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Spatial variation of soil organic carbon stock in a typical agricultural farm of hot arid ecosystem of India

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Soil organic carbon (SOC) is the largest among three major carbon pools of global ecosystems. During the past few years, global warming and forcible land-use changes have resulted in a huge loss of this major carbon pool and as a consequence, concentration of atmospheric CO_2 has increased. To mitigate the potential risks arising from atmospheric abundance of CO_2, adoption of carbon sequestration strategies at different landscape scales is a major option. For this purpose, proper estimates of SOC stock per unit area are essential. In this study, we have estimated the SOC stock of a typical agricultural farm from hot arid ecosystem of India and also its spatial variation within the farm. The surface map of the SOC stock revealed that introduction of cultivation practices in fragile lands of the desert region has resulted in huge depletion of soil carbon. For example, the SOC stock of 10-years cultivated plots was found to be almost half of the SOC stock of recently cultivated plots of the farm. The results also showed that previous reports on large-scale estimates of SOC stock for hot arid region of India do not match with the current estimate from a farm scale of the same region. Consideration of spatial variation of SOC during calculation of SOC stock has helped us prepare a surface map of SOC stock of the farm, which may further be used as an essential requirement for implementation of site-specific carbon sequestration strategies and proper carbon credit programmes in the agricultural farms of India.

Keywords: Agricultural farm, hot arid ecosystem, soil organic carbon, spatial variation.

SOIL organic carbon (SOC) stock is the largest contributor to total global carbon stocks, contributing 1550 Pg (1 Pg = 10^{15} g) of carbon to 1 m depth, which is about three times that of biotic and twice that of the atmospheric pools[1]. Presently, in the context of global warming scenarios and forcible land-use changes under increased population pressure, soil carbon is continuously being lost to the atmosphere[2,3]. Intensive cultivation in dryland regions has resulted in decline of its meagre SOC pool (~ less than 1 g kg^{-1} in most areas) at a faster rate and even more under climate change-related desertification processes[4]. It was also reported that a great share (~ 80%)

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*For correspondence. (e-mail: priyabrata.iitkgp@gmail.com) of the applied farmyard manure (FYM) in subtropical humid situation is lost through the oxidation process[5,6]. Addition of FYM or compost in drylands for restoration of soil carbon has not been a viable option because of favourable agroclimatic condition for its rapid oxidation.

At present, there has been great interest to reduce the atmospheric CO_2 level through a chain of increasing vegetation carbon pools first and then to store them as soil carbon pool[7–9]. To quickly assess the soil carbon restoration programmes, it is important to know how much soil carbon is stored in an agricultural farm through adoption of different land management practices. Average SOC content is considered in most soil carbon pool calculations in spite of its large spatial variation in landscape, and thus leads to inaccurate estimate of SOC stock for an area. Therefore, reliable estimates of SOC pools and their spatial variability are essential to establish the soil carbon sequestration programmes at different landscape scales.

Techniques of SOC stock estimation may be grouped into two broad categories: (i) point measurements of the SOC content for different strata of a study area and then multiplication of mean SOC content of a stratum with the aerial extent of that stratum and (ii) modelling spatial variation of SOC content of a study area through geostatistical approaches to estimate the SOC stock[10]. The first approach has been commonly used, but has major limitations of errors in upscaling the same based on a few samples to a large mapping area. The second approach is considered as most prudent to calculate SOC stock specifically for a farm scale mainly because of three reasons: (i) it considers the minute variation of SOC content in an area and thus leads to accurate estimate of SOC stock; (ii) it helps delineate boundary line of homogeneous SOC stocks within a farm and (iii) spatial variation of SOC content will help easily assess different cropping systems within a farm in terms of its carbon-capturing potential. In India, the reported literature on SOC stock estimation was mostly concentrated on a regional scale and based on the first approach[11–13]. Several studies on SOC stock changes under different cropping systems and management practices are also available over India[6,14,15]. But, the study on calculation of SOC stock by considering its spatial variation within a farm is limited in India. Therefore, the present study mainly aims to (i) determine the spatial variation of SOC content in an agricultural farm located at Jaisalmer District, Rajasthan; (ii) calculate SOC stock of the farm after considering its spatial variation and (iii) assess different land management units typically for a hot arid agroecosystem of India in terms of carbon management.

The present study was carried out at a typical agricultural farm from a hot arid ecosystem of India located at Badoda village, Jaisalmer District. The farm lies between 26°52′30″–26°53′30″N and 71°12′15″–71°13′15″E (Figure 1) and 20 km away from Jaisalmer city in the eastward direction. Elevation of the farm ranged from 232 m amsl to 248 m amsl, with an overall slope from south to north. Total area of the farm was 0.76 sq. km, 85.38% of which was under cultivation in four main blocks: A, B, C and D (Figure 1). Cultivation in these four blocks started with the digging of tube wells at each block in successive stages. The first tube well in the farm was dug in 1999 and cultivation was started in block A. Then cultivation was successively started in blocks D, B and C with the establishment of tube wells in 2003, 2005 and 2008 respectively. Average depth of groundwater in these four tube wells in 2009 was 95 m. Cultivation in a particular plot of the farm has been practised once a year and the land kept fallow for the remaining periods of the season since 1999. Groundnut was the major crop in blocks A and C. However, mustard is often cultivated at the eastern patch of blocks A and C. At block B, mustard and mung bean were mostly cultivated. Wheat was the major crop in block D. Cluster bean was cultivated in scattered small patches of the farm. The soil of the farm was sandy to loamy sand in texture and taxonomically defined as Typic Torripsaments.

To achieve the aforesaid objectives, a total of 116 surface soil samples (0–15 cm) were collected from different locations of the farm during October 2009 (Figure 1). The spatial coordinates of each sampling point were recorded using handheld global positioning system (GPS, Model Etrex H). Collected soil samples were air-dried and passed through 2 mm sieve. The processed soil samples were used in the laboratory for determination of SOC content using wet digestion method[16]. It has been well established that about 60–86% of SOC is oxidized in the Walkley and Black method, and therefore, a standard correction factor of 1.32 (considering recovery of 76% of SOC) was used to obtain the corrected SOC value[17]. Although the recovery percentage of carbon varies due to land-use, texture, etc. we considered a constant factor of 1.32 because enough variation in fine texture and land-use was not observed within the farm. Recently, it was reported that the Walkley and Black method underestimates the SOC content of soils having high amount of clay–humus complexes, even after applying the standard correction factor of 1.32 (ref. 18). However, the amount of clay–humus complexes in sandy soils of hot arid ecosystem is negligible and thus the correction factor of 1.32 was considered sufficient to obtain the true estimate of SOC content.

Spatial variation of SOC content within the farm was examined by calculating the semivariogram $\hat{\gamma}(h)$, which measures the average dissimilarity between data separated by a lag distance h. It was computed as half the average squared difference of a variable between sampling pairs:

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2, \qquad (1)$$

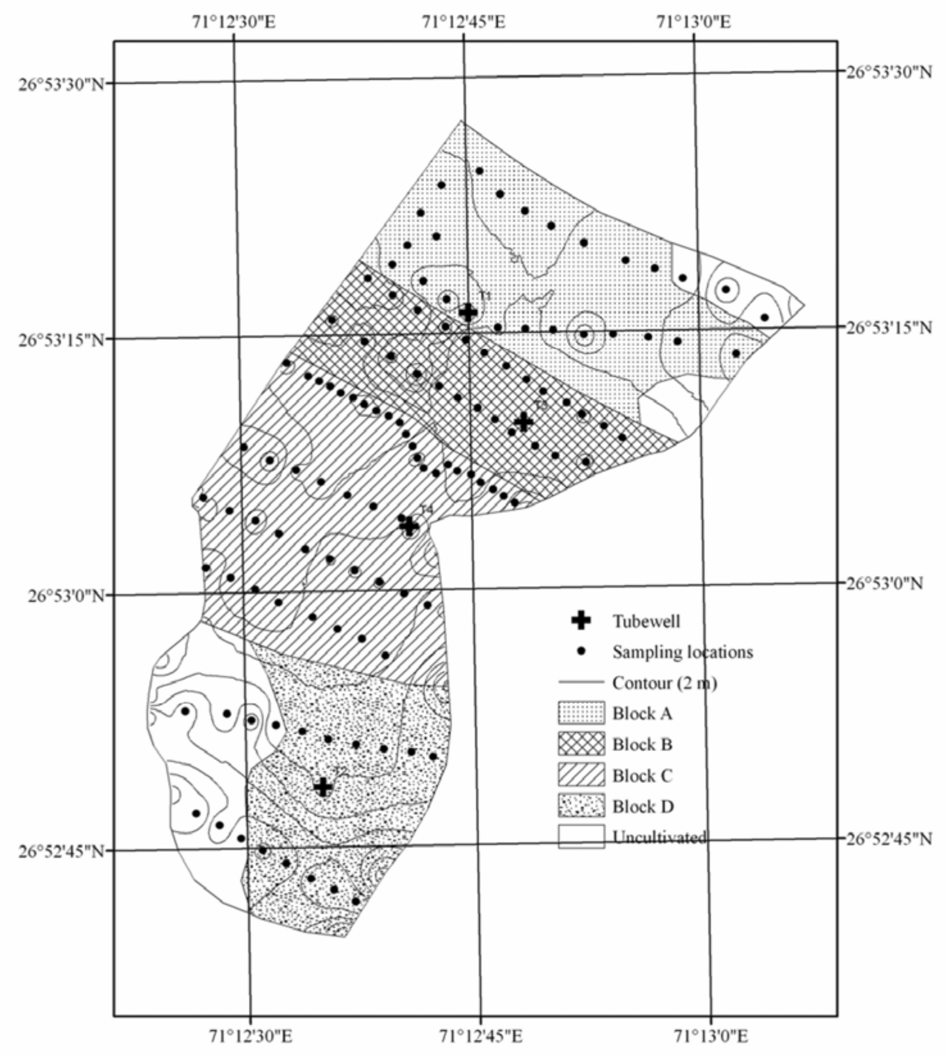

Figure 1. Layout of the agricultural farm along with the location of sampling points within it from hot arid ecosystem of India located at Badoda village, Jaisalmer District, Rajasthan.

where $N(h)$ is the number of data pairs within a given class of distance and direction, $z(x_i)$ is the value of SOC content at location x_i, and $z(x_i + h)$ is the value of SOC content at a lag of h from the location x_i. The semivariogram values were computed using VESPAR software (available from the personal website of B. Minasny; www.usyd.edu.au/su/agric/acpa/software) and plotted with lag distance h. During pair calculation for computing the semivariogram, maximum lag distance was taken as 500 m, which was about half the minimum extent of sampling area of the farm, and thus the border effect was avoided. During computation of experimental semivariogram, number of lag classes and the lag tolerance was taken as 10% and 25% respectively. The directional trend of SOC content within the farm was found negligible and hence omni-directional semivariogram was computed. The computed semivariogram values [$\hat{\gamma}(h)$] for corresponding lag (h) were fitted with available theoretical semivariogram models using weighed least square technique. Weight for each lag was directly proportional to the number of sampling pairs and inversely proportional to the standard deviation of experimental semivariogram values. Best-fit model with lowest value of Akaike Information Criterion (AIC)[19] was selected for defining the spatial correlation parameters of SOC content:

$$\mathrm{AIC} = n\ln\left[\sum_{i=1}^{n}\frac{N_i(h)}{\sigma[\gamma_i(h)]}[\gamma_i(h)-\hat{\gamma}_i(h)]^2\right]+2p, \qquad (2)$$

where n is the number of lag classes ($n = 10$), $\sigma[\gamma_i(h)]$ is the standard deviation of $\gamma_i(h)$ at the lag h, $N_i(h)$ is the number of sample pairs at the lag h, $\gamma_i(h)$ is the measured value of experimental semivariogram at the lag h, $\hat{\gamma}_i(h)$ is the estimated semivariogram value at the lag h, and p is the number of parameters in the model. The model with

Table 1. Soil organic carbon (SOC) content (g/kg) of 0–15 cm layer of an agricultural farm at Jaisalmer District, Rajasthan

Blocks	Number of samples	Mean SOC content (g/kg)	Standard deviation of SOC content (g/kg)	Minimum SOC content (g/kg)	Maximum SOC content (g/kg)
A	22	1.06	0.70	0.20	3.47
B	25	1.24	1.10	0.20	5.25
C	47	2.13	1.78	0.10	6.34
D	11	1.69	0.94	0.50	3.55
Others	10	1.71	0.76	0.68	2.97

the lowest value of AIC was adjudged the best one to describe the spatial variation of SOC content. AIC was used in this study as a selection criterion among several evaluation criteria like residual sum of squares (RSS), root mean squared residual (RMSR), R^2, etc. because AIC considers both the residual term and the number of parameters involved in the tested model.

Three commonly used semivariogram models were tried to fit the computed semivariogram values of SOC content. These are the spherical, exponential and Gaussian models. Expressions of these three models are commonly available in the literatures[20]. Surface map of SOC content of the farm was prepared using the spatial correlation parameters (C_0, C and a) through ordinary kriging (OK). Kriged map of SOC content was prepared using geostatistical wizard of ArcGIS 9.1. Accuracy of the prepared SOC map was evaluated through leave-one-out cross-validation approach[21].

The SOC stock of 0–15 cm soil layer of the farm was calculated by following the stepwise methodology described in the literature[22]. In the first step, SOC content (g kg^{-1}) was multiplied with the bulk density (kg m^{-3}) to obtain the SOC content on volumetric basis (g m^{-3}). The reported mean bulk density of 1.45×10^3 kg m^{-3} for sandy soils from hot arid zones was used here for the above conversion[22]. In the second step, SOC content on volume basis (g m^{-3}) was multiplied with the thickness of the soil layer (m) and the area (m^2) to obtain SOC stock (kg). All the above calculations were performed using raster calculator option of ArcGIS 9.1. At the end of the second step, surface map of SOC stock of the farm was obtained. In the third step, SOC stock of 0–15 cm soil layer within the total farm area or for different blocks of the farm was obtained by cumulating the SOC stock of grids lying within the desired polygon boundary. For block-wise calculation of SOC stock, grid data within the polygon of each block were extracted using extraction option of the spatial analyst tool of ArcGIS 9.1.

SOC content (g kg^{-1}) in different blocks of the agricultural farm is presented in Table 1. The average SOC content of the farm was 1.66 g kg^{-1}, and ranged from as low as 0.11 g kg^{-1} to 6.34 g kg^{-1}. Soils of groundnut-cultivated plots were comparatively higher in SOC content (1.88 g kg^{-1}) than the remaining cultivated plots of the farm. Among groundnut-cultivated plots, the highest SOC content (2.51 g kg^{-1}) was observed in block C and the lowest (0.86 g kg^{-1}) in block A of the farm. Natural fallow lands at the southeastern and southern portions of the farm, where deposition of aeolian sands was very common and rocky outcrops with presence of a few grass species of *Eleusine compressa*, *Lasiurus sindicus*, etc. are the dominant landscape features, had average SOC content of 2 g kg^{-1}. Farm areas under cluster bean, mustard and mung bean cultivation were comparatively lower in SOC content (1.58 g kg^{-1}, 1.54 g kg^{-1} and 0.77 g kg^{-1} respectively) than the rest of the plots. Comparatively higher SOC content in groundnut-cultivated plots was possibly due to the spreading nature of the groundnut crop, which covered a major portion of the soil surface and thus protected carbon stock of the soil from loss through wind-eroded aeolian sediments. Overall, it was found that the soils under block A of the farm, where cultivation was started recently, had the lowest SOC content (1.06 g kg^{-1}). The highest SOC content (2.13 g kg^{-1}) was observed in block C, where cultivation was started just a year ago in 2008. Thus cultivation of land even once in a year had resulted in a significant reduction of SOC content over last 10 years. It is notable here that sand content (0.02–2 mm) of the soils within the farm ranged from 85% to 90% and therefore texture is considered homogeneous throughout the farm. Disturbances of soil surface through cultivation resulted into loose soil surface and thus aggravated the rate of SOC depletion through wind erosion events, which are dominant land-degradation processes in the farm of 0.76 sq. km area.

Spatial variation structure of SOC content of the farm was fitted in three standard semivariogram models and the resulting AIC values are presented in Table 2. Other semivariogram models were also tried, but the fitting result was poor. The spherical model was found with the lowest value of AIC and thus was considered as the best to fit the computed semivariogram values. The fitted semivariogram of SOC content of the farm is depicted in Figure 2. The nugget (C_0) and sill ($C_0 + C$) were 0.77 and 2.12 respectively. It was found that the nugget, which indicates the small-scale variation of a regionalized variable, was 36% of the sill. However, the contribution of nugget to sill may be reduced through adoption of intensive sampling efforts, but depends on the budget for sampling. The range (a) parameter of SOC content was

Table 2. Semivariogram parameters of SOC content (g/kg) in the farm

	Semivariogram parameters				
Semivariogram models	Nugget (C_0)	Partial sill (C)	Range (a) (m)	Akaike Information Criterion (AIC)	$\Delta AIC = AIC - AIC_{min}$
Spherical	0.77	1.35	146	–23.02	0
Exponential	0.00	2.13	41	–21.20	0.82
Gaussian	1.02	1.12	73	–22.78	0.24

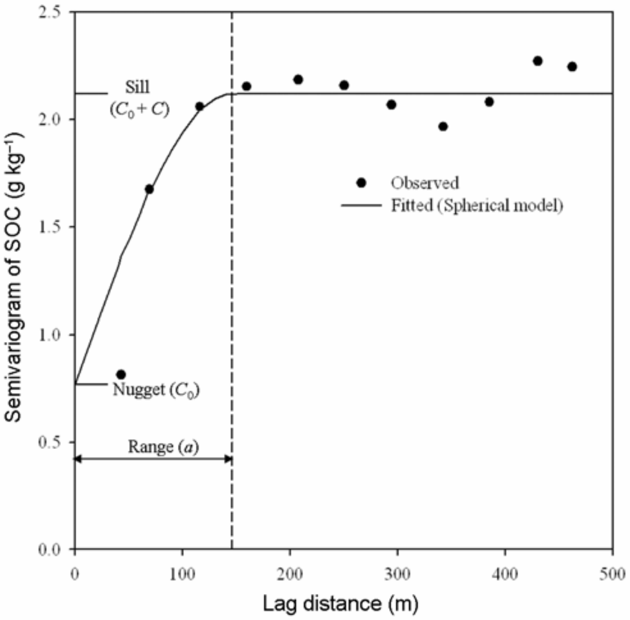

Figure 2. Semivariogram of soil organic carbon (SOC) content (g/kg) within the farm area.

146 m. These spatial correlation parameters indicated that SOC content was highly variable in two-dimensional soil surface and such spatial variation might be captured only through sampling strategy with minimum separation distance ≤ 150 m. Surface map of SOC content of the farm was prepared through OK approach using the semivariogram parameters obtained from the best-fitted spherical model. Cross-validation of the prepared map of SOC content resulted in a root mean squared residual of 1.22 g kg^{-1}.

Surface map of SOC content of 0–15 cm thick surface soil of the agricultural farm is presented in Figure 3. The computed SOC stock was found to be the lowest at the northwestern part of the farm, whereas it was the highest in the middle portion of the farm. Total SOC stock of the farm was calculated as 272 tonnes, with an average density of 3.57 tonnes ha^{-1}. Block-wise distribution of SOC stock of the farm is presented in Table 3. Block C covering 28.14% area contributed 41.41% SOC stock of the farm. On the contrary, SOC stock of block A was 52.38 tonnes, which is 19.26% of the total SOC stock of the farm, but covers 23.84% of the farm area. Here it is to be noted that block A has been cultivated since the last 10 years from 1999, whereas in block C cultivation was started in 2008. The results showed that continuous cultivation of loose sandy soils in hot arid areas may deplete the SOC stock at a faster rate. Among cultivated areas of the farm, the SOC stock was higher in plots where cultivation was just started (5.26 tonnes ha^{-1}) than those plots where cultivation was started almost 10 years ago (2.89 tonnes ha^{-1}). It was also observed that areas with rocky outcrops of the farm had SOC stock of 1.41 tonnes ha^{-1}.

In the present study, SOC stock of a farm from the hot arid agro-ecological region of India was calculated considering its spatial variation within the farm. SOC stock of the total farm area was also calculated following the common approach of multiplying mean SOC content with the total area. The SOC stock calculated based on mean SOC content of several soil profiles in the same region was 275 tonnes, with a density of 3.61 tonnes ha^{-1}, which was close to SOC stock calculated using our approach. However, the wide variation in SOC stock observed at different portions of the farm could not be captured in the mean SOC calculation approach. For site-specific carbon management within a farm, knowledge on the spatial variation of SOC stock is important. Moreover, regional-scale estimates of SOC stock based on global mean may either underestimate or overestimate the SOC stock at a small farm scale. For example, in the present study, we obtained SOC stock of 3.57 tonnes ha^{-1} for an agricultural farm located at an extremely hot arid region of western Rajasthan. SOC stock of 78.68 tonnes ha^{-1} for 0–30 cm soil layer in hot arid ecoregion of India (Punjab, Haryana and Rajasthan) has been reported in the literature[23], which is higher than that reported in the present study. Some portion of this huge difference in SOC stock between the reported value and our calculation may possibly be due to the difference in the methods of SOC determination in the laboratory. SOC content based on dry combustion method obviously will lead to higher SOC stock than that based on the Walkley and Black method, which was followed in our study. On the contrary, the reported SOC stock of 1550 kg km^{-2} for 0–25 cm soil layer of Typic Torripsamments soil profile in hot arid region of Rajasthan[13] is lower than the estimated SOC stock in the present study. Therefore, assessment of SOC stock at small farm scale is essential for successful implementation of the carbon sequestration programme.

Spatial variation of SOC content within a typical agricultural farm from hot arid ecosystem of India located at

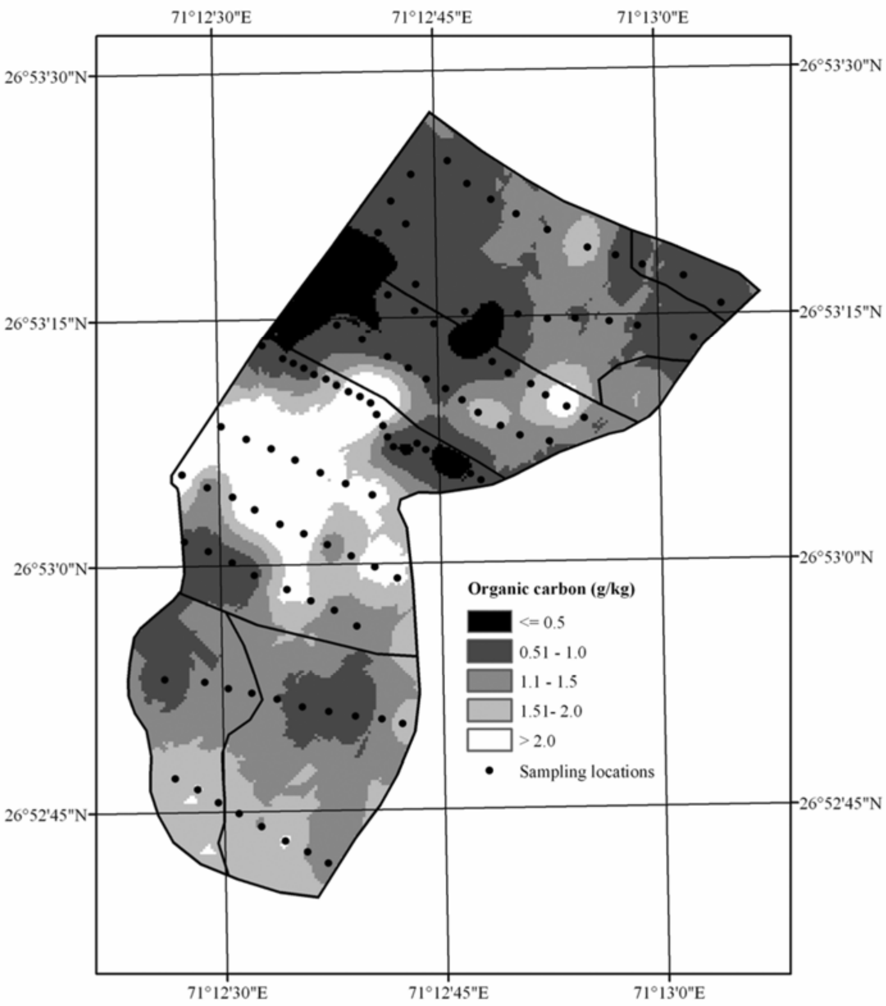

Figure 3. Spatial distribution of SOC content (g/kg) of 0–15 cm soil layer in the agricultural farm at Jaisalmer District, Rajasthan.

Table 3. SOC stock in 0–15 cm soil layer of four blocks of the farm under cultivation for different time-periods

Blocks	Number of years of cultivation	Area (ha)	SOC stock (*t*)	SOC stock for 0–15 cm soil layer (t/ha)
A	10	18.15 (23.84)	52.38 (19.26)	2.89
B	4	11.86 (15.58)	36.36 (13.34)	3.06
C	~ 1	21.42 (28.14)	112.68 (41.41)	5.26
D	6	13.56 (17.81)	54.97 (20.20)	4.05
Others	–	11.13 (14.62)	15.70 (5.77)	1.41

Jaisalmer District, Rajasthan followed the spherical model with a range of 146 m. SOC stock for different portions of the farm was calculated considering its spatial variation, and it was observed that continuous cultivation of farmlands for 10 years had resulted in considerable depletion of SOC stock. The rate of SOC loss due to conversion of native rangeland to arable farming system over the 10-year-period was approximated as 0.23 tonnes C ha^{-1} year^{-1}. A review of the net C loss due to conversion of native grassland to arable farms from several studies reported a loss rate of 0.95–1.7 tonnes C ha^{-1} year^{-1} (ref. 24). Disturbances of soil surface through cultivation resulted in loose soil surface and thus aggravated the rate of SOC depletion through wind erosion events in the arid and semi-arid areas.

Comparison of SOC stock of hot arid region of India between the present study and several reports published in the literature revealed that regional-scale estimate resulted in either underestimation or overestimation of SOC stock for a farm scale. This is because most of the previous studies on SOC stock assessment were based on mean SOC content for a region or for a specific soil type, and the methods of SOC estimation were different in most cases. Consideration of spatial variation may result in accurate estimation of SOC stock of a farm and will also lead to a surface map of SOC stock, which may be an essential requirement for adoption of site-specific carbon sequestration strategies.

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Petrographic studies on a newly discovered Indo-Arabian stone anchor from the Gulf of Kachchh, Gujarat: implications for source area

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Finding of stone anchors in the onshore and offshore regions of India points to maritime contacts with neighbouring countries. This communication reports a new Indo-Arabian type stone anchor recovered from a depth of 53 m off the coast of Gulf of Kachchh, Gujarat, India. The anchor stone is composed of sharp angular quartz and feldspar grains floating in a ferruginous matrix with point contacts between them as seen under a microscope. SEM–EDS studies showed few and isolated zircon and apatite grains as accessory mineral phases. The rock is identified as epiclastic sandstone derived from pyroclastic source rocks. A similar rock has been reported from the Habo Formation exposed near Jhikadi village, Kachchh, Gujarat.

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