African Journal of Agricultural Research Vol. 7(47), pp. 6313-6319, 13 December , 2012
Available online at http://www.academicjournals.org/AJAR
DOI: 10.5897/AJAR12.1168
ISSN 1991-637X ©2012 Academic Journals

Full Length Research Paper

Altitudinal variations in soil carbon storage and distribution patterns in cold desert high altitude microclimate of India

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Accepted 16 October, 2012

A study was conducted to assess the soil carbon distribution in cold desert high altitude region of Ladakh in India at different altitudes and their correlation patterns with the altitude. The role of carbon dynamics in the exchange of CO_2 between the terrestrial biosphere and the atmosphere has important implications in this study of global climate change. The present study was done in Ladakh region of India from where soil samples were collected on the basis of different altitudes range and thereafter samples were analyzed for organic carbon and calcium carbonate content. Results of our study show that the soil organic carbon (SOC) content and storage increased significantly with the increase in the altitude where as when compared with the altitude of 10000 ft amsl, soil inorganic carbon (SIC content and its storage decreased significantly ($P < 0.05$) at an altitude of 11000 ft up to 12000 ft amsl. The SOC content and storage were observed positively ($P < 0.01$) correlated with altitude, while soil inorganic carbon storage and contents were negatively ($P < 0.05$) correlated with altitude. Hence, our study indicates that very harsh and unique climatic conditions in Ladakh influences storage and distribution pattern of soil carbon along the altitudes or elevation gradients. So investigations along altitude gradients is a useful approach to the study of environmental change and its effect on the soil processes, which can complement data obtained from controlled, large scale field studies as well as other practical and theoretical approaches to climate change research.

Key words: Cold desert, high altitude, carbon distribution pattern, altitudinal variation, soil carbon, micro-climate.

INTRODUCTION

Soil is the largest carbon reservoir pool of terrestrial ecosystem and plays a key role in the global carbon budget and greenhouse effect (Jha et al., 2003). It contains 3.5% of the earth's carbon reserve as compared with 1.7% in the atmosphere, 8.9% in fossil fuels, 1.0% in biota and 84.9% in the oceans (Lal et al., 1995). Soil reserve about 1550 gT of carbon as soil organic carbon (SOC) and 1700 gT as carbonate carbon (soil inorganic carbon, that is, SIC).

Soil carbon (C) balance plays an important role in exchange of CO_2 between atmosphere and biosphere. Hence, even a minor change in SOC storage could result in a significant alteration in atmospheric CO_2 concentration (Davidson and Janssens, 2006; Schipper et al., 2007). SOC and SIC are important as it determine ecosystem and agro ecosystem functions influencing soil fertility, water holding capacity and other soil characterristics. Therefore, the accurate estimation of SOC storage and its distribution is critical for predicting feedbacks of soil carbon to global environmental change (Callesen et al., 2003; Wynn et al., 2006).

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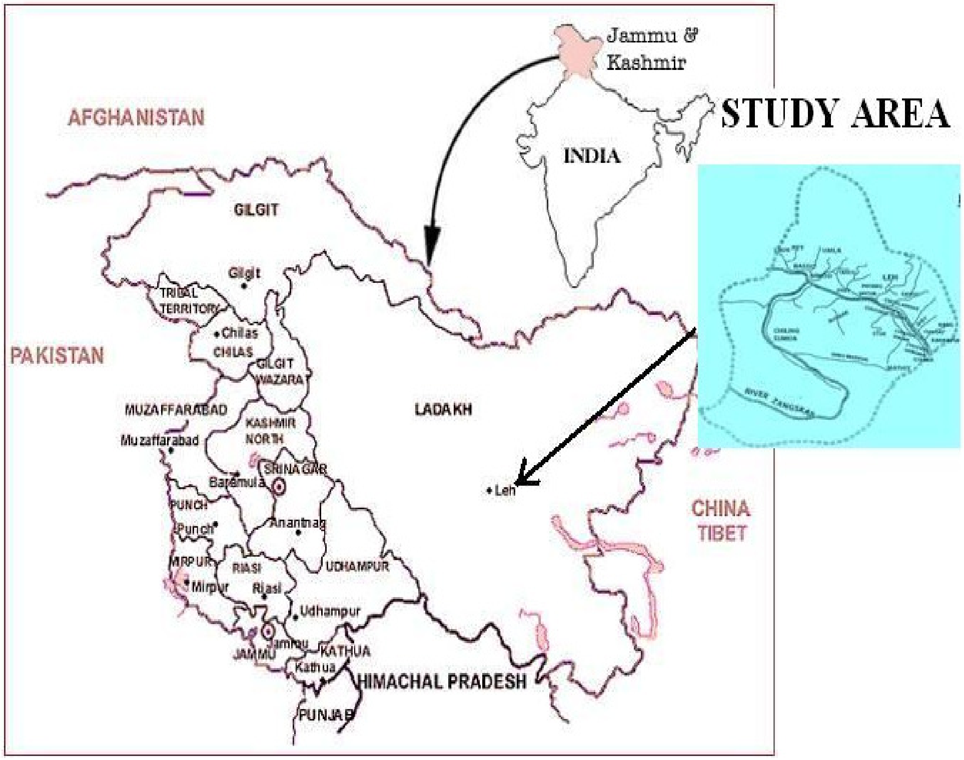

Figure 1. Map of study site.

The Himalayan region (western and eastern zones) constitutes 19% of total geographical area in India and contributes 33% SOC and 20% SIC stocks of the country. Western zone of Himalayan region in which cold desert Ladakh plateau comes, contribute 19% SIC stock of India while it covers 10% area of TGA (Bhattacharyya et al., 2008). Ladakh, a cold desert high altitude area in India is situated at an altitude of 3000 to 5000 m above mean sea level (amsl). Soils in high-altitude ecosystems play an important role in the global terrestrial carbon cycle because of their large carbon stock and potential sensitivity to climate warming (Zimov et al., 2006; Yang et al., 2008; Post et al., 2009). The changes in climate along the altitudinal gradient influence the composition and productivity of vegetation, consequently affect the quantity and turnover of soil organic matter (SOM) (Garten et al., 1999; Quideau et al., 2001) and also influences SOM by controlling soil water balance, soil erosion and geologic deposition processes (Tan et al., 2004). However, the storage and spatial patterns of SOC in high-altitude ecosystems remain largely uncertain, due to insufficient field observations and large spatial heterogeneity (Garnett et al., 2001; Liu et al., 2006; Yang et al., 2007). Measuring the quantity and spatial distribution of SOC is essential for evaluating soil function and understanding soil carbon sequestration processes (Venteris et al., 2004; Wei et al., 2006). But little is known about storage and distributions of SOC and SIC along the altitude gradients in cold desert high altitude ecosystems. Thus direct observations from high-altitude ecosystems are urgently needed to improve our understanding of biogeochemical cycles for cold desert high altitude regions and their potential feedbacks to global environmental change. Present experiment thus has been planned with the objective to assess the altitudinal variations in storage and distribution of soil carbon in Ladakh.

MATERIALS AND METHODS

Study site

This present study was conducted on soil samples collected from Leh district of Ladakh in India (Latitude, 32° 15'-36° N; Longitude, 75° 15'-80° 15' E and an altitude above 3500 m amsl) and as the sampling of study area is shown in Figure 1. Ecologically Ladakh region in Tibetan Plateau is a high altitude cold desert under the rain shadow of the Himalayas. Since the region lies in the rain shadow it is one of the driest places on the earth. Geographically, Ladakh is one of the divisions of Jammu and Kashmir province in India, divided into two districts namely Kargil and Leh. Leh is situated in the eastern Ladakh Plateau and come under cold hyper arid ecosystem (ESR) surrounded by the Indus and Zanskar Rivers. Leh district is situated between 32° to 36° N latitude and 75°to 80°E longitude and at an altitude ranging from 2900 to 5900 m. This study area lies between 33°59.362 to 34°17.722 N latitude and 077°12.023 to 077°45.669 E longitudes and with at an elevation ranging from 10526 ± 32.30 to 13063 ± 20.20 ft. amsl.

Table 1. Climatic data (for the year 2008-09) of study area.

Month	Temperature (°C)				Relative humidity (%)			
	2008		2009		2008		2009	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
January	-15.21	-3.95	-13.92	0.40	35.39	48.29	27.42	39.97
February	-16.21	-2.81	-10.89	3.98	29.10	47.93	23.50	36.75
March	-6.31	9.44	-6.90	8.45	27.61	41.23	21.71	33.06
April	-1.66	13.42	-2.07	13.78	27.30	45.57	21.40	30.50
May	2.61	18.18	1.98	17.82	27.58	52.23	21.77	28.94
June	10.96	26.22	5.24	21.15	22.63	33.70	26.70	28.17
July	12.34	27.31	10.97	24.62	22.90	39.16	21.13	37.00
August	9.82	25.40	14.16	26.55	25.39	51.87	20.06	29.13
September	3.77	17.80	6.67	21.08	27.30	45.93	21.53	35.57
October	-2.41	15.03	-0.57	13.85	26.26	41.55	21.33	38.97
November	-8.62	11.03	-10.03	4.07	21.03	33.40	29.07	47.40
December	-11.64	5.95	-17.78	2.45	22.55	37.16	24.65	32.46

Annual temperature in this region ranges from -30 to +40°C and annual minimum and maximum average temperature is -1.46°C and +13.48°C, respectively. Annual minimum and maximum average relative humidity is 24.70 and 39.03%, respectively. Annual precipitation is less than 100 mm mostly in form of snowfall and as the climatic data of this study area is presented in Table 1. Due to high altitude and low humidity, the radiation level is amongst the highest in the world (up to 6-7 Kwh/mm). Longer photoperiod (more than 12 h) and about 330 sunny days and only one cropping season in a year (span from May to October) are typical characteristics of this region. Nevertheless, by diverting glacial fed rivers into stone built terraces, gathering soil through sedimentation, enriching the soil with organic manure and other practices, local farmers are able to cultivate staples under such harsh climatic conditions in this region.

Major crops grown on agriculture fields are *Triticum aestivum, Hardeum vulgare* and *Medicago sativa*. Waste lands are covered by thorny shrub, *Hippophea spp*. Forest around agriculture fields, and glacier Valleys are covered by *Salix spp.* (Willow) and *Populus spp.* (poplar). Grasslands were spread with *Carex melanantha* and *Agropyron repens* as major grass species. Soil of Ladakh is taxonomically classified as typic cryorthids, physically thin, porous, with low water holding capacity and sandy in nature, which may be because of more quantity of stone and gravels content in dry mountains of this region.

Soil sampling and processing

This study area was situated in Leh district of Ladakh. Three sites were selected on the basis of altitudinal gradients, site-I (10,000-11,000 ft. amsl), site-II (11,001-12,000 ft. amsl) and site-III (>12,000 ft. amsl). Soil samples were collected from the agriculture soil and altitude of sampling sites were recorded by putting the GPS (global positioning system), a site locator instrument in the centre of sampling plot. For soil sampling, a plot of 100 × 20 m size was laid, and six sampling points were selected and one small sample was collected at each sampling point at the depths of 15 cm (plough layer). A total of 75 soil samples (25 from each altitudinal site) were collected.

All soil samples were air dried at room temperature, sieved with <2.0 mm test sieve. Litter, root parts and other plant residues were removed from the soil. For analysis of soil organic carbon and calcium carbonate, soil samples were again sieved with 0.2 mm test sieve. For the bulk density determination, soil samples were collected at the same time and from same sampling sites using a standard container with 100 cm^3 in volume and oven dried at 105°C for 24 h.

Analysis of soil sample

Chemicals used in the analysis of soil organic carbon and calcium carbonate were GR grade, purchased from Merck, Germany. Soil organic carbon was analyzed with wet digestion method (Walkley and Black, 1934). In this study, the term carbonates refer to the sum of $CaCO_3$, $MgCO_3$ or other carbonate minerals in soils, of which $CaCO_3$ is dominant and dolomite [$CaMg(CO_3)_2$] and $MgCO_3$ are usually minor components (Doner and Lynn, 1977). A factor of 0.12, the mole fraction of carbon in $CaCO_3$, was used to convert calcium carbonate to SIC content. The SOC and SIC content in the soil were converted to total SOC and SIC storage (Kukal et al., 2009).

Total SOC or SIC storage = % SOC or SIC/100 x (BD x 1500).

Where: Total SOC or SIC storage in t/ha; SOC or SIC is soil organic and inorganic carbon (%); BD is soil bulk density of 0–15 of soil depth (Mg/m^3); 1500 is the volume of 1 ha furrow slice (0.15 m) (m^3)

Statistical analysis

Data generated in this study were analyzed for mean and standard error (SE). Significance level was generated among the different altitude range by one way ANOVA using SPSS statistical software (SPSS Inc, 1999). Pearson correlation coefficient (r^2) was done for the analysis of correlation among the studied parameters.

RESULTS

SOC and SIC content

One way analysis revealed that the SOC contents (%) (N = 25, P < 0.05), with the increasing altitude (Table 2).

Table 2. Soil organic and inorganic carbon contents at different altitudes in CDHA microclimate.

Altitude range (ft. amsl)	SOC (%)	SIC (%)
10000-11000	0.81[a] ± 0.04	0.96[b] ± 0.21
11001-12000	1.00[b] ± 0.05	0.31[a] ± 0.03
>12000	1.32[c] ± 0.09	0.38 [a] ± 0.04

Values (N=25; Means ±S.E) in the same column bearing different superscripts (a, b, c) vary significantly (p < 0.05).

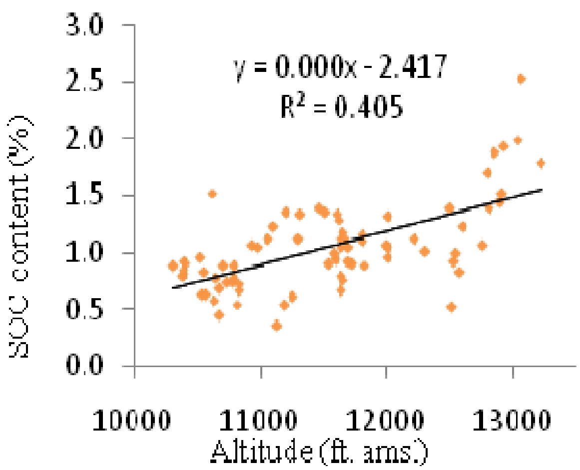

Figure 2. Correlation between altitude and SOC content in CDHA microclimate.

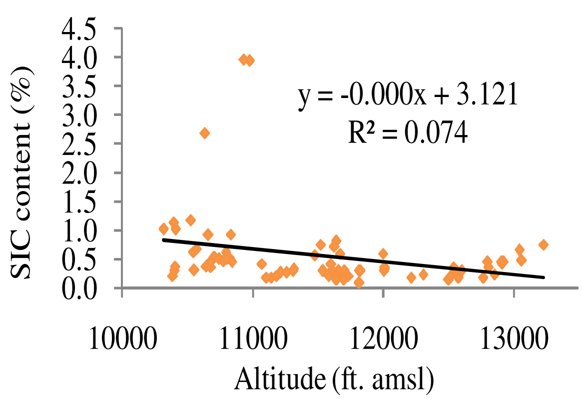

Figure 3. Correlation between altitude and SIC content in CDHA microclimate.

The maximum SIC content (%) was reported at site-I (N = 25, P < 0.05) than the site II and III. There was no significant difference in SIC content between site-II and site-III.

SOC and SIC stock

Statistical analysis (one way ANOVA) disclosed that the SOC stock from site-I to site-III was found increasing significantly (N = 25, P < 0.05, degree of freedom (between groups 2, within the group 72 and total 74) with increase in altitude range (Table 3). SIC stock was reported highest at site-I and found significantly (N= 25, < 0.05, degree of freedom (between groups 2, within the group 72 and total 74) higher as compared to other sites. SIC stock at site-II and Site-III did not shown any significance among each other (Table 3).

Correlation between content and stock of SOC and SIC with altitude

From our present study in cold desert high altitude soil samples, Pearson correlation coefficient (r^2) study revealed that the SOC content (%) was positively significantly ($p \leq 0.0001$) correlated with altitude (r = 0.637) (Table 4; Figures 2 and 4). Same trend was seen in SOC stock which was positively significantly ($p \leq 0.0001$) correlated with altitude (r = 0.694). On the other hand the SIC content (%) and stock (t/h) was found negatively significantly ($P < 0.018$ and $P < 0.020$, respectively) correlated with altitude (r = 0.273 and 0.269, respectively) (Table 4; Figures 3 and 5).

DISCUSSION

SOC content and stock in agriculture soil of cold desert high altitude region of Ladakh in this present study showed an interesting results as SOC content increased as altitude increased, while the same trends were reported in case of SOC stocks at all study sites of different altitudes. SOC in this present investigation is at higher side as compared to national average of soil organic carbon content of India. Bhattacharyya et al. (2008) reported that the lower atmospheric temperature at subzero levels causes hyper aridity which does not support vegetation growth and this may be the reason that cold arid microclimatic of Ladakh contain more content of SOC. Above ground litter fall and root mortality are the two primary processes that contribute to soil carbon inputs along elevation gradient. Jackson et al. (1996) and Yang et al. (2009) reported that the plants of high-altitude ecosystems have their own larger root: shoot ratios and shallower root distributions. This may result in to higher carbon concentration in the soil. Findings of this present investigation are in agreement with Chambers (1998) who reported that in the Great Smoky Mountains National Park, the soil respiration declines with increasing altitude leading to reduced loss of carbon. Other studies also indicated that the soil carbon concentrations or stocks increases with altitude in mountainous terrain (Townsend et al., 1995; Trumbore et al., 1996; Conant et al., 1998; Garten et al., 1999; Bolstad and Vose, 2001).

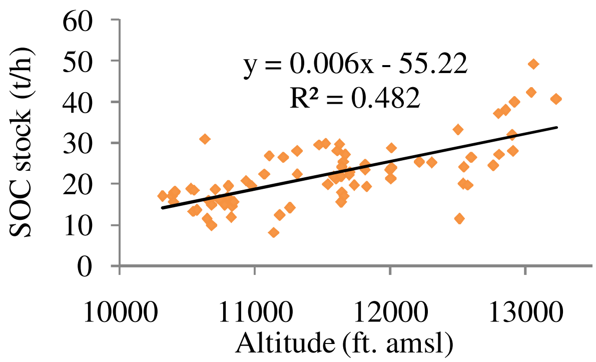

Figure 4. Correlation between altitude and SOC stock in CDHA microclimate.

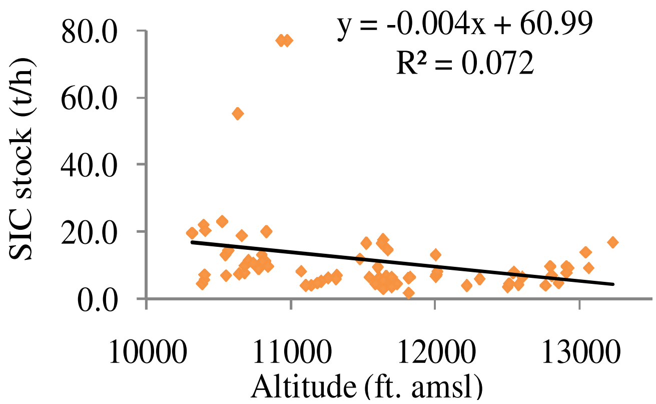

Figure 5. Correlation between altitude and SIC stock in CDHA microclimate.

Table 3. Soil organic and inorganic carbon stock (storage) at different altitudes in CDHA microclimate.

Altitude range (Ft. amsl)	SOC(t/h)	SIC(t/h)
10000-11000	16.74^{a} ±0.80	19.51^{b} ±3.99
11001-12000	21.69^{b} ±1.08	6.82^{a} ±0.74
>12000	28.83^{c} ±1.70	8.32^{a} ±0.84

Values (n=25; Means ±S.E) in the same column bearing different superscripts (a, b, c) vary significantly ($p < 0.05$).

Temperature is one of the dominant abiotic factor that affect carbon dynamics in cold desert high altitude ecosystems. Trumbore et al. (1996) found that the turnover time of soil C increased with elevation or declining mean annual temperatures (MAT). Here in cold desert high altitude region of Ladakh the MAT decreases with altitude due to higher mean annual precipitation (MAP) mostly in form of snow. Lower temperature decreases soil organic matter decomposition and provide longer residence time. Increasing trends of SOC content and stock with increase in altitude could also be due to constant carbon inputs and constant rate of carbon loss but reduced decomposition of organic matter due to lower soil temperature at higher altitude as compared to lower altitude. Glenn et al. (1992) reported that the dry land soil are less likely to lose carbon than the wet soils, as the lack of water limits soil mineralization and therefore the flux of carbon to the atmosphere also get lowered. As a result the residence time of carbon in the dry land soils is comparatively longer.

The SIC content as well as storage in agriculture soil at cold desert high altitude region in Ladakh in our study decreased above the altitude of more than 11000 ft amsl as SIC and stock at site-I (10000 to 11000 amsl) was significantly higher as compared to both the sites II and III. These decreasing trends of SIC concentration and stocks may be due to some biotic and abiotic factors like, temperature, humidity, precipitation and type of the parent materials. Temperature is one of the most important abiotic variable which control SIC sequestration in cold desert high altitudes, as it affect $CaCO_3$ equilibrium directly through its influence on the solubility constant and indirectly through its effects on the partition of precipitation inputs between evapo-transpiration and leaching (Lal and Kimble, 2000; Feng et al., 2002). It can be said that SIC and its storage above 11000 feet amsl remain uniform and at lower concentration as compared to lower altitude with special reference to Ladakh region. Feng et al. (2002) reported that the SIC content showed a stronger positive correlation with evaporation and negative correlation with MAT and MAP. At lower altitudes in cold desert high altitude region of Ladakh, comparatively higher evaporation rate of soil due to high MAT, wind velocity and low MAP than the higher altitudes may result in higher accumulation of SIC as compared to higher altitudes.

Decrease of water content or partial pressure of CO_2 or increase of Ca^{2+} or HCO^{-}_{3} concentrations can lead to a favorable environment for the precipitation of pedogenic form of inorganic carbon (Wilding et al., 1990). Availability of water is also an important factor in SIC accumulation. Studied area in this present experiment has marked depletion of water. Pedogenic form of inorganic carbon accumulation in arid and semiarid soils occurs because water deficit (evapotranspiration > precipitation) constrains significant leaching, favoring pedogenic inorganic carbon accumulation (Nordt et al., 2000).

The SOC content and storage were increased with increasing altitude at all study sites. Thus it is apparent that the carbon distribution is positively correlated with altitude at cold desert high altitude in Ladakh. This may be due to the decrease in MAT, increased MAP, lesser litter decomposition, longer residence time for SOM, higher plant root:shoot ratio and shallower root distribution at higher altitude than the lower altitude. Sims and Nielsen (1986) reported that the SOM is positive correlated with altitude. An exactly opposite results were

Table 4. Correlation analysis of carbon contents and their storage with altitude in CDHA microclimate.

	SOC (%)	SIC (%)	SOC (t/h)	SIC (t/h)
Pearson correlation coefficient (r)	0.637(**)	-0.273(*)	0.694(**)	-0.269(*)
Sig.	0.000	0.018	0.000	0.020

**, Correlation is significant at the 0.01 level (2-tailed). *, Correlation is significant at the 0.05 level (2-tailed).

observed in case of SIC content and storage in the studied area.

Conclusion

There are no published reports on soil carbon distribution along the different altitudes in cold desert high altitude region of Ladakh in India as well as in other similar regions of the world. As per this study, SOC content and stocks in agriculture soil increases while SIC content and stocks decreases with increasing the altitude. Further,
SOC concentration and storage are positively correlated, whereas SIC content and stocks are negatively correlated with altitude in cold desert high altitude region of Himalayan range. However further studies on the interrelationship of environmental variables like temperature, precipitation, N availability, litter chemistry and soil carbon storage pattern in such unique harsh climatic conditions of Ladakh and other similar regions in the globe needs to be further worked out for designing the policies related to global warming as well as for recommendations regarding soil management practices for improving agricultural productivity and sustainable development of population living in these regions.

ACKNOWLEDGEMENTS

Authors are grateful to Defence Research and Development Organisation, New Delhi, India for providing financial support to carry out this work. We are very thankful to Shri Stanzin Tsetar and the farmers of the region for their kind cooperation during soil sampling.

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