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Organic carbon stock map for soils of southern India: A multifactorial approach

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Data acquired during soil resource inventory of central Western Ghats, India, were supplemented with other available environmental data to estimate/map soil organic carbon (SOC) stock at the regional level. For an area (about 88,000 sq. km) stretching between Goa and the Palghat Gap, a model was developed linking SOC stock to the different environmental parameters known to control SOC levels, particularly type of land cover. Forests of different status, presenting varying stages of degradation, still occupy 43,000 sq. km in this area. This can explain the higher SOC stock (0.44 Pg) estimated compared to figures published earlier.

Keywords: Biodiversity hotspot, data mining, land cover, soil organic carbon.

CONSIDERABLE efforts have been made in India over the last twenty years to provide the country with a modern and homogeneous soil map^{1–5}, for which acquisition of voluminous data was required. In the meantime, the role of the soil carbon pool in the global carbon cycle has attracted a lot of attention, especially since the Rio Summit in 1992. It has long been established^{6–8} that temperature, rainfall, soil texture, pH and type of vegetation or land cover are the major factors controlling the level of soil organic carbon (SOC). Despite this, most of the estimations of SOC pool at the global level^{9,10}, or at European¹¹ or Indian¹² scales are based only on the soil type (soil taxa based approach)¹³, i.e. the SOC content or stock is calculated and averaged for a soil unit or a group of units and these values are used to compute global statistics or to prepare maps. There is therefore disagreement between the objectives of such studies, which aim at providing landscape managers with tools for enhancing C sequestration in soils; their actual usefulness is limited by the fact that land-cover changes can hardly be taken into consideration to estimate soil carbon pool evolution.

Land-use changes cannot be ignored where carbon management is concerned and, in their pioneering study

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of the organic matter reserves in Indian soils, Jenny and Raychaudhuri¹⁴ noticed for the Deccan Plateau: (i) similar C and N contents for the different types of soils (viz. dark-grey, black, brown or red according to the soil types they considered) and (ii) a considerable fall (60% or more) in C or N content following deforestation for cultivation. It must be pointed out that they studied the effect of a particular factor, considering 'other things being equal'. It was therefore impossible under such conditions to study the combined effect of two or more factors on the SOC level.

Here, our objectives were (i) to reliably assess the SOC stock at regional scale (10^4 – 10^5 sq. km), (ii) to distinguish in its variations those due to environmental factors considered as stable at the human timescale (soil parameters, physiography, etc.) from those that are quickly modified by man (land use and land cover), and (iii) to use these results to prepare a SOC stock map explicitly taking into account the land cover. We must emphasize here that climatic parameters were considered as stable for the period covered by our study (i.e. the last 25 years); for this reason, our results cannot be used to calculate SOC stocks of the past, under colder conditions, or of the future, after significant warming.

In its principles, our method followed the state factor approach to soil genesis proposed by Jenny¹⁵, which states that the soil (*S*) is a function of climate (*cl*), organisms (*o*), topography (*r*), parent material (*p*) and time (*t*):

$$S = f(cl, o, r, p, t). \quad (1)$$

Soil being a complex body, the eq. (1) has remained a conceptual model, except for particular and simple cases¹⁶. However, as already mentioned by Vitousek¹⁷, the state factor approach is attractive in addressing ecological modelling. For our study, the Jenny equation (eq. (1)) was modified to give SOC stock in terms of environmental and soil parameters for which maps are either available or can be prepared easily using existing data (generic equation, eq. (2)).

$$\text{SOC stock} = f(\text{bioclimate, altitude, physiography, rock, soil, land cover}). \quad (2)$$

We applied recent data-mining methods to a soil-profile database to solve eq. (2) and GIS facilities to compute solutions for the entire study area. It was thus necessary (i) to compile a soil-profile database for the study area and (ii) to prepare a GIS layer for each of the environmental or soil variables considered.

The study area lies on the western side of the Indian peninsula (inset, Figure 1) and consists of three major physiographic units: (i) the low coastal area, (ii) the Western Ghats escarpment, and (iii) the southern part of the Deccan Plateau (or Peninsular Plateau). The Ghats escarpment plays the role of an orographic barrier blocking

the bulk of the monsoon rainfall; the general morphology affects the distribution of climate and vegetation types and also partly that of soils and human activities. This gives rise to a mosaic of highly diverse and contrasting landscape units. The study area thus covers the main vegetation types and major soil–crop–climate complexes of southern India.

From different surveys and studies^{1–5,18–20} concerning this area, 361 soil profiles representing 1643 horizons (and analysed samples) were selected for the soil-profile database. Information on the location (latitude, longitude, altitude), geological substratum, physiography and land cover for each soil profile was taken from the description sheets and complemented with analytical results of gravel, clay, silt, sand and carbon contents for each horizon. In both soil laboratories (NBSS & LUP, Bangalore, and French Institute, Puducherry), the analytical methods were similar with respect to the sieving of fine earth and particle-size analysis (pipette method after organic matter destruction and soil dispersion using sodium hexameta-phosphate), but differed in the determination of carbon content: wet oxidation method (Walkley–Black) in Bangalore and dry combustion (using a Carmograph[®] apparatus) in Puducherry. A conversion factor of 1.33 was applied to

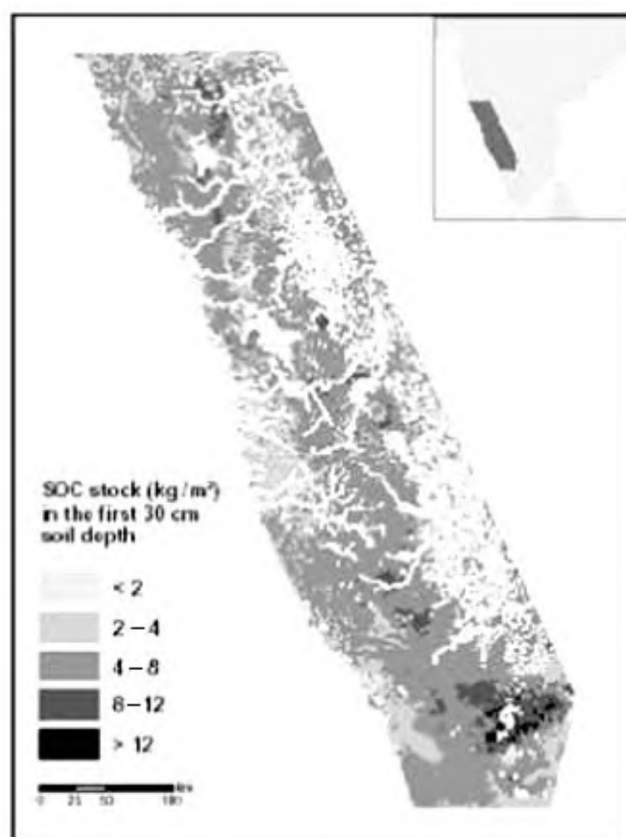


Figure 1. Map of study area showing soil organic carbon stock in the first 30 cm soil depth for 1999.

Table 1. Characteristics of the ten predictor variables used for the SOC stock model

Predictor variable	Type of variable	No. of classes	Sources, reference
Elevation	Numeric, in metres	–	http://srtm.usgs.gov/ and http://srtm.csi.cgiar.org/
Climate, number of dry months	Categorical, orderable	7	Bioclimate map, 30
Climate, mean annual rainfall	Categorical, orderable	7	Bioclimate map, 30
Climate, mean annual temperature	Categorical, orderable	4	Bioclimate map, 30
Geology (rock type)	Categorical, non-orderable	6	Geological maps, 31 and http://pubs.usgs.gov/
Physiography	Categorical, non-orderable	11	Soil maps: 1–5
Land-cover status	Categorical, non-orderable	11	Forest maps, 32–34 and remote sensing data
Soil great group ^a	Categorical, non-orderable	25	Soil maps, 1–5
Soil gravelliness	Categorical, orderable	3	Soil maps, 1–5
Soil surface texture	Categorical, orderable	3	Soil maps, 1–5

^aAccording to the 5th edition of the Keys to Soil Taxonomy.

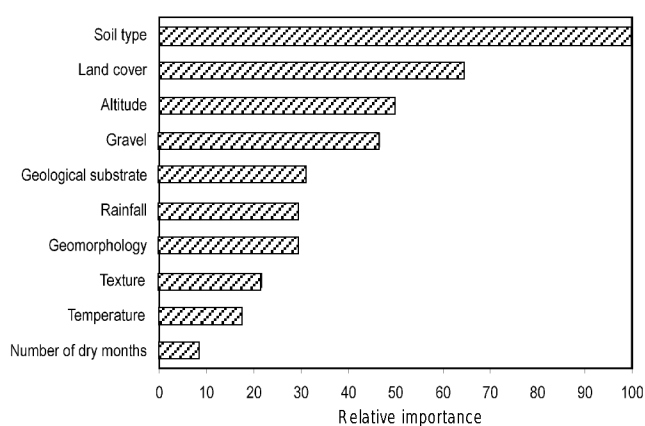


Figure 2. Bar chart giving the relative importance of the ten predictor variables used for estimation of SOC stock.

the results of carbon determined by the Walkley–Black method^{10,21}.

Following recommendations from the Intergovernmental Panel on Climate Change²², the SOC stock of each profile was calculated for the top 30 cm depth as the sum of the SOC stock of the different horizons (1, 2 or 3) sampled in the 30 cm. For each horizon, the SOC stock (g/sq. m) was calculated by multiplying the OC content (g/g) by the bulk density (g/cubic m) and by the thickness (m) of the horizon.

Bulk density (BD) is usually not measured during regular soil surveys and, in this study, it had been determined only for 147 horizons pertaining to 65 soil profiles. Thus for the remaining horizons corresponding to missing values of bulk density another generic (eq. (3)) model was proposed and solved using a recent data-mining method.

$$BD = f(\text{soil type, land cover, horizon, texture, gravel, C}). \quad (3)$$

The data-mining method selected to solve eqs (2) and (3) is the Multiple Additive Regression Tree (MART) method²³,

which is a Boosted²⁴ version of the Classification and Regression Tree (CART) method²⁵. MART inherits the main advantages of tree-based models such as: (i) the input variables can be a mix of different types – numeric or categorical, (ii) the trees are invariant to change in the relative scales of the predictor variables, and (iii) their performance is highly resistant to the inclusion of extra irrelevant variables. The boosting of the tree models ensures that their main disadvantage, inaccuracy, is overcome²⁶.

The model of bulk density was computed using soil taxa, land-cover type, horizon type, texture (clay, silt, sand and gravel contents) and organic carbon content of the horizon as predictor variables for 147 horizons. These variables were categorical and non-orderable for soil, land cover and horizon types, and numeric for the remaining ones.

Similarly, the model of SOC stock was constructed using ten soil and environmental parameters (Table 1) for 361 soil profiles stored in the database and considered as the training dataset.

The relative importance of the ten predictor variables in the SOC model is given in a bar chart (Figure 2). A bar chart was also obtained for BD but is not shown here.

The 1999 SOC stock map for the first 30 cm soil depth is also presented here (Figure 1), to illustrate the result obtained with our approach. The SOC stock varies from 0.2 to 20 kg m⁻² in the study area (values obtained from the soil-profile database). The map illustrates this wide range of values and shows the intricacy of their distribution. A root mean square error of 1.8 kg/sq. m was obtained between observed and predicted values computed on the test dataset, a randomly selected 10% subset of the training dataset.

For the first 30 cm soil depth, and for the entire study area, the computed SOC stock corresponding to the 1999 land-cover status represented 0.44 Pg of C. This value can be discussed in comparison with those published by Bhattacharyya *et al.*¹² for all Indian soils and for the same soil depth. Only two of the five physiographic units that they have considered in their study are actually present in our study area, viz. the coastal zone, which has a mean

Table 2. Mean SOC stock for each type of land cover in the study area

Land-cover type	Total area (10 ³ ha) (a)	Total SOC stock (10 ⁶ t) (b)	Mean SOC stock (t ha ⁻¹) (c)	Mean biomass C (t ha ⁻¹) (d)*
High elevation and montane evergreen forest (>1400 m)	46	5	110.2	
Montane grassland (>1800 m)	30	2	82.6	
Other dense evergreen forests	351	23	64.0	64.5
Secondary/disturbed evergreen forests	1160	73	63.2	33.3
Moist deciduous forest, dense or disturbed	296	22	73.1	
Dense dry deciduous forests	291	19	65.0	
Plantations	661	45	68.0	
Degraded forests, pastures, wastelands	2212	100	45.1	8.0
Peninsular Plateau, unirrigated croplands	970	35	35.6	8.0
Peninsular Plateau, irrigated croplands	1852	89	48.0	8.0
Coastal lowlands, cultivated/not cultivated	655	25	37.9	

*These data were computed from table 1 of Bhadwal and Singh²⁹, considering that 1 kg of biomass corresponds to 0.5 kg of carbon.

SOC stock of 5.48 kg m⁻², and the Peninsular Plateau, for which it is only 3.42 kg m⁻². The SOC stock calculated from these mean values for our study area (comprising 16,301 sq. km of the coastal zone and 69,432 sq. km of Peninsular Plateau) gives 0.33 Pg of C, which is significantly lower than what we have calculated with our method. The difference, 0.11 Pg of C (representing 33% of what was calculated by Bhattacharyya *et al.*¹²) can be considered as the 'forest cover effect' in this area recognized as part of a biodiversity hotspot because of its well-preserved forest cover. The magnitude of this difference is in itself a proof of the need for taking into account the land-cover status in SOC stock estimation.

Forestry options are often proposed in India as important components of carbon sequestration strategies^{27,28}. We will now briefly illustrate how our model can be used to document them. The organic carbon stored in the biomass is usually²⁹ the only compartment taken into consideration to evaluate the efficiency of forestry options for carbon sequestration. When the soil carbon pool is mentioned^{27,28}, it is often in general terms and without any link with the land cover or forest types. At least two reasons can explain this: (i) the fact that within the framework of clean development mechanism projects, it is often difficult to include soil carbon stocks in a verifiable and transparent manner in the calculation of benefits towards climate-change mitigation, and (ii) the lack of precise data regarding SOC for different land-cover types. Our study has provided preliminary results giving this kind of data for the study area (Table 2) and has shown that, under forest, the SOC stock in the first 30 cm depth of soil is of the same magnitude, if not more, than the carbon stored in the biomass (see columns (c) and (d) in Table 2).

Table 2 also gives SOC stock values averaged for different land-cover types, with the knowledge that locally, the values are also dependent on various other factors such as soil type, altitude and soil gravelliness. They can nevertheless be used as a first estimate for the expected change in SOC stock accompanying an eventual change in land-cover type at a given location.

The method presented here can be considered as an improvement over existing methods for evaluating SOC stock over large areas. First, it takes into account different factors, including type of land cover, which was shown to be one of the most important among the different predictor variables (Figure 2), whereas other methods typically use only one: soil type. Thus, this method is capable of explaining differences observed in SOC stocks due to a combination of factors. Second, it can be directly applied to other areas, provided adequate reliable data are available there. Third, it can be used at different dates for the same area so that variations of SOC stocks over a period of time can also be evaluated. Finally, the method can be used for simulating different scenarios of land-cover changes in time, with a quick estimate of the expected loss or gain of SOC stock, which may be an appropriate tool for land-use planning in the context of biodiversity conservation and mitigation of greenhouse gas emission. Future improvements of the SOC stock evaluation can nevertheless be expected both with improvements in data-mining methods and in the quality of available soil and environmental data.

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Earthquake patterns based on diurnal and semidiurnal electromagnetic emissions related to earthquakes/volcanoes observed with 24 h periodicity

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Electromagnetic (EM) emissions related to earthquakes and volcanoes were observed in a very wide frequency band from VLF to microwave. These were found to be diurnal and semidiurnal type occurring only during certain hours of the day. It was also found in these examples that the occurrences of earthquakes/eruption of volcanoes were simultaneous with the timings of these EM emissions. From this study, it can be concluded that the semidiurnal stresses on the earth and on the moon are solely caused by the position of the Sun. The causes of diurnal stresses are not precisely known.

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