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**I, Todd L Longbottom M.S., hereby submit this original work as part of the requirements for the degree of Master of Science in Geology.**

It is entitled:

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

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2771

# **Climatic and topographic controls on soil carbon storage and dynamics in the Indian Himalaya: Potential carbon cycle and climate change feedbacks**

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by

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## Abstract

Soil organic carbon affects soil fertility and agricultural production, and organic C storage can also mitigate increasing atmospheric CO<sub>2</sub> concentrations on decadal time scales or longer. However, soil organic C storage is dependent on climatic conditions, especially temperature and precipitation, and changes in these parameters associated with climate change can act as feedback mechanisms to atmospheric CO<sub>2</sub> concentrations. The objective of this study is to evaluate regional organic carbon abundance in northern India across orographically-limited precipitation regimes. We hypothesized that soil organic carbon (SOC) and total nitrogen (TN) gradients exist corresponding to these bioclimatic barriers, a result of this large precipitation and assumed vegetation discrepancy. Samples were collected from the Kulu Lesser Himalaya, Lahul Himalaya, and Zaskar and measured for SOC/TN inventory as well as  $\Delta^{14}\text{C}$  and  $\delta^{13}\text{C}$  analysis of soil organic matter (SOM). Average annual carbon accumulation and C turnover time were estimated for selected soil chronosequences, and results varied widely among the areas investigated. It was revealed that soil organic C stocks in the Indian Himalaya are sensitive to precipitation, C3 vegetation has been consistently dominant up to ~6ka B.P., and rates of accumulation and turnover are influenced greatly by variations in climate, vegetation, and topography. Examining the distribution of soil organic carbon stock can be useful in helping to predict the potential effects of warming and precipitation on C storage in this region.



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## **Introduction**

Soil carbon (C) is the backbone of soil organic matter (SOM), and the primary driver of biochemical transformations in the pedosphere (Cheng and Kimble, 2001). Soil is the largest pool of terrestrial organic C in the global C cycle, but current estimations are plagued with uncertainties: low sample numbers, high spatial variability, and the need for a standard sampling protocol (Grüneberg et al., 2010; Kimble et al., 2001; Sheik et al., 2009). Anthropogenic modifications to the global soil organic C (SOC) pool have become areas of interest in numerous past studies, 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 soil carbon and nitrogen dynamics from local to global scales. Of particular interest is the response of SOC to changing climate, as increased temperature and precipitation may increase C mineralization and erosion, respectively. Understanding the pools, fluxes, and drivers of C & N 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 carbon transported to coastal margins (Townsend-Small et al., 2005; 2008). Most importantly, soil and vegetation C can help mitigate increasing atmospheric CO<sub>2</sub> (Sitaula et al., 2004).

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 (Bird et al., 2001). Past studies have examined the relationship between SOC and changes in climate (Martin et al., 2010; Singh et al., 2011), as changes in global SOC stock could directly affect the concentration of greenhouse gases in the atmosphere (Zhang et al.,



2008). Furthermore, changes in climatic parameters associated with anthropogenically-driven climate change could potentially act as feedback mechanisms to atmospheric CO<sub>2</sub> concentrations (Kirschbaum, 2000). A few previous studies have elucidated the response of SOC and total nitrogen (TN) pools to geographic variations in precipitation and elevation. SOC decreased with increased drought-stress, along an aridity gradient in China (Yang et al., 2011), while SOC increased with along an increasing precipitation gradient in Negev Desert, Israel (Shem-Tov et al., 1999). In Rajasthan, India 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; Sheik et al. 2009). It is generally accepted that 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).

The Indian Himalaya is particularly vulnerable to climate change as it is a large component of the cryosphere, commonly referred to as Earth's "third pole" due to the large number of valley-style glaciers the region houses (Bagla, 2009). These glaciers are extremely sensitive barometers of climate change, and are retreating at throughout the Himalaya (Anthwal et al., 2006; Chaujar, 2009; Dobhal et al., 2004; Kulkarni et al., 2005; Kumar et al., 2008; Naito et al., 2006) and in numerous other localities globally (Barry, 2006; Jordan et al., 2005; Podlech et al., 2004; Theakstone and Knudson, 1986). Evidence for global glacial retreat may entail a change in SOM dynamics in both uplands and lower-lying areas. It is possible that carbon stocks in the Himalaya, and the world at large, could be destabilized as a result of rapidly changing annual precipitation and temperature. Changes to climate and the atmosphere (temperature, precipitation, CO<sub>2</sub> concentration) could affect net primary production (NPP), which balances the

C losses of soils, as well as rates of turnover/decomposition of soil C (Falloon et al., 2007; Townsend et al., 2005). Previous work defining SOC stock in the Himalaya have shown high SOC densities in forest soils, with deciduous forests (the dominant forest type in India) revealing a pool of 2.64 Pg C in the top 1m soil depth (Chhabra et al., 2003). This region is also the headwaters of one of Earth's largest rivers, the Indus, which is one of the largest sources of sediments and associated organic matter to the world's oceans (Ahmad et al., 1998; Ali and De Boer, 2007).

A significant precipitation gradient has previously been established for portions of Northern India, revealing a difference in annual precipitation in northern and southern ranges which spans from 200-1,000mm/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. We sampled along a stark precipitation gradient that exists between the Lesser Himalaya, Lahul Himalaya, and the Zaskar range. We hypothesized that SOC and total nitrogen (TN) stock would decrease along a gradient of decreasing annual precipitation and increasing elevation, and that C turnover times would decrease with decreasing precipitation and increasing altitude. We measured SOC and TN stocks, SOM  $\delta^{13}\text{C}$ ,  $\Delta^{14}\text{C}$ -derived SOM turnover times and compiled topographic (elevation) and climatic (precipitation) parameters in the study area.

## **Materials and Methods**

### *1.1 - Regional Setting*

The Indian Himalaya occupies an area of 59 million ha. The total geographic area is comprised of 27.8% forests, 36.2% pasture, 9.2% agriculture, and 1.2% orchards (Sidhu et al., 1997). Sample sites were chosen along the 'Manali-Leh highway' in northern India in

September 2011 (Table 1; Figure 1). The southernmost sites (sites 1-3) were sampled in the Kulu Lesser Himalaya near the town of Manali, Himachal Pradesh. These four locations resided in the northern section of the Kulu valley in close proximity to the Beas River, a major tributary of the Indus River. These regions is characterized by a temperate climate, with high variation in inter-annual rainfall, 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 bioclimatic barrier comprised of the Pir Panjal range, effectively dividing the Kulu and Lahul valleys.

The Lahul Himalaya (sites 5 & 6) are comprised of two distinct mountain ranges, the Pir Panjal and the Great Himalaya, which trend NW-SE. The climate of the Lahul is varied according to altitude, receiving a total annual rainfall of ~555mm and having a mean annual temperature of ~8.5°C. These factors intensely limit the distribution of natural vegetation which transitions from mixed deciduous forests at lower altitudes, to coniferous forests to alpine between elevations of 3350-4850m, to sparse vegetation above 4850m (Owen et al., 1996; Sehgal, 1973). Site 7 was sampled atop the high mountain pass named Baralacha-La which serves to connect the Lahul valley with the Ladakh region to the north. Finally, sites 8 & 9 were sampled in the Zaskar Range, an area composed of a series of mountain valleys and ranges, resembling a high-altitude alpine desert created through the orographic effect. This region is drained primarily by the Zaskar River (Mitchell et al., 1999). A 30-year record of climate measurements in Leh, Ladakh are thought to be most representative of the Zaskar region, revealing an annual precipitation of ~115mm/yr. The majority of yearly precipitation falls during monsoon season (July-September) with very little arriving during autumn (Taylor and Mitchell, 2000).

Surface exposure dates of moraine sediments in the Ladakh range and Lahul Himalaya have also previously been documented. In Ladakh, Owen et al. 2006 reported the oldest existing moraine dates in the Himalayan-Tibetan orogen (some dates are upwards of 350ka). Glaciations in this region were shown to decrease progressively over the past five glacial cycles and are markedly different from heavily monsoon-influenced areas (Owen et al., 2006). Additionally, chronologies established for glaciation in the Lahul Himalaya spanned from late Glacial to early Holocene times (Owen et al., 2001).

### *1.2 - Site Selection, Soil Sampling, and Laboratory Analyses*

The study was designed to clarify the relationship between altitude, climate and regional organic carbon abundance in northern India. Samples were collected from the O, A, and B horizons at 9 unique sites in a transect spanning the Kulu Lesser Himalaya, Lahul Himalaya, and the Zaskar range. Sites were initially chosen by 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 90-800mm/yr (Figure 1). A total of four regimes were defined using an ordinary kriging method, and soil cores from 5-6 soil profiles were taken at each sampling site.

At each site, a central core and 4-5 additional cores each positioned roughly 5 m away were obtained in order to ensure a representative set. Coordinates and altitudes were recorded for each site with a handheld GPS unit. The samples were collected in September of 2011 using an AMS soil recovery probe and plastic liners to a maximum of ~30 cm in length. Prior to sampling, the surface of each site was cleared of leaf litter, plants, and humus in order to limit the amount of SOC and TN contributed by these materials.

Individual cores were sectioned into 5 cm increments to characterize SOC/TN distribution with depth in the soil profile. The samples were oven-dried at 60°C for 48 hours, hand-crushed, sieved (<2mm sieve, separating fine and coarse fractions), weighed for bulk density determination, and ground in a mechanical ball/mill grinder. Bulk density (BD) was calculated as (Raciti et al., 2011):

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

C/N concentration was determined, and total SOC/TN in units of kg C/N m<sup>-2</sup> was revealed at depth after combustion in a CE Elantech Flash 2000 carbon and nitrogen analyzer. SOC/TN stocks were calculated by multiplying thickness, bulk density, and C/N concentration for each sample increment. All samples were acidified using 2 N HCl to neutralize carbonates, and then again measured for C and N concentration. Soil bulk density was determined through the core method as each 5 cm core increment of known volume was weighed individually on a balance (Brasher et al., 1996; Grossman and Reinsch, 2002).

Representative cores exhibiting ideal and expected SOC/TN 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, the samples were thoroughly rinsed to obtain a pH of ~7, and then oven-dried overnight.  $\Delta^{14}\text{C}$  measurements were made via accelerator mass spectrometer (AMS)  $^{14}\text{C}$  measurements prepared using a modified sealed tube zinc reduction method for CO<sub>2</sub> to-graphite conversion at the University of California, Irvine (Xu et al., 2007). Sample preparation backgrounds have been subtracted based on measurements of  $^{14}\text{C}$ -free coal. All results have been corrected for isotopic fractionation according to the conventions of Stuiver and Polach (1977), with  $\delta^{13}\text{C}$  values measured on prepared graphite using the AMS spectrometer. These can differ from  $\delta^{13}\text{C}$  of the

original material, if fractionation occurred during sample graphitization. Stable carbon isotope ratios were measured from a CO<sub>2</sub> aliquot collected during the combustion process, using a gas bench coupled with a Finnigan Delta-plus Isotope-ratio mass spectrometer (IRMS).  $\Delta^{14}\text{C}$  and  $\delta^{13}\text{C}$  values are expressed in permil notation relative to the Oxalic Acid and Pee-Dee Belemnite standards, respectively.

### *1.3 - C accumulation/turnover modeling*

Modeling techniques were based on using radiocarbon methods to quantify rates of C accumulation and decomposition. The net change in C storage ( $dC/dt$ ), or annual C inputs ( $I$ ) minus decomposition ( $kC$ ) for a particular year, is given by:

$$dC/dt = I - kC(t) \tag{2}$$

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

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

Where  $C(t)$  is C inventory ( $\text{kg C m}^{-2}$ ) in year  $t$ ,  $I$  is annual C inputs ( $\text{kg C m}^{-2}\text{yr}^{-1}$ ), and  $k$  is the decomposition rate constant ( $\text{yr}^{-1}$ ). In order to ultimately determine constants  $I$  &  $k$ , the cumulative C stocks [ $C(t)$ ] for chosen profiles were plotted versus radiocarbon age, or years before sampling ( $t$ ). The data was then fit with Equation (3) to derive long-term estimates for  $I$  &  $k$ , while turnover times were obtained from taking the inverse of these  $k$  values (Trumbore and Harden, 1997; Harden et al., 1997, O'Donnell et al., 2011). As a result of the alteration of  $\Delta^{14}\text{C}$ -CO<sub>2</sub> levels from above-ground nuclear weapons tests throughout the 1950's and 1960's, some samples revealed a  $\Delta^{14}\text{C}$  value above 0, and are approximated as "modern" (Rethemeyer et al., 2005). For the purpose of long term C turnover derivation, modern samples were arbitrarily

assigned an age of 0 years BP. This estimation is a source of uncertainty in the calculations, and is coupled with relatively coarse stratigraphic resolution (5cm), as limiting factors in the accuracy of  $I$  &  $k$  estimates.

## **Results**

### *2.1 - SOC, TN, Bulk Density vs. Profile Depth*

SOC stock generally decreases with an increase in depth in the soil profile, a trend that is consistent across the observed climatic and geomorphic gradients (Figure 2). The obvious exception to this trend occurs at sample site 5, which revealed extremely low SOC stock in the O and A horizons. This anomaly can possibly be attributed to soil composition, as the substrate was primarily sand and gravel with a high bulk density ( $< 1\text{g/cm}^3$ ). Due to the site's proximity to the Bhaga River it is possible 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. The TN stock of the measured samples largely follows the noticeable SOC patterns (Figure 3), with a consistent SOM C:N ratio of ~10:1.

The computed bulk density (BD) of the samples maintains an expected distribution at depth (Figure 4). Profiles at  $< 25$  cm maintain an undulating appearance where  $\rho$  is lowest in the O horizon as a result of the contribution of low-density materials such as surface plants, leaf litter, and/or humus. Bulk density of the samples decreases at greater depths, with a marked drop after the maximum effective root depth, where organic matter is much less prevalent. There is no discernible relationship between BD and topography/parent material.

## 2.2 - $\delta^{13}\text{C}$ & $\Delta^{14}\text{C}$ vs. Profile Depth

The  $\delta^{13}\text{C}$  values of SOM consistently ranged from -20 to -28‰ across all sample sites and depths (Table 2), consistent with dominant C3 vegetation at all of the study sites.  $\delta^{13}\text{C}$  is increasingly enriched in subsurface horizons (Figure 5A).  $^{14}\text{C}$  ages are approximately modern in surface soils, and become progressively older with depth, as expected (Figure 5B).  $^{13}\text{C}$  measurements of SOM could not be employed for C turnover time calculation due to the apparent consistency in vegetation through time. Variation of  $^{14}\text{C}$  and  $^{13}\text{C}$ , with older soils exhibiting more enriched  $^{13}\text{C}$  values, is perhaps indicative of prolonged degradation (Figure 5C). Surface soils were dominated by bomb-enriched radiocarbon, while older horizons became progressively less  $^{14}\text{C}$  –enriched with increases in profile depth, with the exception of site 5, which yet again, represents a reversed or buried soil stratigraphy (Figure 6).

## 2.3 - Elevation

The overall relationship between SOC stock and elevation is seemingly more complex, as the greatest SOC stocks were noticed at median elevations (~3,000 to 3,800 m) with the exception of site 5. Comparatively, lower elevations (1,900 to 2,500 m) have less SOC. The highest elevations (above 4,000 m) reveal the lowest SOC stocks. SOC stock in the top 15 cm across all sample sites showed no significant trend with elevation ( $r^2 = 0.1092$ ; Figure 7A). The total nitrogen (TN) largely follows the noticeable SOC stock patterns, showing no correlation with elevation ( $r^2 = 0.1167$ ; Figure 7B), while TN stock is consistently smaller than SOC stock by an order of magnitude. Finally, a significant relationship was not established for elevation versus SOM  $\delta^{13}\text{C}$  ( $r^2 = 0.0472$ ; Figure 7C) or  $\Delta^{14}\text{C}$  ( $r^2 = 0.0099$ ; Figure 7D).

## 2.4 - Annual Precipitation



SOC stock was positively correlated with annual precipitation ( $r^2 = 0.6877$ ,  $p < 0.04$ ; Figure 8A), as was TN ( $r^2 = 0.6362$ ,  $p < 0.04$ ; Figure 8B), supporting the notion of a North-South SOC gradient correspondingly generally with topographic-controlled precipitation barriers. SOM  $\delta^{13}\text{C}$  and  $\Delta^{14}\text{C}$  values were not strongly correlated with annual precipitation (Figure 8C, D).

### 2.5 - C accumulation / Turnover

The results for C accumulation and turnover was heavily varied throughout the sites in question (Table 3; Figure 9). There was no discernable trend recognized between C turnover time and precipitation/elevation. The highest average annual accumulation rates were retrieved for sites 4, 6, and 8 ( $0.0159 \pm 1.64 \times 10^{-6} \text{ kg C m}^{-2} \text{ yr}^{-1}$ ,  $0.0282 \pm 3.56 \times 10^{-9} \text{ kg C m}^{-2} \text{ yr}^{-1}$ , and  $0.0332 \pm 1.37 \times 10^{-5} \text{ kg C m}^{-2} \text{ yr}^{-1}$ , respectively). Conversely, sites 3 and 7 had comparatively lower C accumulation rates ( $0.0046 \pm 8.62 \times 10^{-5} \text{ kg C m}^{-2} \text{ yr}^{-1}$ ,  $0.0019 \pm 6.70 \times 10^{-6} \text{ kg C m}^{-2} \text{ yr}^{-1}$ ). Turnover times were somewhat short for sites 6 and 8 (~222 years and ~63 years, respectively), longer in sites 3 and 4 in the south (~714 years, ~500 years), and extremely long for site 7 atop the Baralacha La (~3,333 years). Average annual C accumulation and turnover was 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 Equation (3) could not be adequately fit to the unusual vertical distribution of SOC and associated radiocarbon ages.

## Discussion

We have shown that SOC stocks in the Indian Himalaya are most sensitive to precipitation as opposed to other physical factors (altitude/temperature). This has profound implications for the future, as increasing precipitation in arid regions may increase SOC sequestration due to increasing precipitation growth. On the other hand, soils in the Himalayas

are also made more vulnerable to erosion in an increased precipitation scenario, such as that observed in the 2000 (Krishnan et al., 2003) and 2002 (Bookhagen et al., 2005) abnormal monsoon years (AMY), and recent anomalously heavy rain events in 2010 (Lau et al., 2012).

### *3.1 - SOC stock – comparison to other areas in India & Indian Himalaya*

SOC stocks for the areas investigated were normalized to a depth of 15cm for the purpose of comparison with previously published data for other localities in India. Areas that revealed the highest average SOC stocks proved somewhat surprising: sites 1, 4, and 6 had the highest SOC inventories with  $6.6 \text{ kg C m}^{-2}$ ,  $5.3 \text{ kg C m}^{-2}$ , and  $4.8 \text{ kg C m}^{-2}$ , respectively. The geographic distribution of these sites might imply that SOC inventory is not uniformly limited by annual precipitation and elevation. Instead, these sites may represent ideal conditions of temperature and precipitation to sequester C in soils. Sites 2, 3, and 7 showed median SOC inventories of  $4.4 \text{ kg C m}^{-2}$ ,  $2.6 \text{ kg C m}^{-2}$ , and  $3.6 \text{ kg C m}^{-2}$ , respectively. Finally, the lowest SOC stocks were observed in sites 5, 8, and 9. The measurements obtained for sites 8 and 9 in the Zaskar range were expected, as the small amount of annual precipitation (regime 4) coupled with sparse vegetation in Zaskar inhibits SOC stocks greatly.

A study involving SOC stock was conducted in Rajasthan, India where, like Zaskar, erosion, periodic drought, low productivity, and dwindling water resources have limited the amount of SOC in arid and semiarid soils (Singh et al., 2007). Regional estimations of SOC stock were reported as  $\sim 1230.7 \text{ Tg}$  for the state of Rajasthan, which is possibly the closest approximation for regional SOC stock for the Manali-Leh highway. Previously only one study has evaluated SOC stock and its relation to climate in the western Himalaya (Himachal Pradesh). Singh et al., 2011 reported SOC stock results for sub-tropical forests ( $6.2 \text{ kg C m}^{-2}$  from 0-30cm), horticulture/agriculture land use types ( $3.3 \text{ kg C m}^{-2}$  and  $2.7 \text{ kg C m}^{-2}$  from 0-30cm),

temperate (10.4 kg C m<sup>-2</sup> for 0-30cm), lower alpine (10.0-10.9 kg C m<sup>-2</sup> for 0-30cm), and upper alpine forests (7.9 kg C m<sup>-2</sup> for 0-30cm); results that corroborate well with our presented data for the Lesser and Greater Himalaya.

Records for SOC inventory and dynamics are better constrained for other areas in the Himalayan range and elsewhere in the Indian subcontinent. Sheik et al., 2009 established SOC stock for differing forest types in the Gahrwal Himalaya to the southeast. The largest SOC stock was noticed for *Quercus leucotrichopohra* forest soils, ranging from 160.8 t C ha<sup>-1</sup> (~14.58 kg C m<sup>-2</sup>) to 185.6 t C ha<sup>-1</sup> (~16.84 kg C m<sup>-2</sup>), while *Pinus roxburghii* forest soils ranged from 124.8 t C ha<sup>-1</sup> (~11.32 kg C m<sup>-2</sup>) to 141.6 t C ha<sup>-1</sup> (~12.85 kg C m<sup>-2</sup>). Such values are significantly higher than those reported for the Manali-Leh highway, as even the site with the highest SOC in the Kulu Lesser Himalaya (site 1) was lower by a discrepancy of ~8 t C ha<sup>-1</sup>. Furthermore, Martin et al., 2010 evaluated SOC storage for differing physiographic units in Gahrwal, noting large variation in SOC (2.3-34.5 kg C m<sup>-2</sup>) from 0-15cm between hilltops/ slopes, valleys, and piedmont plains. Chhabra et al., 2003 compiled a database of published SOC measurements across a suite of Indian forest ecosystems using estimated mean SOC densities and forest area derived from satellite data, reporting 37.5 t C ha<sup>-1</sup> (~3.40 kg C m<sup>-2</sup>) in tropical dry deciduous forests, 92.1 t C ha<sup>-1</sup> (~8.36 kg C m<sup>-2</sup>) in littoral/swamp forests from 0-50cm depth. In addition, estimates for tropical dry deciduous forests (69.9 t C ha<sup>-1</sup>, or ~6.34 kg C m<sup>-2</sup>) and Montane temperate forests (161.9 t C ha<sup>-1</sup>, or ~14.69 kg C m<sup>-2</sup>) were calculated for 1 m soil depth (Chhabra et al., 2003).

### 3.2 - <sup>13</sup>C and <sup>14</sup>C patterns

The selected samples showed no evidence for C4 plants along the transect of interest, however, it is important to note that the composition of these ecosystems may change with

continued warming.  $^{13}\text{C}$  measurements of SOM could not be employed for C turnover time calculation as a result of the apparent consistency in vegetation through time. Surface soils were dominated by bomb-enriched radiocarbon, while older horizons became progressively less  $^{14}\text{C}$  – enriched with corresponding increases in profile depth.

### *3.3 - SOC stock – comparison to tundra and desert soils*

On the basis of precipitation and strong seasonality, soils of interest in this study (specifically sites 4, 6, and 7) can be considered 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 increase SOM decomposition through climate change, primarily a positive shift in temperature. (White et al., 2004), which could increase bacterial growth rate (Rinnan et al., 2007) and change species composition and plant productivity (Jonasson et al., 1999).

Data retrieved for SOC storage in the Arctic region has shown very high C concentration in the active layer. Ping et al., 2008 reported an average value of  $21.7 \text{ kg C m}^{-2}$  in the active layer representing a wide range of SOC stock values. SOC storage from 0-15cm for sites 4, 6, and 7 fall within this range, and have C turnover times on the scale of centuries. Sites 4 and 6 have relatively large accumulation rates possibly suggesting extended periods of net primary production exceeding respiration for long durations. Conversely, site 7 has the lowest calculated C accumulation rate, but has a corresponding turnover time of greater than 3,000 years. The Baralacha La pass is of unique interest from these findings, as the C flux did not heavily 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.

Sites 8 and 9 in the Zaskar range are seemingly 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. Average SOC stock has been measured in other semiarid regions; Kunkel et al., 2011 report an average value of  $2.1 \text{ kg C m}^{-2}$  for 0-30 cm in a mountainous watershed in Idaho; Mills and Cowling, 2010 reported stocks ranging from  $18 \text{ t C ha}^{-1}$  ( $\sim 1.63 \text{ kg C m}^{-2}$ ) to  $52 \text{ t C ha}^{-1}$  ( $\sim 4.72 \text{ kg C m}^{-2}$ ) in the top 25cm in subtropical thickets in semiarid South Africa. Values obtained for SOC stock for sites 8 and 9 are consistent with these published values; site 8 defined as having  $1.8 \text{ kg C m}^{-2}$  and site 9 was extremely low at  $0.9 \text{ kg C m}^{-2}$ . Meanwhile, the derived C accumulation rate for site 8 was unexpectedly high ( $0.0332 \pm 1.37 \times 10^{-5} \text{ kg C m}^{-2} \text{ yr}^{-1}$ ) and the C turnover time for the selected soil profile was also the shortest ( $\sim 63$  years), possibly suggesting that soil respiration has not been the dominant mechanism for C-removal in the past. Soil respiration is generally limited by water availability, potentially suggesting that a recent increase in rainfall has already affected the Puga valley. Furthermore, the approximately modern ages retrieved for the first 15cm of sample site 8 could be explained by enhanced illuviation, where organics have been displaced in the soil profile through the action of percolating rainwater.

### *3.4 - 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 10cm of site 5 seem to be a function of parent material, closely resembling ages of  $\sim 6\text{k BP}$  (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 found to be modern in age. 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 component of anthropogenic climatic change effects on the C/N budget 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. 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).

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 semiarid 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).

Monsoon rainfall is a primary mechanism through which flooding is driven 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). Through the onset of the ‘global warming period’ the activity of the south Asian monsoon has been shown to increase in low and extreme rainfall events in south peninsular India (Naidu et al., 2012), a trend that could dramatically impact SOC dynamics on a regional scale.

The complex interaction between SOC storage and climate in northern India could propagate 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). The increase in respired CO<sub>2</sub> from the global soil pool would increase the concentration of CO<sub>2</sub> in the atmosphere, effectively warming climate even further.

## **Conclusions**

Regional organic carbon and nitrogen abundance and dynamics in northern India were evaluated along altitudinal and climatic gradients (Figure 10). The investigated portion of the Manali-Leh highway exhibits a decrease in SOC and TN stock from higher to lower precipitation regimes, identifying annual precipitation as a significant control on C/N storage. Using radiocarbon methods and modeling techniques, average annual C accumulation and turnover times were derived for selected soil chronosequences, and showed significant variability across orographic barriers. A number of high-altitude study sites exhibit an analogous relationship with tundra soils due to their history of C sequestration and lengthy turnover times. Vulnerability of the transect as a terrestrial C pool is evident; a change in global temperature and

the number of abnormal monsoon years could enhance processes of soil respiration and erosion, implicating a transition from a net sink to source.



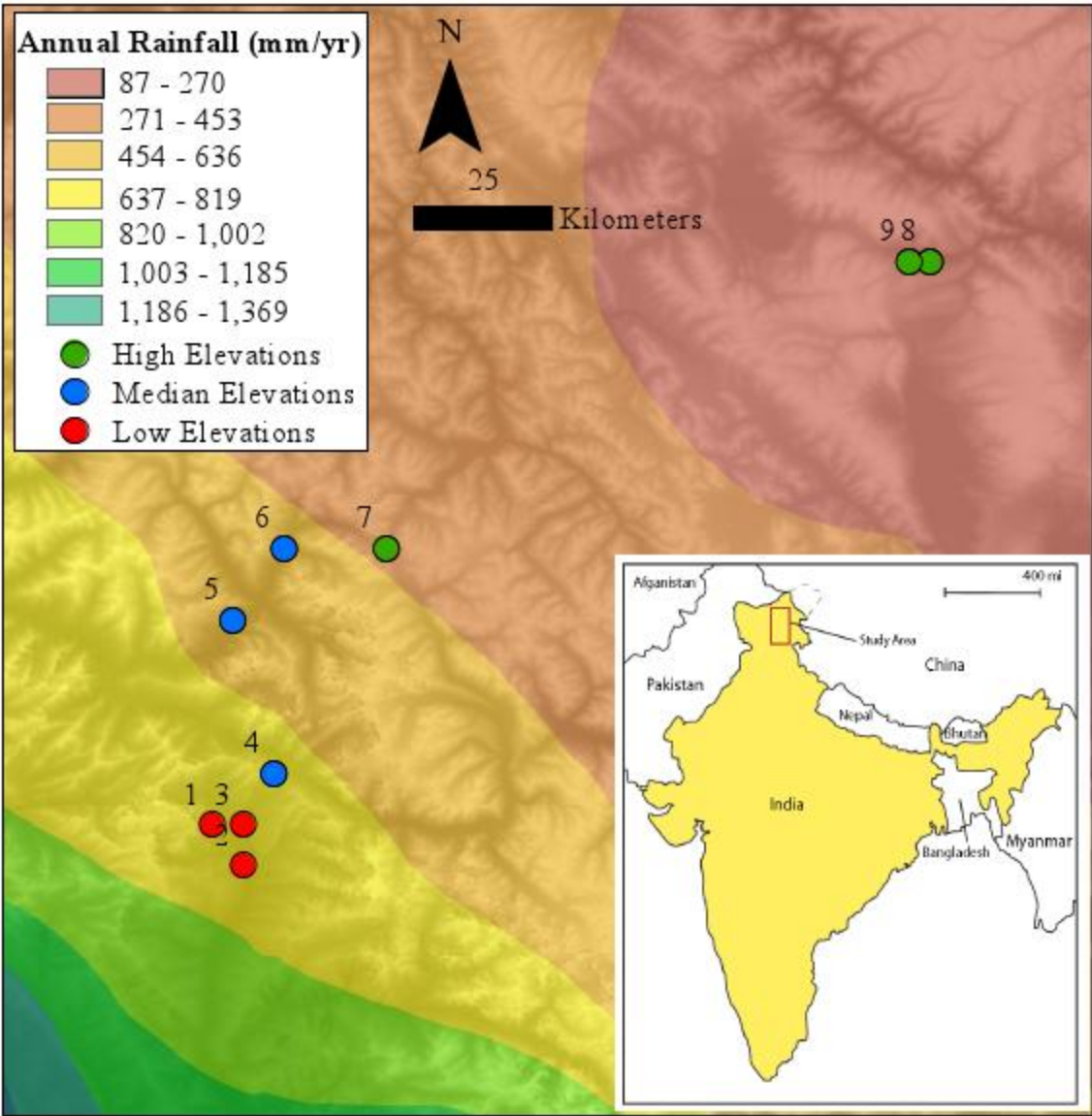


Figure 1 – Geographic distribution of sample sites overlain by NASA TRMM satellite precipitation data (in mm/yr) for years 1998-2011.

| Site No. | Latitude   | Longitude   | Elevation (m) | Rainfall (mm/yr) | Slope (degrees) | Description        |
|----------|------------|-------------|---------------|------------------|-----------------|--------------------|
| 1        | 32°18.975' | 077°08.705' | 2940          | 636.0 - 819.0    | 23              | Solang Valley      |
| 2        | 32°14.303' | 077°11.332' | 1891          | 636.0 - 819.0    | 16              | Manali             |
| 3        | 32°18.988' | 077°1.459'  | 2543          | 636.0 - 819.0    | 24              | S. of Rohtang Pass |
| 4        | 32°23.173' | 077°94.724' | 3460          | 636.0 - 819.0    | 35              | N. of Rohtang La   |
| 5        | 32°38.299' | 077°10.951' | 3285          | 453.0 - 636.0    | 47              | Jispa, Lahul       |
| 6        | 32°45.414' | 077°15.323' | 3810          | 453.0 - 636.0    | 33              | Patseo             |
| 7        | 32°45.284' | 077°25.326' | 4885          | 270.0 - 453.0    | 7               | Baralacha La       |
| 8        | 33°13.338' | 078°18.921' | 4424          | 87.0 - 270.0     | 17              | Puga Valley        |
| 9        | 32°57.408' | 078°16.018  | 4553          | 87.0 - 270.0     | 17              | Tso Moriri         |

Table 1: Site numbers, latitude/longitude, elevation, rainfall regime, slope, and descriptions of sample sites in this study.

| Sample ID    | $^{13}\text{C } \delta$ | $\pm$ | Fraction Modern | $\pm$  | $\Delta^{14}\text{C}$ | $\pm$ | $^{14}\text{C}$ age (BP) | $\pm$ |
|--------------|-------------------------|-------|-----------------|--------|-----------------------|-------|--------------------------|-------|
| India3C-5    | -23.3                   | 0.15  | 1.0107          | 0.0013 | 3.1                   | 1.3   | >Modern                  |       |
| India3C-10   | -22.5                   | 0.15  | 0.9440          | 0.0017 | -63.0                 | 1.7   | 465                      | 15    |
| India3C-15   | -22.8                   | 0.15  | 0.8110          | 0.0014 | -195.1                | 1.4   | 1685                     | 15    |
| India3C-20   | -21.2                   | 0.15  | 0.7298          | 0.0013 | -275.7                | 1.3   | 2530                     | 15    |
| India3C-24.4 | -22.0                   | 0.15  | 0.6421          | 0.0015 | -362.7                | 1.5   | 3560                     | 20    |
| India4B-5    | -25.7                   | 0.15  | 1.0344          | 0.0023 | 26.7                  | 2.3   | >Modern                  |       |
| India4B-10   | -24.1                   | 0.15  | 0.8854          | 0.0015 | -121.2                | 1.5   | 980                      | 15    |
| India4B-15   | -24.3                   | 0.15  | 0.9241          | 0.0016 | -82.8                 | 1.6   | 635                      | 15    |
| India4B-17   | -24.0                   | 0.15  | 0.9050          | 0.0017 | -101.7                | 1.7   | 800                      | 15    |
| India5B-5    | -26.4                   | 0.15  | 0.4723          | 0.0010 | -531.2                | 1.0   | 6025                     | 20    |
| India5B-10   | -27.2                   | 0.15  | 0.5379          | 0.0009 | -466.2                | 0.9   | 4980                     | 15    |
| India5B-15   | -27.9                   | 0.15  | 0.9936          | 0.0019 | -13.9                 | 1.9   | 50                       | 20    |
| India5B-20   | -28.1                   | 0.15  | 0.8905          | 0.0016 | -116.1                | 1.6   | 930                      | 15    |
| India5B-25   | -24.7                   | 0.15  | 1.1486          | 0.0025 | 140.0                 | 2.5   | >Modern                  |       |
| India5B-30   | -27.2                   | 0.15  | 1.0187          | 0.0021 | 11.1                  | 2.1   | >Modern                  |       |
| India5B-34.8 | -27.2                   | 0.15  | 0.6897          | 0.0013 | -315.5                | 1.3   | 2985                     | 20    |
| India6F-5    | -24.5                   | 0.15  | 1.1299          | 0.0021 | 121.4                 | 2.1   | >Modern                  |       |
| India6F-10   | -23.0                   | 0.15  | 0.9691          | 0.0020 | -38.1                 | 2.0   | 250                      | 20    |
| India6F-14.4 | -25.0                   | 0.15  | 0.9085          | 0.0020 | -98.3                 | 2.0   | 770                      | 20    |
| India7C-5    | -21.3                   | 0.15  | 1.0054          | 0.0020 | -2.1                  | 2.0   | >Modern                  |       |
| India7C-10   | -22.7                   | 0.15  | 0.7567          | 0.0016 | -248.9                | 1.6   | 2240                     | 20    |
| India7C-15   | -22.5                   | 0.15  | 0.5571          | 0.0012 | -447.0                | 1.2   | 4700                     | 20    |
| India7C-20   | -22.3                   | 0.15  | 0.6444          | 0.0013 | -360.4                | 1.3   | 3530                     | 20    |
| India7C-25   | -21.9                   | 0.15  | 0.6293          | 0.0013 | -375.4                | 1.3   | 3720                     | 20    |
| India7C-30   | -21.1                   | 0.15  | 0.4699          | 0.0010 | -533.6                | 1.0   | 6065                     | 20    |
| India7C-34.1 | -21.0                   | 0.15  | 0.4727          | 0.0011 | -530.8                | 1.1   | 6020                     | 20    |
| India8C-5    | -25.5                   | 0.15  | 1.0842          | 0.0023 | 76.1                  | 2.3   | >Modern                  |       |
| India8C-10   | -24.9                   | 0.15  | 1.1196          | 0.0021 | 111.3                 | 2.1   | >Modern                  |       |
| India8C-15   | -24.9                   | 0.15  | 1.1002          | 0.0020 | 92.0                  | 2.0   | >Modern                  |       |
| India8C-20   | -24.2                   | 0.15  | 0.9736          | 0.0022 | -33.6                 | 2.2   | 215                      | 20    |
| India8C-22.5 | -24.2                   | 0.15  | 0.8243          | 0.0015 | -181.9                | 1.5   | 1550                     | 15    |

Table 2: Carbon isotope data for selected samples.

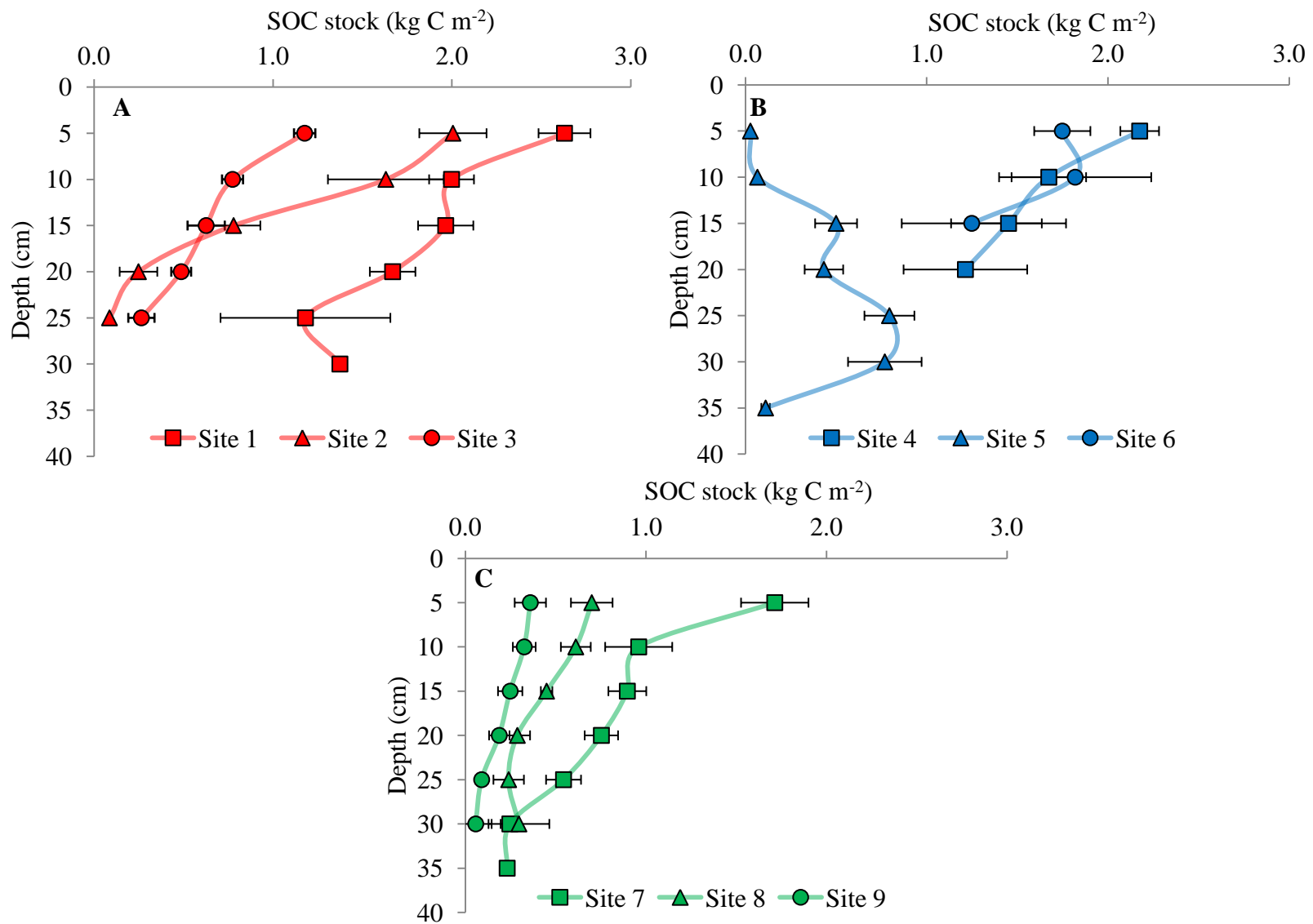


Figure 2: SOC stock ( $\text{kg C m}^{-2}$ ) at depth for all sample sites. Plots are grouped by elevation: (a) 1,900 – 2,500m (b) 3,000 – 3,800m and (c) 4,000m and above.

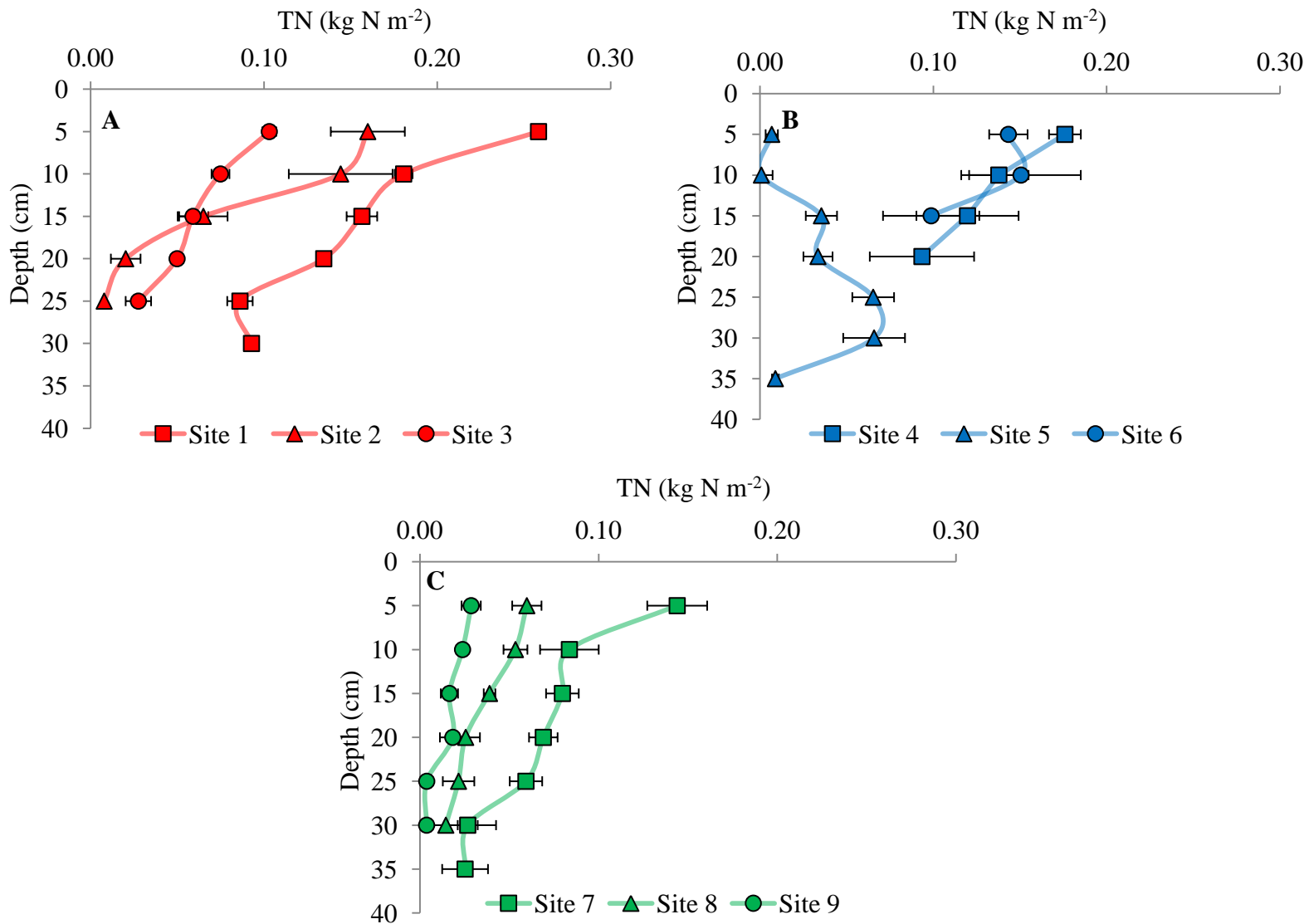


Figure 3: TN (kg N m<sup>-2</sup>) at depth for all sample sites. Plots are grouped by elevation: (a) 1,900 – 2,500m (b) 3,000 – 3,800m and (c) 4,000m and above.

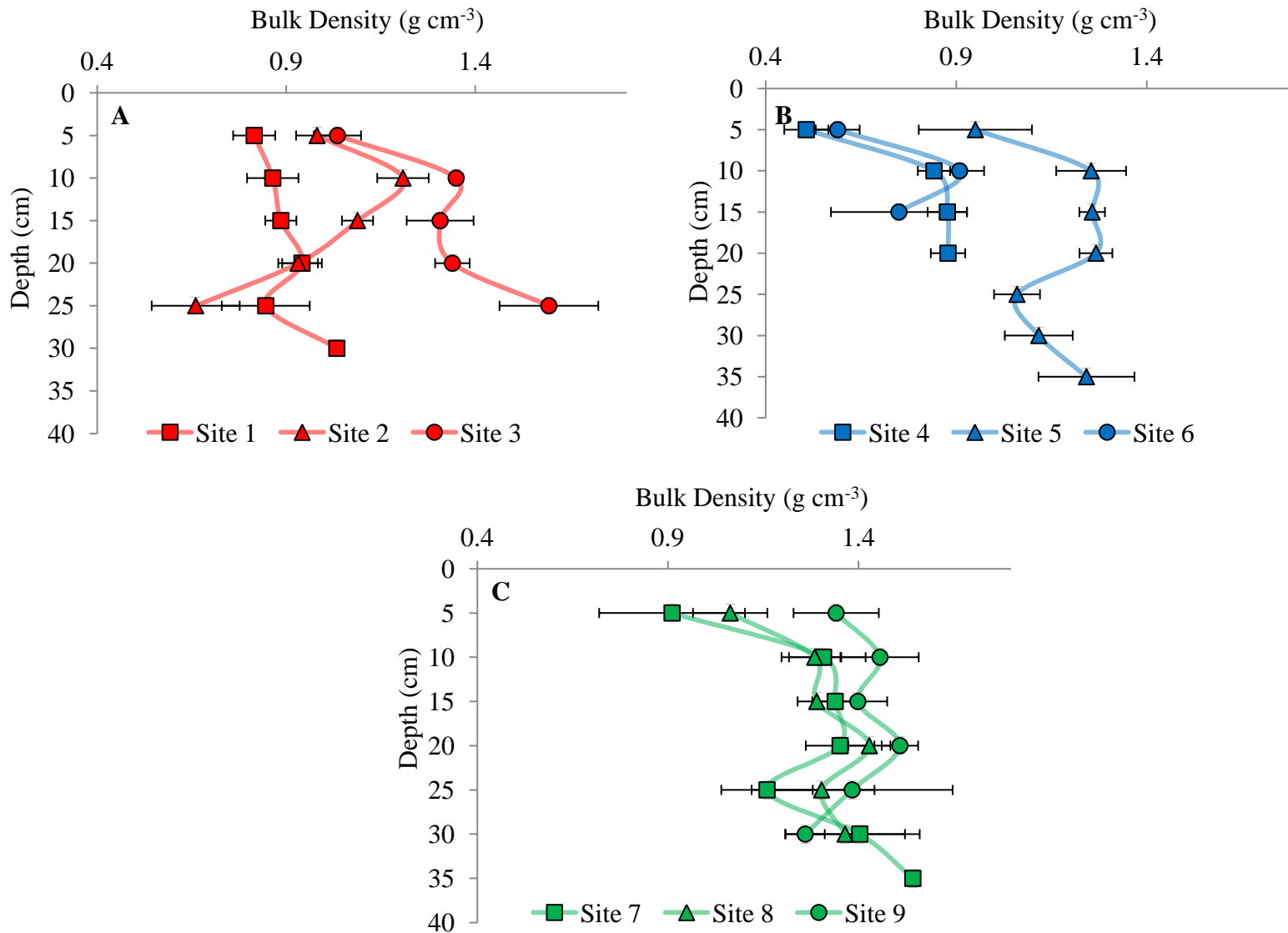


Figure 4: Bulk density (g cm<sup>-3</sup>) at depth for all sample sites. Plots are grouped by elevation: (a) 1,900 – 2,500m (b) 3,000 – 3,800m and (c) 4,000m and above.

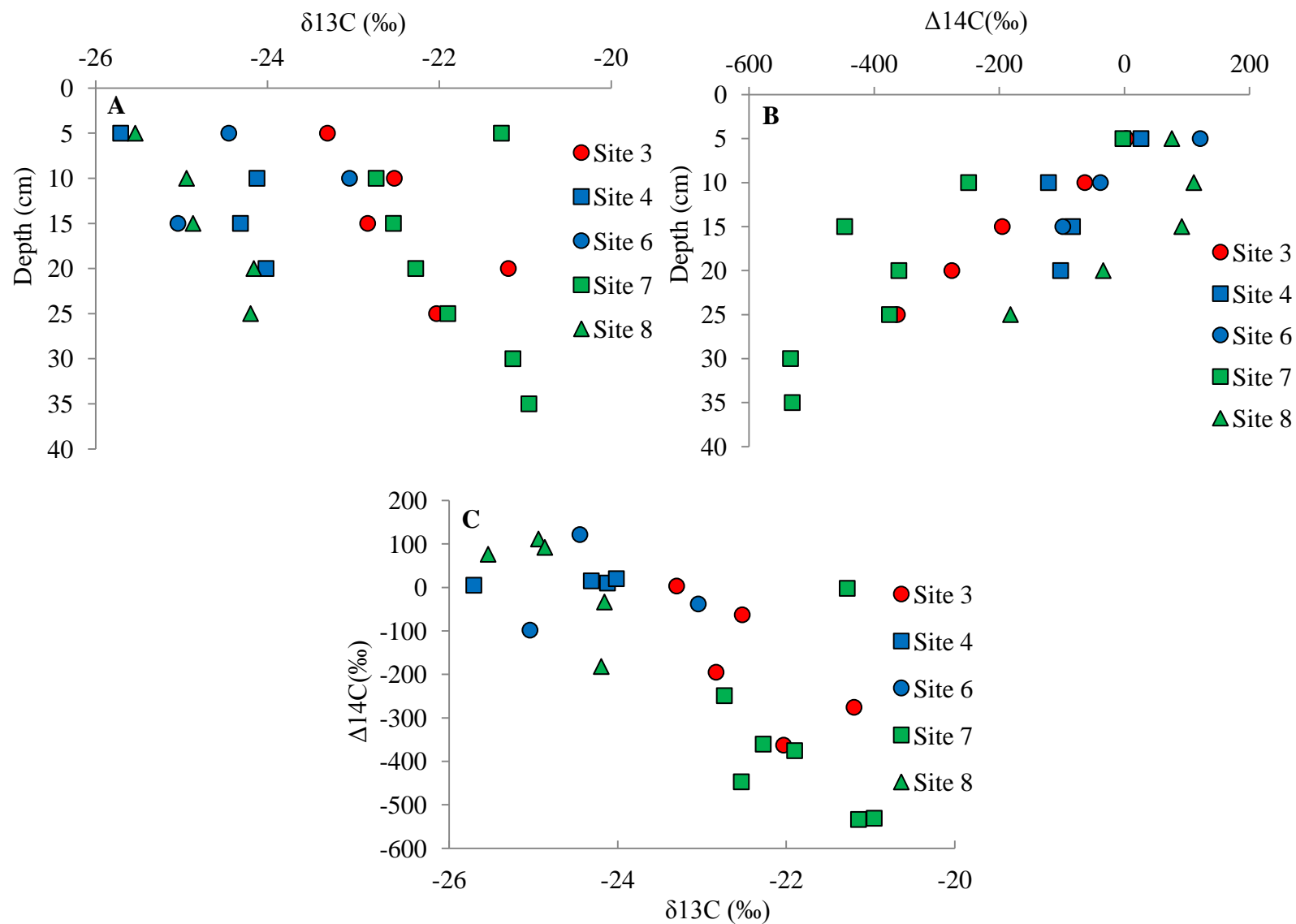


Figure 5: (a) Stable isotopic composition of SOM for selected samples versus depth; (b) Radiocarbon content of SOM versus depth; (c)  $\delta^{13}\text{C}$  of SOM presented versus radiocarbon content ( $\Delta^{14}\text{C}$ ) of the same samples.

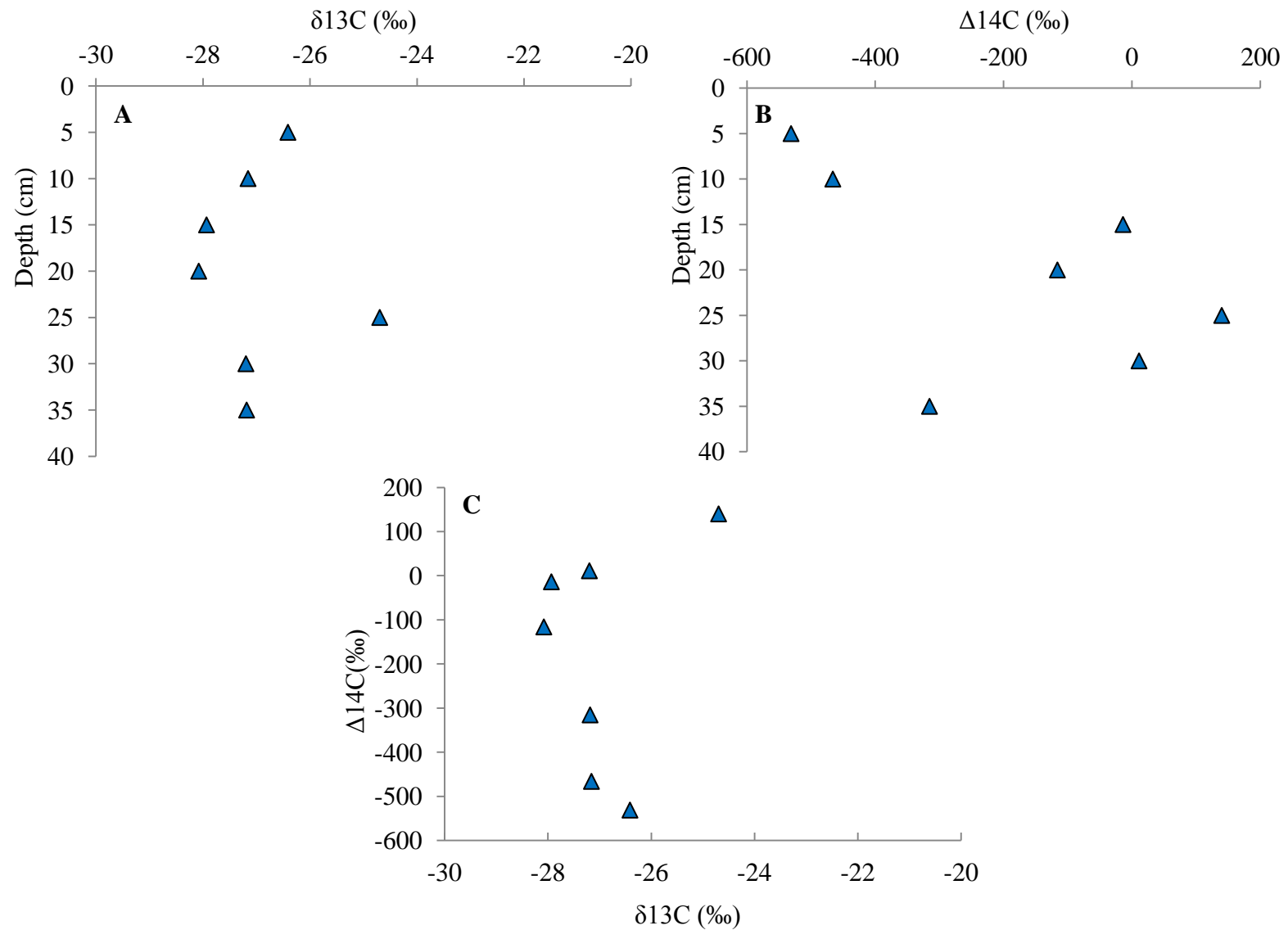


Figure 6: (a) Stable isotopic composition of SOM for samples site 5 versus depth; (b) Radiocarbon content of SOM of site 5 versus depth; (c)  $\delta^{13}\text{C}$  of SOM presented versus radiocarbon content ( $\Delta^{14}\text{C}$ ) for site 5.



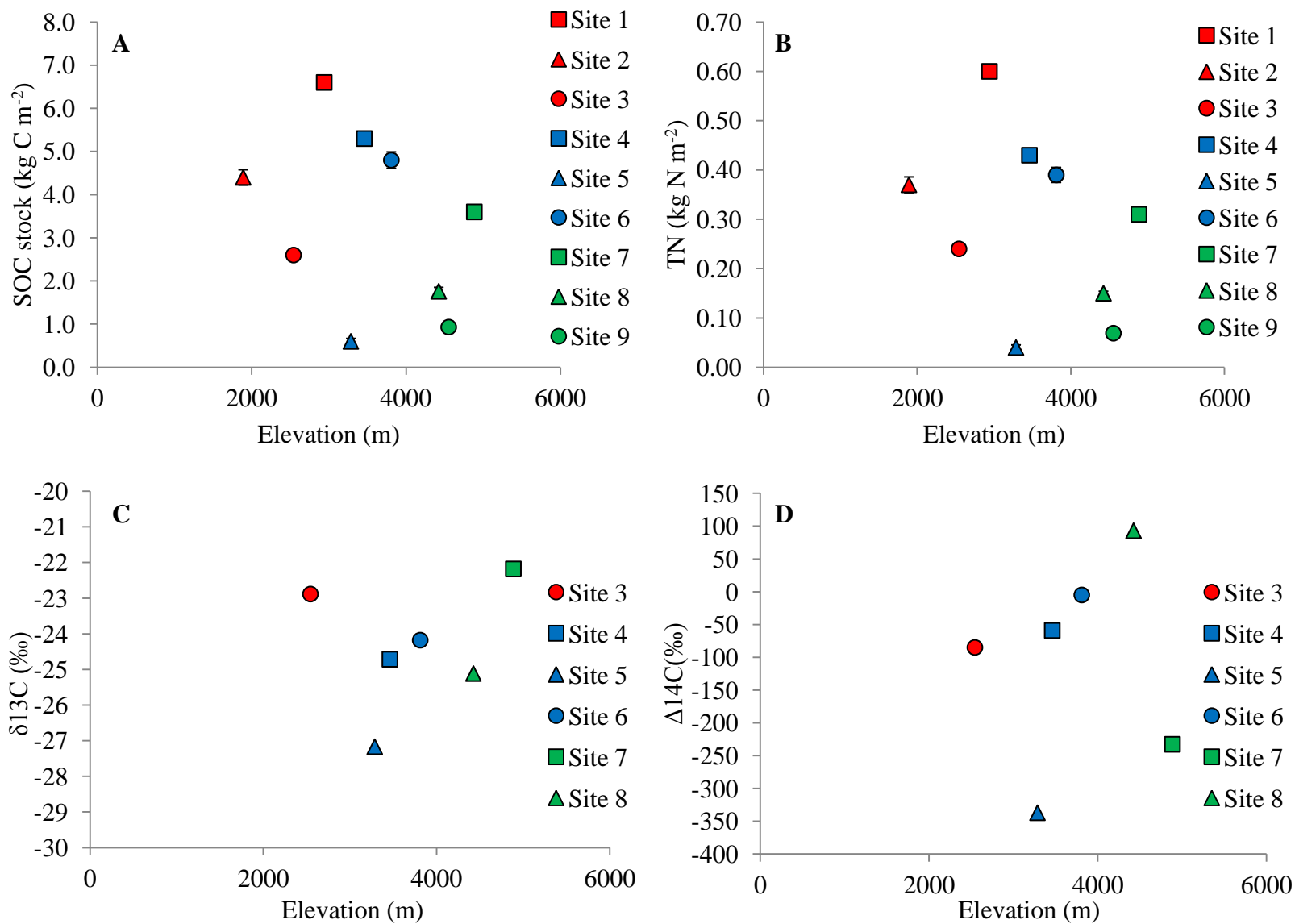


Figure 7: (a) Average SOC stock versus elevation for all sites; (b) Average TN versus elevation for all sites; (c) Average  $\delta^{13}\text{C}$  versus elevation for selected sites; (d) Average  $\Delta^{14}\text{C}$  versus elevation for selected sites. All values are normalized to a depth of 15cm.

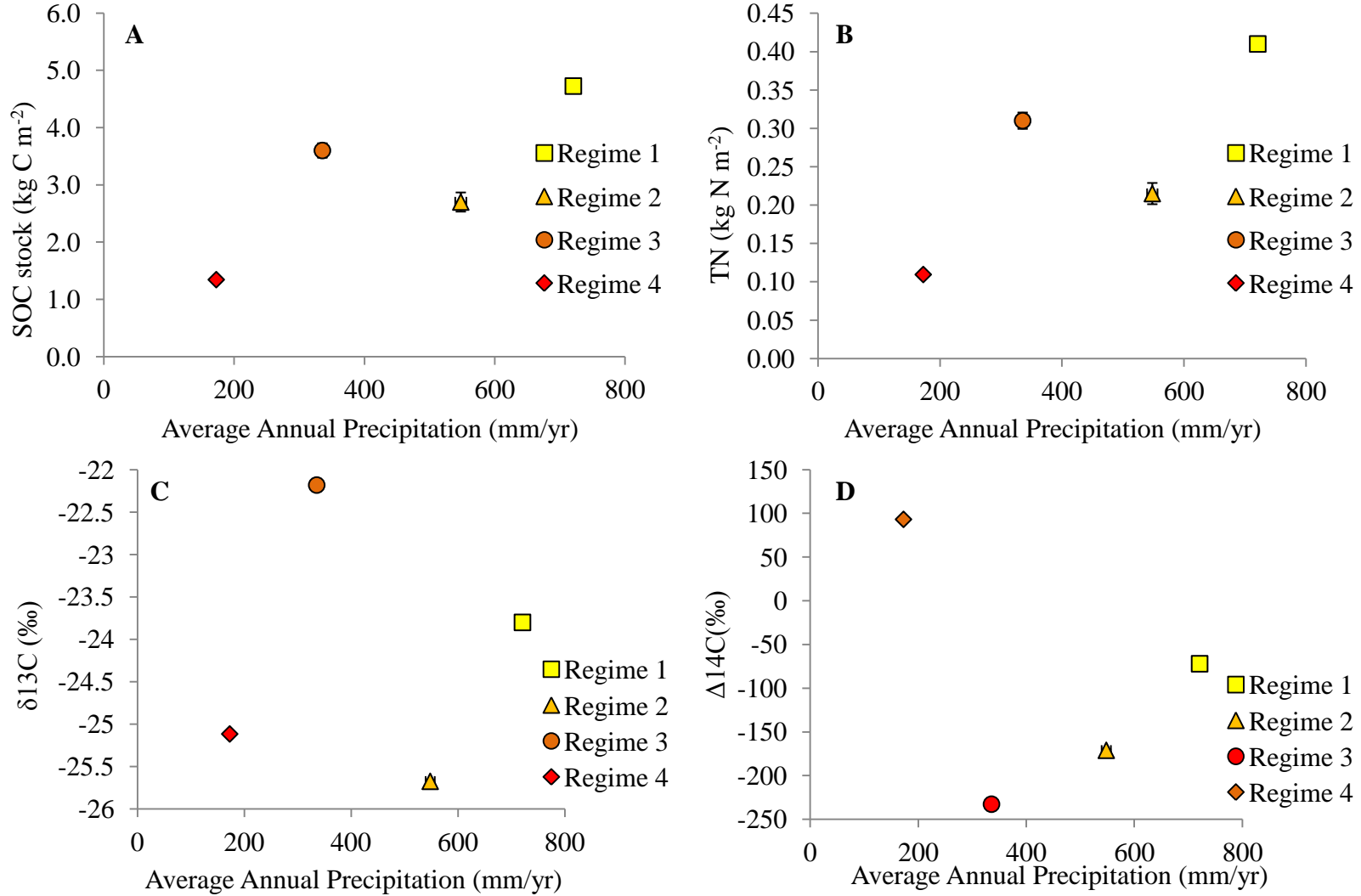


Figure 8: (a) Average SOC stock versus annual precipitation; (b) Average TN versus annual precipitation for all sites; (c) Average  $\delta^{13}\text{C}$  versus annual precipitation for selected sites; (d) Average  $\Delta^{14}\text{C}$  versus annual precipitation for selected sites. All values are normalized to a depth of 15cm.

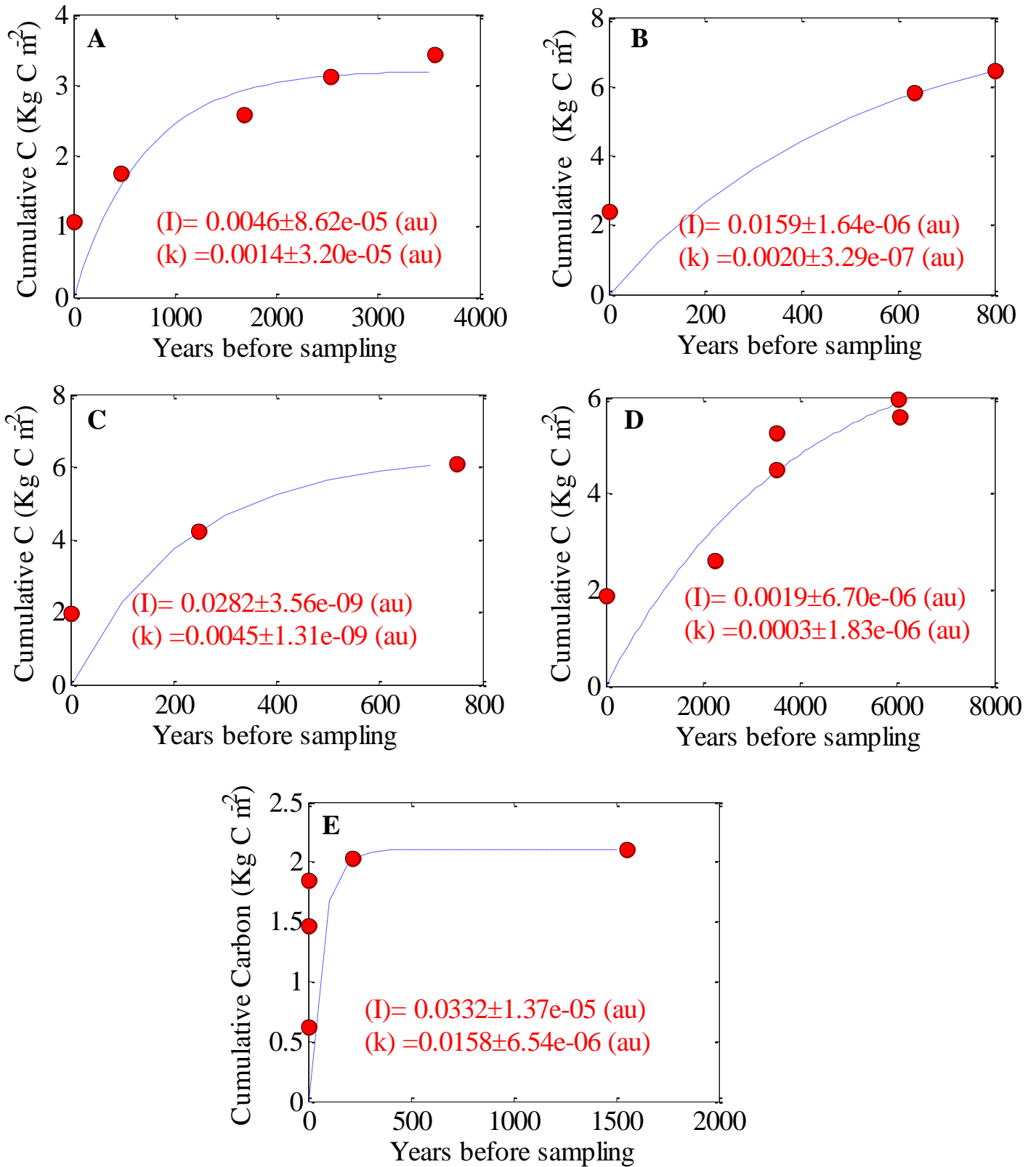


Figure 9: Derivation of C accumulation rates ( $I$ ), and decomposition rate constants ( $k$ ), using equation (3) fit to a plot of cumulative C inventory versus years before sampling (radiocarbon age, B.P.). (a) Curve fit for site 3; (b) curve fit for site 4; (c) curve fit for site 6; (d) curve fit for site 7; (e) curve fit for site 8.

| Site No. | SOC stock (kg C m <sup>-2</sup> ) | TN (kg Nm <sup>-2</sup> ) | I (kg C m <sup>-2</sup> yr <sup>-1</sup> ) | k (yr <sup>-1</sup> ) | C Turnover time (yr) |
|----------|-----------------------------------|---------------------------|--|-----------------------|----------------------|
| 1        | 6.6                               | 0.60                      | ND   | ND                    | ND                   |
| 2        | 4.4                               | 0.37                      | ND   | ND                    | ND                   |
| 3        | 2.6                               | 0.24                      | 0.0046± 8.62e-05                           | 0.0014±3.20e-05       | ~714                 |
| 4        | 5.3                               | 0.43                      | 0.0159±1.64e-06*                           | 0.0020±3.29e-07*      | ~500*                |
| 5        | 0.6                               | 0.04                      | ND   | ND                    | ND                   |
| 6        | 4.8                               | 0.39                      | 0.0282±3.56e-09                            | 0.0045±1.31e-09       | ~222                 |
| 7        | 3.6                               | 0.31                      | 0.0019±6.70e-06*                           | 0.0003±1.83e-06*      | ~3333*               |
| 8        | 1.8                               | 0.15                      | 0.0332±1.37e-05                            | 0.0158±6.54e-06       | ~63                  |
| 9        | 0.9                               | 0.07                      | ND   | ND                    | ND                   |

Table 3: SOC stock (Kg m<sup>-2</sup>), TN (Kg m<sup>-2</sup>), average annual C accumulation (kg C m<sup>-2</sup> yr<sup>-1</sup>), decomposition rate constant (yr<sup>-1</sup>), and C turnover time (yr) values for all nine sites listed by sample site. Values for SOC/TN stock represent an average of the top 15cm.

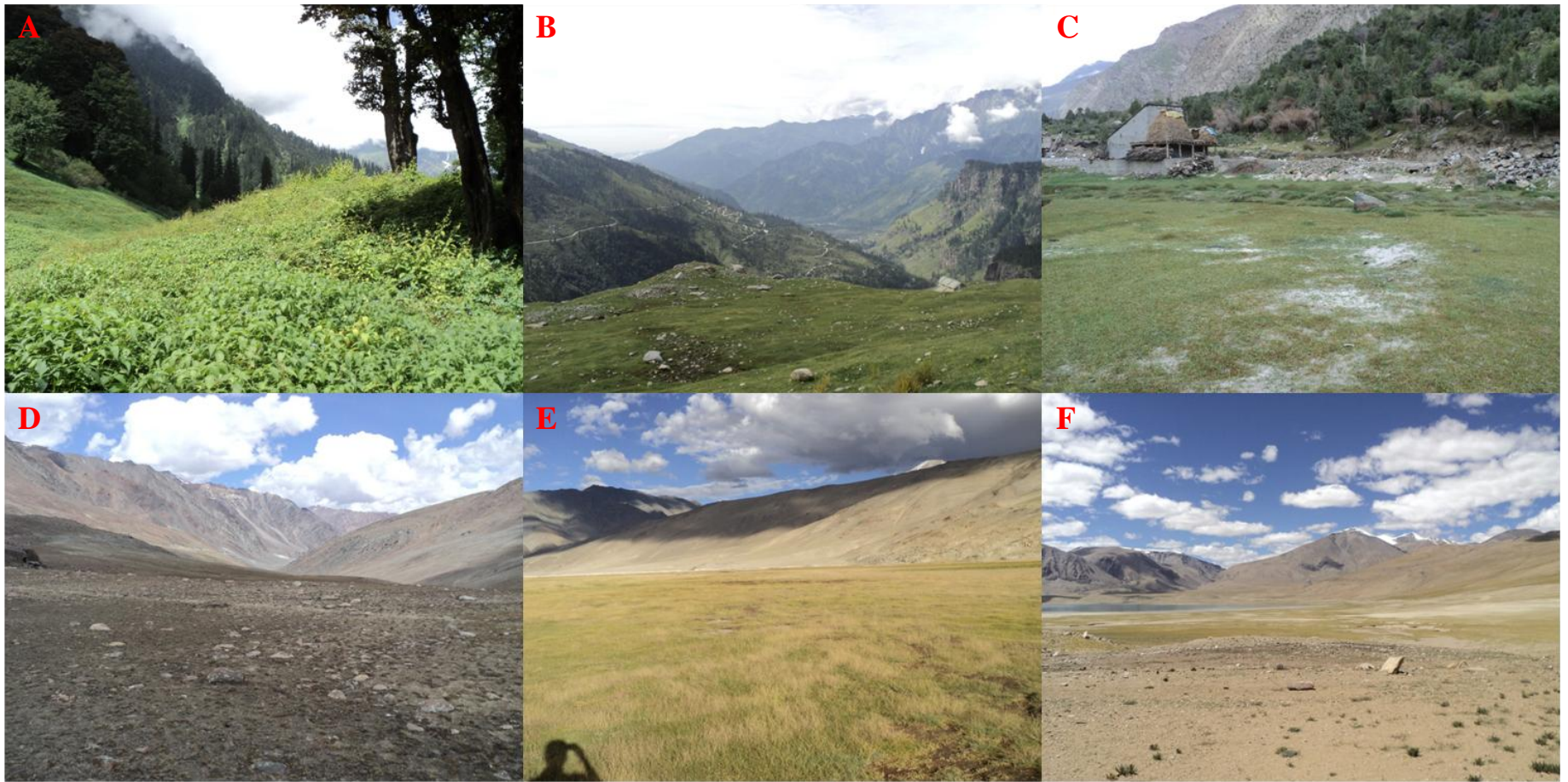


Figure 10: Field photographs illustrating diversity in ecosystem type along the observed N-S transect. (a) Site 1 - Solang Nala; (b) Site 3 - S. Rohtang Pass; (c) Site 5 - Jispa; (d) Site 7 - Baralacha La; (e) Site 8 - Puga Valley; (f) Site 9 - Tso Moriri.

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