidu et al., 2012), a trend that could dramatically impact SOC dynamics on a regional scale, either by increasing vegetation cover due to increased water availability, or by increasing soil erosion rates. On the other hand, the parts of our study area near the Rohtang pass and Tso Moriri receive $>50\%$ of their annual precipitation as snow during the winter months, which is an important source of new ice for glaciers, which supplement water resources throughout the summer (Wulf et al., 2010, 2012). A shift in the ratio of snow to rain in the Himalaya may also impact the local C cycle, as will a change in temperature.

The complex interaction between SOC storage and climate in northern India could propagate these feedback mechanisms in a climate change scenario. Given the rise of global temperature, it is hypothesized that SOM decomposition is more sensitive to temperature than net primary production (Rodeghiero et al., 2009). A positive feedback loop would be initiated as the decomposition of SOM would be increased to a greater extent than NPP (Kirschbaum, 2000; Rodeghiero et al., 2009), leading to a buildup of CO_2 in the atmosphere. However, in the current study, we have shown that increasing precipitation will likely increase SOC storage (Fig. 6A), except in the case of large mass-wasting events triggered by strong storms (Fig. 4).

5. Conclusions

Our data indicate that mean annual precipitation is the greatest constraint on SOC storage in the semi-arid and arid Indian Himalaya, with decreasing SOC stock from higher to lower precipitation regimes. A number of our high-altitude study sites exhibit an analogous relationship with tundra soils due to their history of carbon sequestration and lengthy turnover times, further illustrating the vulnerability of Himalayan regions to anthropogenic climate change. A few of our sites (sites 5 and 8) show evidence for changes in C cycling on decadal timescales.

These sites clearly illustrate the potential impacts of climate change on C cycling in the region: increasing water availability at high altitudes will likely increase SOC storage (site 8), but very large increases in precipitation may destabilize hillslope SOC (site 5), likely leading to greater SOC mineralization at lower altitudes and in river basins.

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