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C sequestration potential of cultivated land and Mango orchard in the plough layer of Alfisols of the tropical sub-humid dry bioclimatic zone of India

Poushali Roy*

Department of Geography, Kashipur Michael Madhusdan Mahavidyalaya, P.O. Panchakoteraj, District Purulia, West Bengal – 723132, India.

Abstract: Conversion of forest area to agricultural land use led to an estimated loss of 36 Pg carbon (C) from soils between 1860 and 1960. Soil organic carbon (SOC) loss through cultivation can, however, be reduced and potentially fixed in soil through proper soil and land management. The objective of this study was, therefore, to determine the effect of crop cultivation *vis-à-vis* forest and plantation, on the SOC concentration, especially in the plough layer, in the SOC-poor soils of Irga watershed in the tropical sub-humid dry region of Jharkhand, India.

Typic Haplustalfs and *Typic Paleustalfs* soils predominate in the two administrative blocks within the watershed – Dhanwar and Birni, respectively. Three plots were chosen for each soil subgroup to represent three predominant land cover conditions *viz*. forest, plantation and mono- cropped area in Dhanwar and Birni. SOC stock was high in the *Mango* orchard in Dhanwar (226 Mg C ha^{-1}); higher in the cultivated land in Birni (242 Mg C ha^{-1}); and least in the plot under *Eucalyptus* plantation in Birni. In the 0-20 cm depth, *Mango* orchard in Dhanwar and cultivated land in both the sites showed an increase in SOC pool in comparison to forests; *Eucalyptus* plantation, on the other hand, registered a low SOC pool at this depth.

The practice of paddy-fallow rotation and the application of animal manure led to an increase in the SOC pool in the plough layer of agricultural soils in the SOC-poor area; and thus have the potential to sequester C in the Irga watershed.

Keywords: *soil organic carbon, bulk density, land use/land cover, Tukey's test*

Introduction

The world faces a dual challenge of reducing atmospheric carbon-dioxide levels to mitigate global warming and maintaining soil fertility to ensure food security. A growing amount of research in resolving both the challenges comes to a one-point solution of sequestering excess atmospheric carbon (C) in organic form in the terrestrial soils which are naturally the largest 'terrestrial sink' for atmospheric carbon (C). The world soils store 1115 to 2200 Pg C as soil organic carbon (SOC) (Batjes 1996), two-third of which is in the form of soil organic matter (SOM) (Victoria *et al.* 2012). Regional variations in SOC stock are observed pertaining primarily to bioclimatic differences. Tropical soils are reported to be inherently low in SOC stock due to the prevailing high atmospheric temperatures (Srinivasarao *et al.* 2012) that hasten the decomposition of SOM (Jenny 1994) leading to rapid oxidation of SOC. Tropical soils thus store 29.5% SOC in the first 30 cm of the soil profile (Batjes 1996); of this, only 9 Pg SOC is stored in the Indian soils (Bhattacharyya *et al.* 2007a). The C flux between SOC pools and the atmosphere further depends on the type of vegetation, biomass production and removal, organic materials input, soil respiration and soil disturbances such as ploughing (Schlesinger and Andrews 2000a; Schrumpf *et al.* 2011; Shi *et al.* 2012) which are, in turn, influenced by land use/land cover (LULC) conditions. LULC change can, therefore, alter the SOC stock (Batjes 1996; Lal 2004; Robert 2006) mainly in the top 20 cm of the soil profile or the plough layer (Smith 2001). The plough layer has a high concentration of SOC due to high SOM content (Jenny 1994) and low density of SOC (Roose and Barthes 2006) in general, and is mostly influenced by tillage operations (Celik *et al.* 2010) in cultivated areas.

Crop cultivation is known to reduce SOC content (Polyakov and Lal 2004); an estimated 36 Pg C was lost from cultivated soils between 1860 and 1960 (Schlesinger *et al.* 2000b), at a current rate of loss of approximately 0.8 Pg C yr^{-1} (Schlesinger and Andrews 2000a). It can be mentioned here that during the succession stage of agricultural ecosystem, inputs and outputs of soil C got imbalanced and the cultivated soils acted as a source of atmospheric C (Ellert *et al.* 2001), leading to the pertinent loss during the period reported by Schlesinger *et al* (2000b). Current C losses from agricultural soils can rather be reduced by 0.01 – 0.05 Pg C yr^{-1} (Paustian *et al.* 1998) and 0.025–0.037 Pg C yr^{-1} can be potentially fixed in soil (Eglin *et al.* 2010) through proper soil and land management. The magnitude of reduction and/or fixation of SOC due to cropping is known to vary among climates and cropping systems (Lal 2004), crop species as well as on the balance between the loss of C by oxidative forces of tillage operation and the quantity and quality of crop residues that are returned and organics added to the soils (Mandal *et al.* 2007).

**Corresponding Author Email*: piu.roy.123@gmail.com

Thus, while a change in crop combination led to a decrease in SOC stock in one of the agro-ecological sub-region of India; a positive SOC stock change was recorded in areas under intensive agriculture involving irrigation and nitrogen-fertilization as well as in areas under subsistence agriculture involving low fertilizer – mainly organic manure – application that led to low crop yield and relatively low SOC removal in other agro-ecological sub-regions (Bhattacharyya *et al.* 2007b).

Despite the importance of tropical areas in terms of the percentage of global SOC stocks, research on the effect of LULC on SOC stock and C sequestration is limited in these regions. SOC stock has been measured for different agro-ecological regions in India (Bhattacharyya *et al.* 2000; Bhattacharyya *et al.* 2008) but assessment of SOC stock and its variation under different LULC or due to LULC change have been confined to the Indo-Gangetic Plain and Himalayan and Black Soil regions (Bhattacharyya *et al.* 2007b; Bhattacharyya *et al.* 2009a; Bhattacharyya *et al.* 2010). Information on similar aspects is lacking in most parts of the Peninsular Plateau which, owing to its low SOC stock, have a good potential of sequestering C with proper land management practices. The objective of the present study was, therefore, to determine the effect of years of crop cultivation *vis-à-vis* forest and plantation, on the SOC pool in the SOC-poor soils of the Irga watershed in the tropical sub-humid dry bioclimatic zone of the Eastern Plateau and Hills region in Jharkhand, India.

Materials and Methods

Site characteristics

The study was conducted in the Irga watershed ($24^0 10^{'}$N to $24^0 30^{'}$N and $85^0 55^{'}$E to $86^0 10^{'}$E) in the Giridih District of the Jharkhand State, India (Fig.1). The area lies in the tropical sub-humid dry bioclimatic zone (Velayutham *et al.* 1999) experiencing an average annual rainfall of 1350 mm with peaks observed in the summer monsoon months of June to September; and an average annual temperature of 25^0C. The area is a part of the Eastern Plateau and Hills physiographic region of India (Velayutham *et al.* 1999). Topography is flat to rolling with a relative relief of 122 m (maximum elevation – 382 m and minimum elevation – 260 m) and 0 to 7.5% slope.

The watershed is characterized by two soil sub-groups of the Order *Alfisols* – *Typic Haplustalfs* (well-drained soils in the upstream area) and *Typic Paleustalfs* (imperfectly drained soils in the downstream area) (Haldar *et al.* 1996). Two sites were, therefore, chosen to be representative of the soil types – Dhanwar in the upstream area and Birni in the downstream area. The mean SOC content of the watershed is 0.5% (unpublished data collected from Damodar Valley Corporation, Hazaribagh, India).

Three predominant LULC conditions – forest, plantation and cultivated land – were identified in the watershed with the help of Survey of India topographic maps and Resourcesat-2 LISS III image interpretation as well as field survey. Three sites were chosen for each soil sub-group to represent the three land uses (Fig. 1). Field sites were selected by visual inspection, aiming to select forest sampling sites subject to minimal anthropogenic disturbances, and agricultural sites where paddy-fallow rotation is practiced.

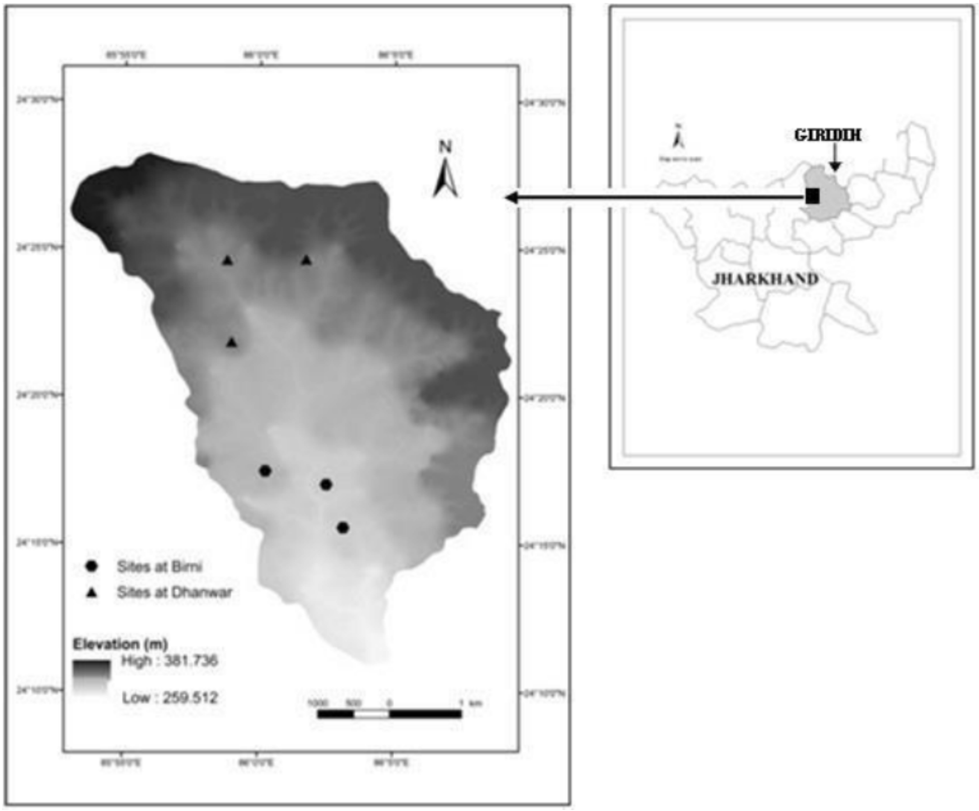

Fig 1 Location of sample sites in the Irga watershed, Jharkhand, India

Forest sites were selected to get an idea about the C levels of native soils that can be viewed as a practical upper limit to C storage potential (Paustian *et al.* 1997). The forests in the Irga watershed comprise of indigenous trees, primarily *Palash* (*Butea Monosperma*) and *Sal* (*Shorea robusta*). In some parts of the watershed, the forests, especially the *Sal* forests, have been completely cleared. But in other parts, the forests had never been totally cleared although they all show some signs of partial logging in the past; sites representative of such native forests were selected for the study. *Mango* orchards are found scattered in some parts of the watershed, espcially in the upstream area. Growth of *Eucalyptus* plantation is mostly due to afforestation and reforestation programs adopted for integrated watershed development. The agricultural practices primarily include rainfed crop production with traditional plough-based method of seedbed preparation; annual crop of *Aman* paddy is produced and fallow rotation system is practiced; farmyard manure (FYM) and compost are mainly used with an additional minimal use of chemical fertilizer. Little crop residue is left in the field so as to meet the alternative demands for fodder and fuel for domestic purposes. The plantation and cultivated plots ranged in approximate age of 50-100 years since conversion from forest (Table 1). Six plots (3 LULC x 2 soil sub-group) were thus selected for the study.

Table 1. Site characteristics

Site	Soil Subgroup	Slope	Drainage	LULC (%)	Location plot	Duration of land use (years)	Crop season	Rotation	Management
Dhanwar	*Typic Haplustalfs*	0-1	Well drained	*Palash* forest	86.00^{0}E 24.41^{0}N	Native	Perennial	NA	NA
				Plantation (*Mango* orchard)	85.98^{0}E 24.41^{0}N	100	Perennial	NA	Partial grazing
				Cultivated	85.98^{0}E 24.36^{0}N	100	*Kharif*	Paddy fallow	Conventional tillage; FYM
Birni	*Typic Paleustalfs*	0-1	Imperfectly drained	Open mixed jungle	86.04^{0}E 24.28^{0}N	Native	Perennial	NA	NA
				Plantation (*Eucalyptus*)	86.00^{0}E 24.29^{0}N	50	Perennial	NA	NA
				Cultivated	86.05^{0}E 24.25^{0}N	100	*Kharif*	Paddy fallow	Conventional tillage; FYM

Soil sampling

Sampling was done during the non-growing phase, *i.e.* over summer, so as to minimize the influence of plant type and growth stage on SOC. Sample cores were taken for every 10 cm layer of each plot for bulk density measurement. Triplicate soil samples were collected from each plot from 0-10 cm and 10-20 cm depths with a narrow flat-bladed shovel and handsaw. The samples were transferred into separate air-tight plastic bags and gently crumbled manually to break the aggregates along planes of weakness while at field moisture content (Jimenez *et al.* 2008). The samples were then allowed to be air-dried for several days in the laboratory before being used for particle size analysis and SOC estimation.

Particle size analysis

Each air-dried soil sample was passed through a 2 mm sieve to obtain fine earth material, *i.e.* soil particles <2 mm diameter (Jenny 1994). Plant residues, mainly leaf and root debris, associated with coarse and fine sand fractions were not separated from the samples. The fine earth materials were then transferred to a nest of sieves (0.25 and 0.05 mm) and shaken mechanically for 30 minutes (Jimenez *et al.* 2008) to collect three particle size fractions – coarse sand (2-0.25 mm diameter), fine sand (0.25-0.05 mm) and silt+clay (<0.05 mm). The sieving duration was sufficient to quantitatively separate the various aggregate size classes while minimizing aggregate abrasion during sieving. Small losses of soil particles were connected with the adhesion of the particles on the sieves and were not removed by washing or any other strong disturbing methods, as they disrupt the aggregates and so affect the natural aggregate composition. Mean weight diameter (MWD) was calculated using the following equation (Gajić *et al.* 2013):

$$\mathrm{MWD} = \sum_{i=1}^{n} \bar{u} m_i$$

where, ū = mean diameter of any particular size range of aggregates separated by sieving, m_i = weight of aggregates in that size range as a fraction of the total dry weight of soil used.

Soil pH analysis

pH of the soil samples was determined by applying the universal pH indicator to a 1:2.5 soil:water suspension using a Soil Testing Kit Model (Jaiswal, 2011; Chaudhuri *et al*., 2013).

SOC estimation

SOC content was determined on three replicates of each plot for both depths using the Walkley and Black wet combustion method (Bhattacharyya *et al.* 2009b; Jaiswal 2011). SOC content was calculated using the following equation:

SOC content (g/100g) = [V x (B – S) x 0.003 x100] / (B x W)

where, V = volume of 1*N* $K_2Cr_2O_7$ solution added, B = blank titre, *i.e.* volume of 0.5*N* $NH_4.FeSO_4$ used for titration of the volume of 1*N* $K_2Cr_2O_7$ solution, S = sample titre, *i.e.* volume of 0.5*N* $NH_4.FeSO_4$ used for titration of soil sample + volume of 1*N* $K_2Cr_2O_7$ solution, W = weight of soil sample used for the analysis.

SOC stock was computed as follows (Jimenez et al. 2008; Jacinthe et al, 2009):

$$\text{SOC stock (Mg ha}^{-1}) = (C/10^3) \times \rho b \times T \times (10^4\ m^2 / ha)$$

where, C = SOC content (g $100g^{-1}$), ρb = bulk density (Mg m^{-3}), T = thickness of soil layer (m).

Statistical analysis

Descriptive statistical analysis with the help of bar graphs was done in MS Excel 2007. Origin 8 software was used to calculate Pearson correlation coefficients between soil properties; and to conduct one-way ANOVA with Tukey's *post hoc* test to compare the effect of LULC on SOC content (Shi *et al.*, 2012). Tukey's test compares the difference between each pair of means with appropriate adjustment for the multiple testing. The results are presented as a matrix showing the result for each pair, either as a P-value or as a confidence interval. Tukey's test, like *t*-test and ANOVA, assumes normality and independence of observations.The Tukey's test results in the present study, showing 'not significant' (0) and 'significant' (1) differences in mean SOC content between LULC groups helped in identifying best land management practice for sequestering C in the selected sites – Dhanwar and Birni.

Results

Soil properties

Soils under native forests and plantation were sandy loam in texture, except under open mixed jungle in Birni which had less than 5% silt+clay content at 0-20 cm depth (Table 2). The cultivated soils had sandy clay loam texture. Particle-size fraction distribution was, in fact, dominated by coarse sand fraction in the 0-10 cm and 10-20 cm depths under all LULC conditions. Coarse and fine sand content, however, decreased with soil depth with a resultant increase in silt+clay content, except in the *Mango* orchard in Dhanwar and open mixed jungle and *Eucalyptus* plantation in Birni. Silt+clay content was higher in the 10-20 cm depth than in the 0-10 cm depth in the cultivated lands in both Dhanwar and Birni.

Soils of the Eastern Plateau and Hills region are primarily acidic; soil pH varies from very strongly acidic (<4.5) to slightly acidic (6 – 6.5) (Agarwal *et al*, 2010). Forest soils in both sites of the study area were very strongly acidic (pH = 4.5 in *Palash* forest in Dhanwar and 4 in open mixed jungle in Birni). Soil pH of the *Mango* orchard in Dhanwar and *Eucalyptus* plantation in Birni was 5.5 and 5, respectively. Soil pH of cultivated land varied from 5.5 in Dhanwar to 6 in Birni (Table 2). Soil pH was same at both depths.

SOC distribution

SOC content in the plough layer was highest in cultivated lands at both sites (0.89 g/100g in Birni and in 0.77 g/100g in Dhanwar), followed by *Mango* orchard in Dhanwar (0.765 g/100g), than in the forest areas (0.56 g/100g in Birni and 0.4 g/100g in Dhanwar) (Table 3). It was least in *Eucalyptus* plantation area (0.21 g/100g). All the plots recorded a decrease in SOC content with depth.

Table 2. Soil properties under different LULC

Site/LULC	Depth (cm)	Coarse sand (%)	Fine sand (%)	Silt+Clay (%)	MWD	Bulk density	pH
Dhanwar							
Palash forest	0-10	57.39	28.38	14.33	0.627	1.39	4.5
	10-20	55.50	27.91	16.59	0.608	1.40	
Mango orchard	0-10	59.20	26.19	14.61	0.645	1.49	5.5
	10-20	61.01	23.27	15.71	0.662	1.58	
Cultivated	0-10	44.12	26.44	29.45	0.491	1.16	5.5
	10-20	42.88	26.46	30.66	0.478	1.44	
Birni							
Open mixed jungle	0-10	65.22	29.59	5.19	0.708	1.51	4
	10-20	66.19	29.87	3.93	0.718	1.29	
Eucalyptus	0-10	52.59	19.54	27.87	0.574	1.44	5
plantation	10-20	55.51	32.23	12.26	0.610	1.67	
Cultivated	0-10	55.09	21.96	22.95	0.601	1.70	6
	10-20	49.17	20.24	30.58	0.539	1.19	

Note: All values are the average of triplicate samples from each plot.

Table 3. Mean, standard deviation and standard error of mean SOC content in selected plots

Site/LULC	Depth (cm)	Mean (g/100g)	Std. Dev.	SE of Mean
Dhanwar				
Palash forest	0-10	0.44	0.01	0.006
	10-20	0.33	0.015	0.008
Mango orchard	0-10	0.81	0.02	0.001
	10-20	0.72	0.015	0.008
Cultivated	0-10	0.85	0.0305	0.017
	10-20	0.69	0.015	0.008
Birni				
Open mixed jungle	0-10	0.63	0.015	0.008
	10-20	0.49	0.007	0.004
Eucalyptus plantation	0-10	0.23	0.01	0.005
	10-20	0.18	0.001	0.0005
Cultivated	0-10	0.94	0.053	0.031
	10-20	0.84	0.007	0.004

SOC stock, however, was found to be highest in the *Mango* orchard in Dhanwar (227.18 Mg ha[1]) in the 0-20 cm depth (Fig. 2). In Birni, on the other hand, highest SOC stock was measured in cultivated land under paddy-fallow rotation (242.76 Mg ha^{-1}). SOC stock was lower in the forests at both the sites – 92.07 Mg ha^{-1} in the *Palash* forest in Dhanwar and 140 Mg ha^{-1} in the open mixed jungle in Birni; and least in the area under *Eucalyptus* plantation (55.98 Mg ha^{-1}).

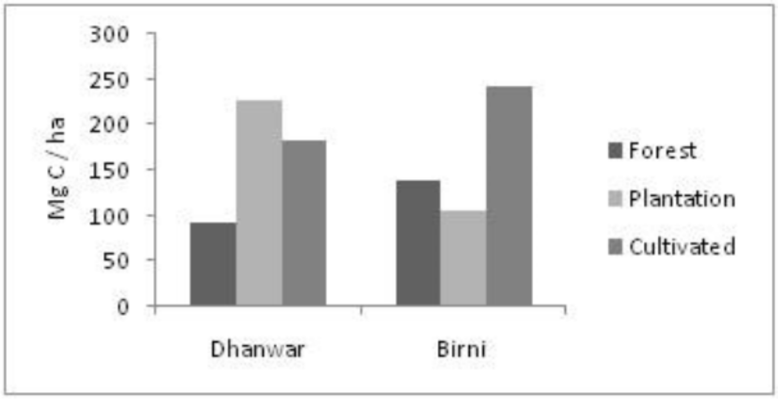

Fig 2 SOC under different LULC at 0-20 cm depth

Relationship between soil properties

MWD decreased with decrease in percentage of coarse sand content (r = 0.99; *P*<0.01) and increase in percentage of silt+clay content (r = - 0.92; *P*<0.01) of soil samples across sites (Table 4). Lower MWD led to significantly lower bulk density (r = 0.361; *P*<0.05) as observed in the soil samples of the cultivated land of Birni (Table 2). There was no significant relationship between bulk density and pH and SOC. Further study is, therefore, required to analyse the variations in bulk density with depth in the study area. SOC was positively correlated with silt+clay content (r = 0.31; *P*<0.05). Consistent with previous studies (Fissore *et al*, 2008), significant positive correlation was observed between SOC and pH (r = 0.61, *P*<0.01) across LULCs (Table 4).

Table 4. Relationship between soil properties at 0-20 cm in selected plots (Pearson correlation coefficient; 2-tailed significance test)

	CS	**FS**	**SC**	**MWD**	**BD**	**pH**	**SOC**
CS	1						
FS	0.345*	1					
SC	-0.918**	-0.676**	1				
MWD	0.993**	0.382	-0.923	1			
BD	0.336*	0.138	-0.312	0.361*	1		
pH	-0.622**	-0.649**	0.755**	-0.634**	0.032	1	
SOC	-0.198	-0.375*	0.319*	-0.206	-0.172	0.610**	1

CS – coarse sand; FS – fine sand; SC – silt+clay

** Significant at 5% level of significance*
*** Significant at 1% level of significance*

Means comparison

One–way ANOVA analysis revealed that the mean SOC content was significantly different (P<0.05) between LULCs in both the sites. Table 5 shows difference in mean SOC content in the selected plots across and within sites. Mean SOC content across soil sub-groups differed significantly (P<0.05 according to Tukey's test) between cultivated land, and area under plantation and native forest at the 0-20 cm depth. In Dhanwar, however, there was no significant mean difference at these depths between *Mango* orchard and cultivated land. In Birni, significant difference in mean SOC content in the plough layer between all the three LULC was observed.

Table 5. Comparison of mean SOC content at 0-20 cm depth in selected plots using Tukey's Test at P≤0.05

Site	LULC	Mean Diff	SEM	Prob	Significance
Across sites	PL NF	0.045	0.109	0.9122	0
	CL NF	0.355	0.109	0.0145	1
	CL PL	0.31	0.109	0.0325	1
Dhanwar	PL NF	0.39	0.039	0.0000001	1
	CL NF	0.388	0.039	0.0000001	1
	CL PL	-0.001	0.039	0.99902	0
Birni	PL NF	-0.360	0.034	0.00000001	1
	CL NF	0.306	0.034	0.0000002	1
	CL PL	0.684	0.034	0	1

Note: PL – Plantation, NF – Native forest, CL – Cultivated land

SOC gains and losses

At 0-20 cm depth, cultivated land in both the sites and *Mango* orchard in Dhanwar showed an increase of 89.93-102.76 Mg SOC ha^{-1} and 135.11 Mg SOC ha^{-1}, respectively in comparison to native forests (Fig. 3). *Eucalyptus* plantation, however, registered a loss 84.02 Mg SOC ha^{-1} at this depth. *Mango* orchard showed the maximum increase in SOC pool at both depths – 62.41 Mg ha^{-1} at 0-10 cm depth and 70.72 Mg SOC ha^{-1} at 10-20 cm depth (Fig. 3a and 3b). The cultivated land in Dhanwar showed a greater increase in SOC pool (54.6 Mg ha^{-1}) at 10-20 cm depth than at 0-10 cm depth (37.67 Mg ha^{-1}). In Birni, on the other hand, cultivated land recorded a greater increase in SOC pool (57.87 Mg SOC ha^{-1}) in the 0-10 cm depth than in the 10-20 cm depth (35.46 Mg SOC ha^{-1}).

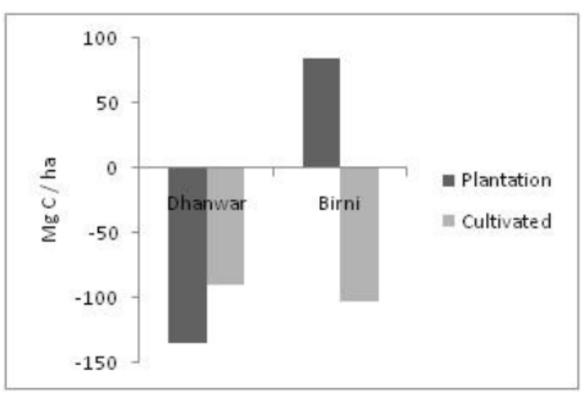

Fig 3 SOC losses and gains from long-term plantation and cultivated land at 0-20 cm depth. Native forest has been used as a baseline.

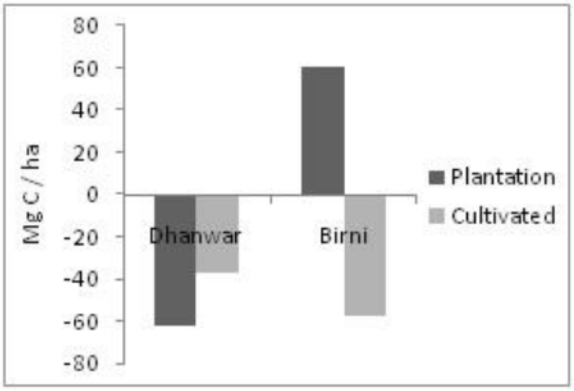

Fig 3a SOC losses and gains from long-term plantation and cultivated land at 0-10 cm depth. Native forest has been used as a baseline.

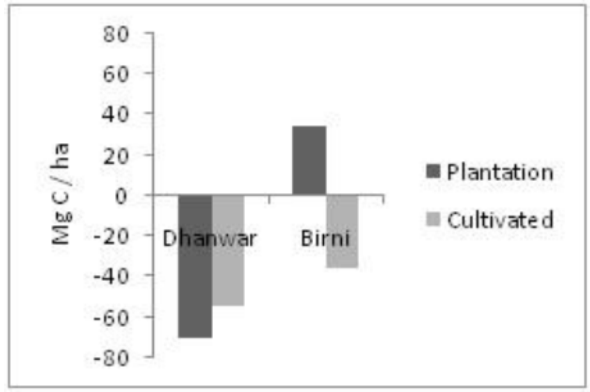

Fig 3b SOC losses and gains from long-term plantation and cultivated land at 10-20 cm depth. Native forest has been used as a baseline.

Discussion

SOC variation across LULC

The most stable SOC size pools are silt+clay domain because of the physical protection afforded by these soil aggregates (Starr *et al.* 2001a; Six *et al.* 2002). But the forests being a repository of the naturally developed sandy soils (Table 2) in the watershed, recorded lower concentration of SOC in the plough layer. Moreover, the forest soils of the watershed being very strongly acidic (4–4.5), had low SOC content ($r = 0.61$; $P<0.05$). SOC content in the cultivated lands, on the other hand, was comparatively higher owing to high percentage of silt+clay particles ($r = 0.31$; $P<0.05$) and high pH values (5.5–6). It was also because of the high concentration of SOC in sand fractions due to the presence of residue-derived particulate organic matter (Velayutham *et al.* 1999; Celik *et al.* 2010, Roy and Sreekesh 2014). Application of fertilizer (Chenu 2006) especially FYM, and poor drainage conditions that are necessarily associated with paddy fields (Celik *et al.* 2010), also led to a higher concentration of SOC in the cultivated lands. Moreover, the practice of keeping the fields fallow after harvesting the monsoon paddy, allowed the soil to regain its fertility. The occasional rainfall in the winter and pre-monsoon seasons allow the growth of light grass cover in the fallows that add to the SOM and is a source of nutrients, when tilled, to the next year crop. Depending on the soil acidity and the type of perennial crop, mean SOC of plantation differed significantly from that of the corresponding forest soil, and was either higher or lower than the forest soil. Although significant difference in mean SOC between plantation and cultivated land was observed across sites as well as in Birni; similar mean SOC content of the two LULCs in Dhanwar can be attributed to similar soil pH (5.5).

The decrease in SOC content with increase in soil depth in all the plots, including the cultivated lands which had higher silt+clay percentage at lower depth, can be attributed to C inputs (plant residues) that are usually localized at the surface (Ellert *et al.* 2001).

SOC variation within LULC

Forests

Despite higher pH and silt+clay content, SOC content of the *Palash* forest soil in Dhanwar was lower than that of the open mixed forest in Birni. The higher SOC concentration in the open mixed forest can be attributed to the imperfect drainage conditions (Mayer, 1994; Xu *et al*., 2011) associated with *Typic Paleustalfs*, unlike the well-drained *Typic Haplustalfs* in the *Palash* forest area. Lower SOC content in the latter can also be due to the low rates of decomposition of *Palash* litter (Manna *et al.* 2004). Different rates of litter decomposition of different species of trees, on the contrary, might have enabled a higher concentration of SOC in the open mixed forest.

Plantations

The high SOC content and stock in the *Mango* orchard in Dhanwar can be attributed to higher soil pH, high amount of plant litter and presence of permanent grass cover. Moreover, partial grazing in the area allows manure incorporation into the soil (Lantz *et al.* 2001) that acts as a bio-fertilizer. Extremely low SOC concentration in *Eucalyptus* plantation, on the other hand, was due to very strongly acidic soil condition as well as lack of adequate surface cover and hence lower incorporation of plant residues to the soil. Low decomposition rates of *Eucalyptus* litter (Bernhard-Reversat 1993) also led to the lower SOC content in this plot.

Cultivated land

SOC content of the cultivated land in Birni was higher than in Dhanwar due to higher pH and lower fine sand content ($r = -0.3$, $P<0.05$) in the former (Table 2). The difference in SOC content of the cultivated land in the two sites can further be attributed to the their location aspect. The higher SOC in the cultivated land of Birni might be due to its location downstream in the watershed that serve as a depositional landscape for C-enriched sediments from the upstream area (Starr *et al.*, 2001b); as well as to the imperfect drainage conditions associated with the *Typic Paleustalfs* that is predominant in this site. It was also observed during field visit that more crop residue was left in the field after harvest in the cultivated land in Birni than in Dhanwar. The crop residues added to the particulate organic matter content of the soil, thereby increasing the SOC content in the samples. Any variation in the rate and amount of fertilizer application and tillage between the two plots needs further investigation to assess the difference in their SOC content accurately.

SOC gain and losses

Increase in SOC pool in the 0-20 cm depth in the cultivated lands in both the sites in comparison to forests, was due to application of organic manure. The cultivated land in Dhanwar showed greater increase in the 10-20 cm depth due to an increase in silt+clay content. On the contrary, increase in the 0-10 cm depth was more in the cultivated land in Birni because of high particulate organic matter content, especially in the coarse sand fractions, consequent upon greater amount of crop residues available in the field. *Mango* orchard showed maximum increase in 0-10 cm as well as 10-20 cm depth, greatest being in the latter, in comparison to forests as well as cultivated land. This can be attributed to adequate undergrowth and high amount of readily decomposable litter, both leading to an increase in the SOC content in each particle aggregate (Roy and Sreekesh 2014). Increase in SOC pool might be recorded in greater depths in the *Mango* orchard due to deeper root systems.

Conclusion

The practice of paddy-fallow rotation, application of manure and the practice of leaving post-harvest crop residue in the field, especially in Birni, led to an increase in the SOC pool in the plough layer of agricultural soils in the SOC-poor area. Thus the agricultural soils in the Irga watershed have the potential to sequester C. Increase in food productivity and C sequestration can be achieved together in this part of the sub-humid dry tropical red soil region with inherently low SOC content, by the adoption of proper cropping techniques through appropriate soil nutrient management practices, and conversion of barren and degraded land to permanent pastures and planting trees, like *Mango*, which have economic value and are also a source of fodder and fuel to the locals.

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