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

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ABSTRACT

Soil organic carbon (SOC) affects soil fertility and agricultural production, and SOC storage can also mitigate increasing atmospheric CO_2 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 CO_2 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 $\Delta^{14}C$ and $\delta^{13}C$. 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.

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 CO_2 (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 CO_2 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

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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 ($\delta^{13}C \sim -25‰$) and C4 ($\delta^{13}C \sim -11‰$) 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 Δ^{14}C, δ^{13}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), Zanskar 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 Zanskar to the north. Finally, sites 8 and 9 were sampled in the Zanskar 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 Zanskar River primarily drains Zanskar to flow into the Indus River. Zanskar 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°1.459′	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