Impact of Land-Use Changes on Soil Properties and Carbon Pools in India: A Meta-analysis

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Land-use changes (LUC), primarily due to deforestation and soil disturbance, are one of the major causes of soil quality degradation and greenhouse gas emissions. Effects of LUC on soil physicochemical properties and changes in soil quality and land use management strategies that can effectively restore soil carbon and microbial biomass levels have been reported from all over the world, but the impact analysis of such practices in the Indian context is limited. In this study, over 1,786 paired datasets (for meta-analysis) on land uses (LUs) were collected from Indian literature (1990–2019) to determine the magnitude of the influence of LUC on soil carbon, microbial biomass, and other physical and chemical properties at three soil depths. Meta-analysis results showed that grasslands (36.1%) lost the most soil organic carbon (SOC) compared to native forest lands, followed by plantation lands (35.5%), cultivated lands (31.1%), barren lands (27.3%), and horticulture lands (11.5%). Our findings also revealed that, when compared to forest land, the microbial quotient was lower in other LUs. Due to the depletion of SOC stock, carbon dioxide equivalent (CO_2 eq) emissions were significantly higher in all LUs than in forest land. Results also showed that due to the conversion of forest land to cultivated land, total carbon, labile carbon, non-labile carbon, microbial biomass carbon, and SOC stocks were lost by 21%, 25%, 32%, 26%, and 41.2%, respectively. Changes in soil carbon pools and properties were more pronounced in surface (0–15 cm) soils than in subsurface soils (15–30 cm and 30–45 cm). Restoration of the SOC stocks from different LUs ranged from a minimum of 2% (grasslands) to a maximum of 48% (plantation lands). Overall, this study showed that soil carbon pools decreased as LUC transitioned from native forestland to other LUs, and it is suggested that adopting crop-production systems that can reduce CO_2 emissions from the intensive LUs such as the ones evaluated here could contribute to improvements in soil quality and mitigation of climate change impacts, particularly under Indian agro-climatic conditions.

Keywords: land-use change, soil carbon pools, microbial quotient, meta-analysis, India

1 INTRODUCTION

Anthropogenic activities have changed the development of livelihood by altering the land-use changes (LUC) in the past century at a very rapid pace (Liu et al., 2005a; 2005b; Hurtt et al., 2006; Liu and Tian, 2010; Tian et al., 2014). The conversion of forest land (FL) into different land use (LU) systems such as barren land (BL), cultivated land (CL), grassland (GL), horticulture land (HL), and plantation land (PL) has been reported at the rate of 13 million hectares (mha) per year through deforestation (FAO, 2006), and sometimes caused a decline in soil quality, thereby reducing its potential for actual productivity (Wei et al., 2014; Nath et al., 2018). Reports from global studies indicated that LUC caused soil degradation resulting from intensive use and uneven terrain coupled with changing climatic conditions (Palni et al., 1998; Abera and Wolde-Meskel, 2013; Kumar et al., 2017; Kumar et al., 2021). This LUC altered the system's capacity as a carbon source or sink (Abera and Wolde-Meskel, 2013; De Blécourt et al., 2013; Guillaume et al., 2015; Fan et al., 2016; Iqbal and Tiwari, 2016). A loss of soil organic carbon (SOC) and biodiversity due to the conversion of FL into different LUs has been well documented (De Blécourt et al., 2013; Ahrends et al., 2015; Guillaume et al., 2015; Nath et al., 2018). Therefore, quantifying the impacts of LUC is critical to better understand the interactions among human activities, climate systems, and ecosystems and to design government policies (Houghton and Hackler, 2003; Tian et al., 2003; Arora and Boer, 2010).

Detecting the impact of management and LUC in soil carbon pools is likely to be more sensitive than total SOC (Campbell et al., 1997; Padbhushan et al., 2015; Padbhushan et al., 2016a; Padbhushan et al., 2016b; Rakshit et al., 2018; Meetei et al., 2020; Padbhushan et al., 2020). Soil microbial activity is the central process in the terrestrial carbon cycle. The microbial quotient (MQ) refers to the ratio between microbial biomass carbon (MBC) to SOC, which is used as a measure of ecophysiological status of soil microorganisms (Anderson and Domsch, 1993). The MQ value can also reflect about the quality and nature of microbial activity in the soil. A large number of studies on MQ have shown its importance to evaluate or monitor the influence of short- or long-term changes in soil biological status due to management and other system-level manipulations (Brookes, 1995; Bastida et al., 2008; Anderson and Domsch, 2010; Padbhushan et al., 2021). Soil properties and SOC stocks may be altered due to soil disturbances (Guo and Gifford, 2002; Paul et al., 2002). A carbon dioxide equivalent (CO_2 eq) emission is a soil indicator that provides information on the amount of carbon loss from SOC stocks into the atmosphere. Through meta-analysis studies, these parameters have been found to be altered in changing LU systems at a global scale (DeFries et al., 2002; Guo and Gifford, 2002; Achard et al., 2004; Houghton, 2008; Don et al., 2011). Therefore, knowledge of soil carbon pools, MQ and CO_2 eq emission helps to understand their impacts in a changing LU system.

India is the world's second largest populous country and is expected to overtake China by 2025 (United Nations Department of Economic and Social Affairs: Population Division, 2019). In India, the human population has increased from 200 million to 1,400 million during 1980–2020 and, coupled with economic growth, has brought significant change in LUs (Tian et al., 2014; World Population Prospects: The 2019 Revision United Nations Population Division, 2020). Total SOC stocks in India are about 20.67 Pg (soil depth 0–30 cm) and 63.19 Pg (soil depth 0–150 cm) covering a total geographical area of 329 m ha. **Figure 1A** depicts the SOC stocks in different physiographic regions of India (Bhattacharyya et al., 2000). The data are summarized into five categories, namely, Northern Mountains, The Great Plains, Peninsular India, Peninsular Plateau, and Coastal Plains and Islands representing the different physiographic regions of India. In the soil depth 0–30 cm, maximum and minimum SOC stocks have been recorded in Northern Mountains and Coastal Plains and Islands, respectively, whereas in the soil depth 0–150 cm, maximum and minimum were recorded in Northern Mountains and Peninsular Plateau. The area covered by the different regions is shown in **Figure 1A**.

Currently, India ranks third with a share of 7% of total CO_2 emissions in the world (IEA, 2019), but ranks 20th in the world for per-capita annual CO_2 emissions, which is approximately 1.94 tons, less than half the global average of 4.8 tons CO_2 (Ritchie and Roser, 2019). The per-capita emissions of CO_2 are lower for India when compared to the other major CO_2 emission contributors of the world (except China). During the period 1880–2020, India has experienced a decline in FL of 18 mha (from 89 mha in 1880 to 71 mha in 2019) and expansion of CL by 49 m ha (from 92 mha in 1880 to 141 mha in 2019) resulted from conversion from FL, GL, and BL into CL (Tian et al., 2014; Bodh, 2019). Due to these conversions, a significant reduction in SOC stocks and its impacts on soil quality and ecosystem health have been observed. **Supplementary Figure S1** presents the trend for the share of FL and CL systems in the total land area during the period 1990 to 2017. Although the magnitude of change is small, the trends are encouraging, i.e., the FL area has increased from 21.5% to 23.7% while the CL area has decreased from 61.1% to 60.4%. Governmental initiatives in recent years have helped to reduce the rate of deforestation rate in India by reducing deforestation, rectifying deforestation by reforestation, and increasing afforestation by establishing forests in new areas (Don et al., 2011). This is evident from the governments' effort to increase the area under forests for achieving the long-term target to fetch 33% of total area under FL cover. However, in the past few years, during 2000–2017, net emissions/removals of CO_2 by the FL have increased (from -18×10^4 gigatons to -11×10^4 gigatons), whereas net emissions/removal of CO_2 of CL and GL remained constant and consistently positive (**Figure 1B**).

A meta-analysis approach has generally been used to assess the magnitude and direction of treatment effects as well as pattern and sources of heterogeneity by combining the findings from several studies under various environmentally and ecologically variable regions (Hedges et al., 1999; Koricheva et al., 2013). For example, meta-analysis has been used to derive general conclusions in ecology, biogeographic patterns of biota, carbon, and nitrogen dynamics and climate change effects at global and regional scales (Treseder, 2008; Meiser et al., 2014; Liu et al., 2020; Porre et al., 2020). Similar research was also conducted
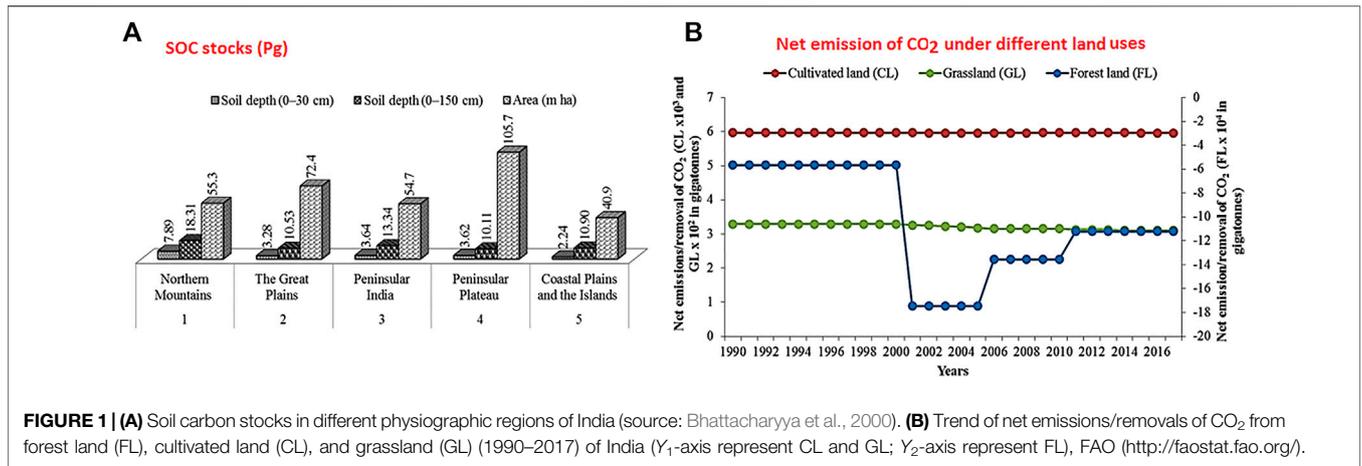
FIGURE 1 | (A) Soil carbon stocks in different physiographic regions of India (source: Bhattacharyya et al., 2000). **(B)** Trend of net emissions/removals of CO_2 from forest land (FL), cultivated land (CL), and grassland (GL) (1990–2017) of India (Y_1-axis represent CL and GL; Y_2-axis represent FL), FAO (http://faostat.fao.org/).
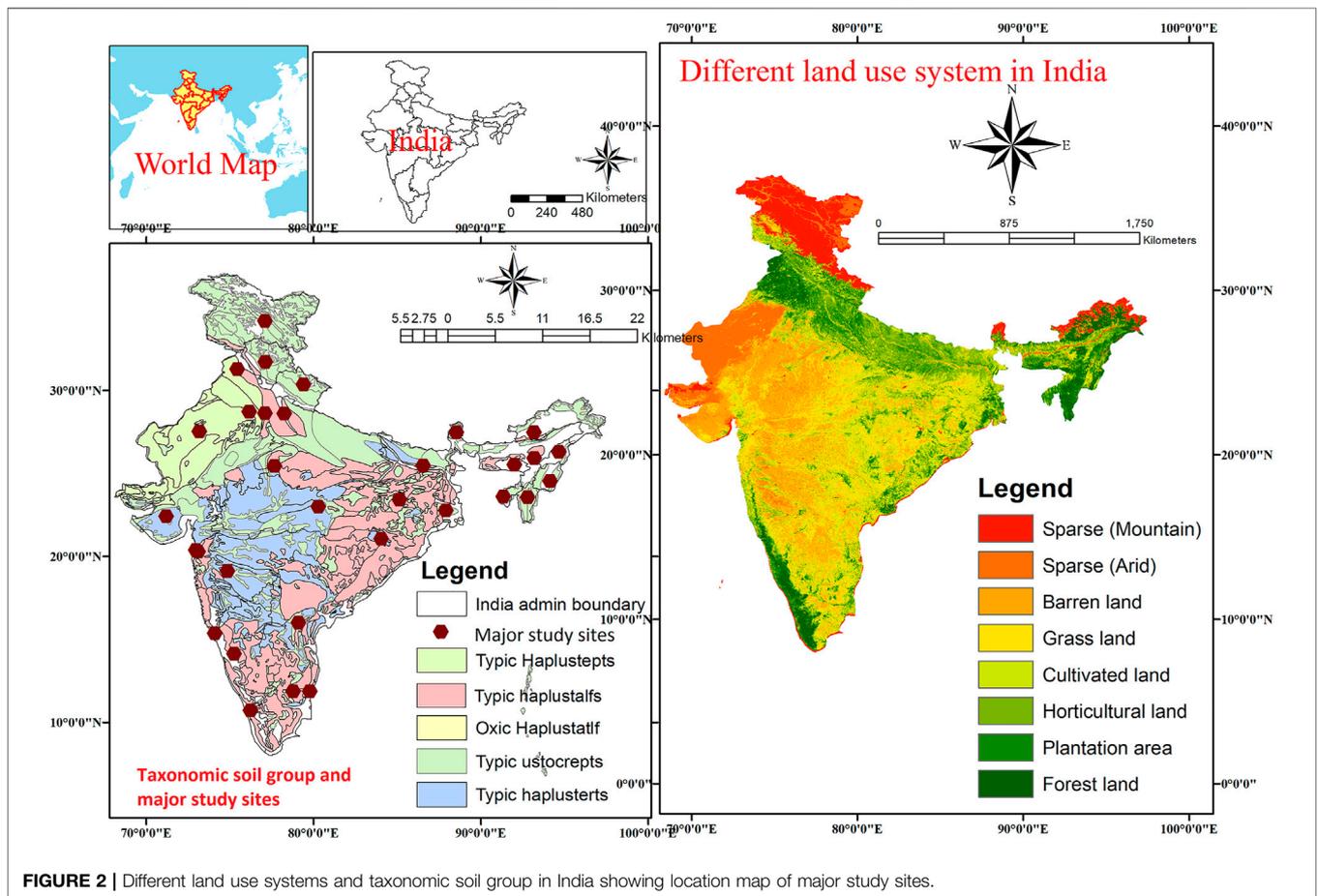
FIGURE 2 | Different land use systems and taxonomic soil group in India showing location map of major study sites.

to quantify the effects of various LUC on the global SOC, soil carbon pools and soil properties through meta-analysis (Guo and Gifford, 2002; Deng et al., 2016) but no such investigations to understand the impact of conversion of FL to other LUs were done in an Indian context.

The main aim of this study is to obtain a quantitative assessment of responses in soil properties under Indian climatic and edaphic conditions including soil carbon stocks, microbial biomass, MQ, and CO_2 equivalent emissions, due to conversion of FL to other LUs. This was done through a meta-analysis approach using datasets obtained from published studies carried out in different regions of India. The general hypothesis was that conversion of FL into LUs with varying degrees of disturbance and plant diversity would cause a general decline in

TABLE 1 | Descriptions of Land uses (LUs) in the study.

S. No	Land uses (LUs)	Descriptions
1	Forest land (FL)	Open to dense forest
		Single species tree cover to several species tree cover
		Himalayan to plain forest
		Low aged to high aged trees
2	Barren land (BL)	Without any vegetation naturally developed
		Without any vegetation developed by human activity
3	Cultivated land (CL)	All types of crop
		All major cropping systems
		Various soil types
		Different management practices
4	Grassland (GL)	Natural one
		No specific grasses grown in the areas
5	Horticulture land (HL)	Orchards
		Agroforestry
6	Plantation land (PL)	Includes arecanut, coffee, mango, oil palm, orange, pine, and teak trees
		Intercultural operations like weeding was performed

SOC stocks along with a decline in soil microbial capacity. Specific goals were to (1) determine the effect of LUC on general soil properties; (2) estimate the effect of LUC on SOC, soil carbon pools, and SOC stocks; (3) determine the relationship between SOC and bulk density (BD) under various LUs; and (4) analyze the variations in MQ and CO_2 eq emission in various LUs in the Indian agroecological context.

2 MATERIALS AND METHODS

2.1 Data Sources and Collections

Data on soil physical, chemical, and biological properties, including soil carbon pools, were obtained from studies that evaluated LUC effects in established experiments covering India's five physiographic regions: Northern Mountains, Great Plains, Peninsular India, Peninsular Plateau, and Coastal Plains and Islands. **Figure 2** shows the major soil taxonomic groups of India and the major study sites (31 locations) from which experimental results were obtained from published literature for the meta-analysis. Data were obtained from published research/ review articles and theses using unique keywords related to the study's objectives. The data were compiled following different categories of LUC, e.g., from FL to BL; from FL to CL; from FL to GL; from FL to HL; and from FL to PL. Data didn't require any specific criteria other than have two minimum LUs including FL. To understand the effect of LUC on soil properties and soil carbon pools, a thorough analysis was conducted on different LU systems in the Indian context (details in **Section 2.2**) and only studies with a minimum of two LUs and with appropriate sets of soil physical, chemical, and biological parameters were considered as part of the selected studies irrespective of years of study as the magnitude of LUC change would depend on the duration that the LU was implemented (details in **Section 2.2**). In all studies with comparable LUs in different agroecological regions, FL use systems are native in nature and other LUs are converted from native forest due to human disturbances. Major soil types covered in this study included alluvial soil, black soil, red soil, laterite soil,

and arid soil. Over the other LUs (BL, CL, GL, HL, and PL), FL was used as a control treatment. This study also covers the Himalayan zone, the Indo-Gangetic plains, the north-eastern region, and the peninsular region, which represent different subtropical climate regions of India. Specific soil types, taxonomy, management methods, crops and cropping systems, as well as specific trees and grasses were not included in this report.

2.2 LU Selection and Soil Parameters Considered for the Study

Figure 2 shows the major LU systems present in the different agroecological regions of India. The description of different LUs selected for the assessment of changes in soil carbon in the Indian soils is given in **Table 1**. Details of the soil parameter data used in this study and the soil characteristics of various LUs are given in **Table 2** and **Table 3**.

2.3 Data Compilation

Various published literatures (original articles, review papers, and theses) were collected from the period of 1990–2019 and reviewed critically in context to the impact of LUC on soil carbon pools and soil properties in different regions of India with an aim of finding the changes in these soil parameters due to conversion of FL to other LUs. Following a general analysis, data from a replicated studies on different LUs were used, with FL data serving as a control to better understand the impact of LUC on BL, CL, GL, HL, and PL in India. To understand the impact of LUC in various soil depths (0–0.15 m, 0.15–0.30 m, and 0.30–0.45 m), 1,786 paired datasets from 31 major study sites (reflected in **Figure 2**) with multiple LU comparisons including the FL system were analyzed for meta-analysis using MetaWin 2.1 software.

2.4 Meta-Analysis: Method of Analysis Using Diverse Datasets

Two stage-based random effect meta-analyses were used to analyze the database and understand the comparative changes

TABLE 2 | Soil parameters considered in the study.

S. No	Soil parameters		Measurement units
1	Soil properties	Soil pH	No unit
		Bulk density (BD)	Mg m^{-3}
		Cation exchange capacity (CEC)	cmol (p+) kg^{-1}
		Soil organic carbon (SOC)	%
		Total carbon (TC)	Mg ha^{-1}
		Soil carbon stocks (SOC stocks)	Mg ha^{-1}
2	Soil carbon pools	Labile carbon (LC)	%
		Non-labile carbon (NLC)	%
		Microbial biomass carbon (MBC)	mg kg^{-1}
3	Microbial quotient (MQ)	MBC/SOC	No unit
4	Carbon dioxide equivalent emissions (CO$_2$ eq. emissions)	Relative SOC stocks loss x 44/12	Mg ha^{-1}

TABLE 3 | Soil characteristics of various land uses from the collected studies.

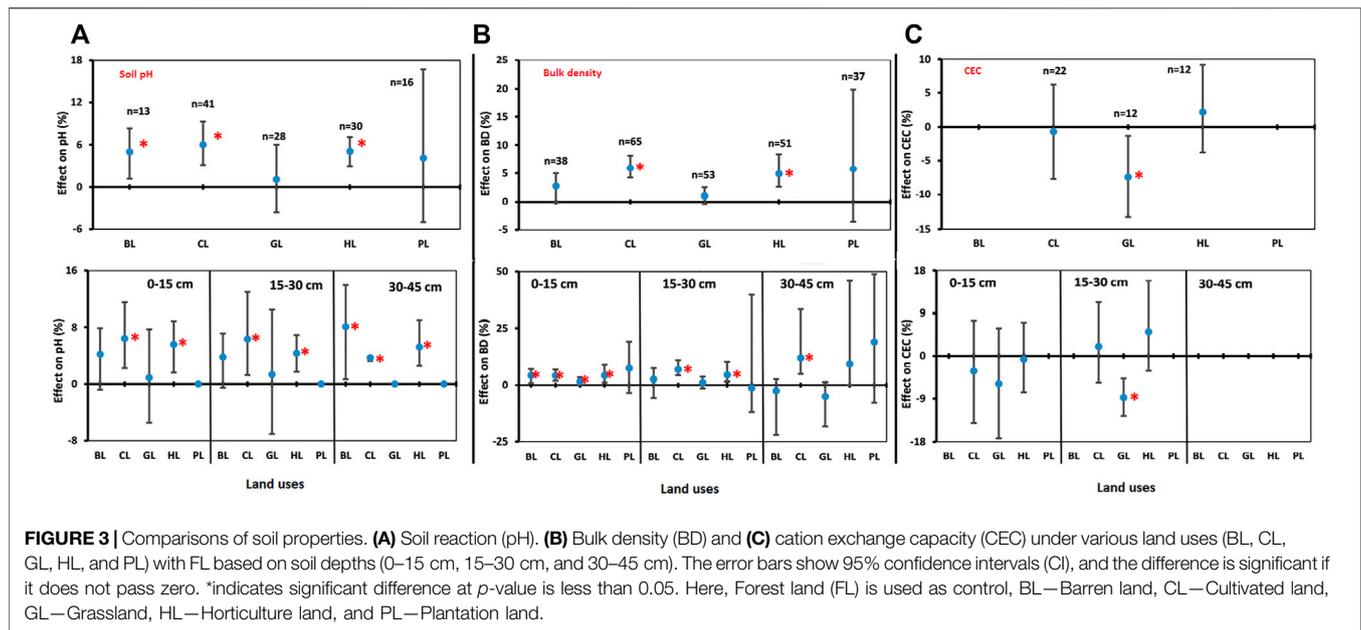| Soil parameters / Land uses	Soil pH	BD	SOC	CEC	TC	LC	NLC	MBC	SOC stocks
Barren land (BL)									
Minimum	4.52	1.38	0.40	17.50	12.00	0.18	0.07	51.10	1.10
Maximum	7.69	1.83	2.51	18.60	43.15	1.50	0.51	154.7	106.1
Average	5.93	1.54	1.08	17.93	19.67	0.50	0.29	97.98	24.13
Standard error	0.08	0.04	0.05	0.04	0.61	0.03	0.01	2.91	1.60
Cultivated land (CL)									
Minimum	4.29	1.60	0.90	5.21	1.60	0.01	0.04	24.1	2.10
Maximum	8.10	1.75	2.90	19.46	108.7	0.93	0.49	486.0	77.00
Average	6.26	1.68	0.77	12.45	12.28	0.17	0.24	155.2	19.68
Standard error	0.07	0.03	0.05	0.38	1.15	0.02	0.01	21.69	1.12
Grassland (GL)									
Minimum	4.36	1.43	0.70	10.51	5.60	0.02	0.05	20.00	1.10
Maximum	6.20	1.69	2.48	17.27	46.11	0.44	0.41	198.2	141.0
Average	5.54	1.49	0.91	14.22	17.59	0.11	0.26	599.7	31.40
Standards error	0.04	0.04	0.05	0.13	0.70	0.01	0.01	16.02	3.04
Horticulture land (HL)									
Minimum	4.59	1.65	0.29	11.98	7.10	0.03	0.20	67.50	9.50
Maximum	8.20	1.71	2.44	20.32	105.6	0.74	0.43	666.0	59.07
Average	6.08	1.68	1.12	15.69	22.24	0.21	0.37	178.3	32.31
Standard error	0.08	0.03	0.09	0.14	1.89	0.01	0.01	20.92	1.11
Plantation land (PL)									
Minimum	4.10	1.26	0.30	3.65	6.72	0.01	0.16	##	7.00
Maximum	8.00	1.59	3.40	6.69	269.3	0.33	143.8	##	67.72
Average	6.08	1.49	1.03	5.03	61.53	0.18	16.22	##	19.67
Standard error	0.09	0.03	0.04	0.08	8.20	0.01	3.43	##	1.23
Forest land (FL)									
Minimum	4.47	1.37	0.50	14.11	1.90	0.01	0.11	52.50	9.20
Maximum	7.80	1.65	4.82	19.90	223.0	0.96	0.71	848.0	192.2
Average	6.03	1.46	1.38	16.06	27.51	0.24	0.45	204.9	37.55
Standard error	0.05	0.03	0.09	0.14	3.61	0.02	0.02	21.72	2.73

##No sufficient data.

(Rosenberg et al., 2000; Chakraborty et al., 2017; Sharma et al., 2019). Under this, the effect size (ES) was calculated for individual parameter as the natural log of the response ratio (InR) using the equation as proposed by Hedges et al. (1999):

$$ES = lnR = ln\left[\frac{X_T}{X_C}\right]$$

Where X_T is the average of response variables (SOC, SOC stocks, soil carbon pools, and other soil parameters) of the treatments (LUs), and X_C is the average of these variables in FL with control.

In the second stage, combined effect estimate was determined as a weighted mean of the effects estimated in the individual studies. A weighted mean is calculated as

FIGURE 3 | Comparisons of soil properties. **(A)** Soil reaction (pH). **(B)** Bulk density (BD) and **(C)** cation exchange capacity (CEC) under various land uses (BL, CL, GL, HL, and PL) with FL based on soil depths (0–15 cm, 15–30 cm, and 30–45 cm). The error bars show 95% confidence intervals (CI), and the difference is significant if it does not pass zero. *indicates significant difference at p-value is less than 0.05. Here, Forest land (FL) is used as control, BL—Barren land, CL—Cultivated land, GL—Grassland, HL—Horticulture land, and PL—Plantation land.

$$\text{Weighted mean} = \frac{N_T X N_C}{N_T + N_C}$$

Where N_T and N_C represent the number of replications for each of the treatments (LUs), in an individual study. If more than one observation was included in a treatment, the weighted are divided by the number of observations from that study. Since the studies were from different soil and environmental conditions and with varying multiple replications, the standard deviation calculated was based on the number of observations with a simple statistical procedure in MS excel. ES from individual studies were then combined using a mixed-effect model to calculate the cumulative effect size and the 95% confidence intervals (CIs) through boot-strapping with 4,999 iterations (Adams et al., 1997). The mixed-effect model is a random-effect meta-analytic model for categorical data (Rosenberg et al., 2000), assuming random variation among studies within a group and fixed variation between groups. The cumulative effect was considered significant if the CIs did not pass over zero. Results were interpreted by back-transformation and presented as change in percentage caused by treatments in relation to control. The comparisons tested for their significance were between FL and different LUs and the meta-analyzed values presented in graphs with statistical significance (for *p* values < 0.05) marked with an asterisk.

2.5 Linear Model for Correlation Among SOC and BD in Different LUs

Data for SOC and BD within different LUs were log transformed for normalization and analyzed for potential relationships using a general linear regression model (Nelder and Wedderburn, 1972), and the regression equations plus R^2 values are shown in the **Figure 8**.
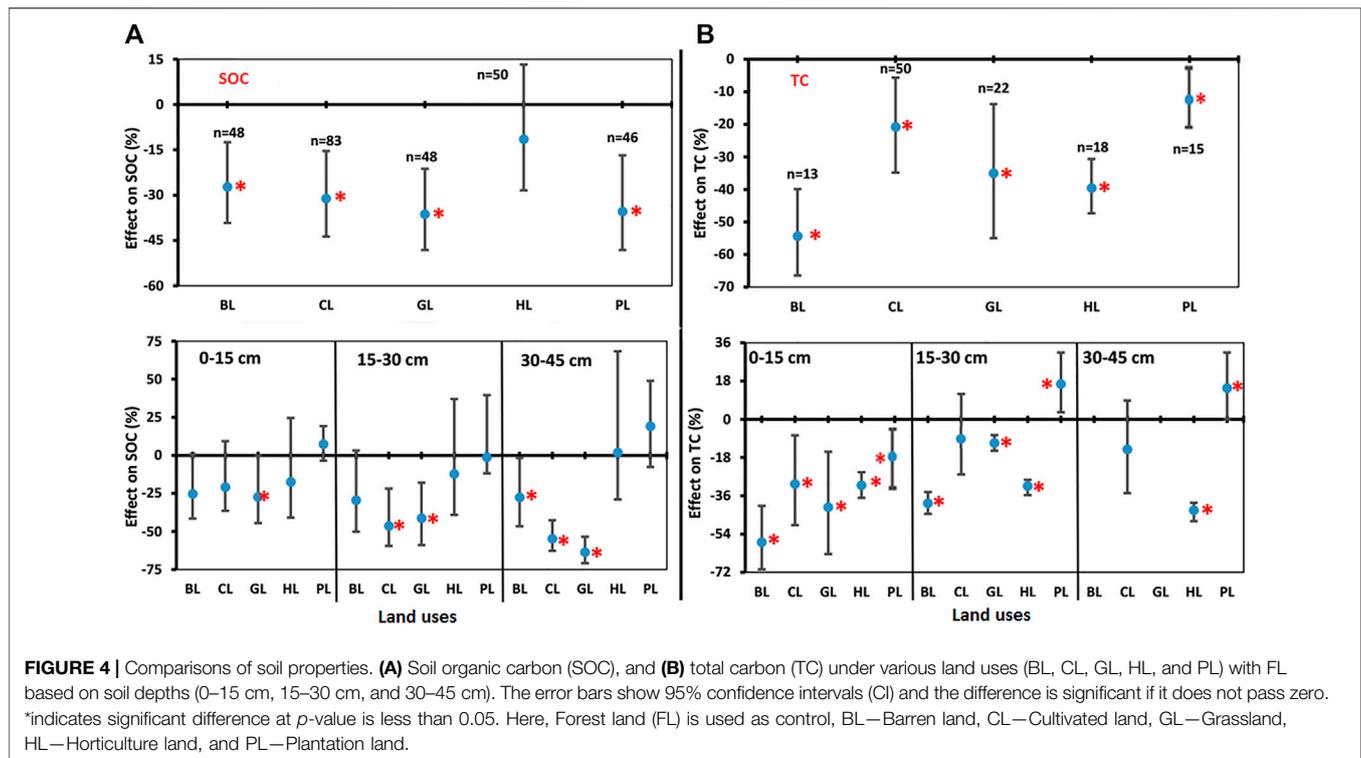
3 RESULTS

3.1 Impacts on Soil pH

LUC showed positive effects on soil pH for LUs like BL, CL, GL, HL, and PL when compared to FL (**Figure 3A**). For example, soil pH increased significantly for BL (5.0%), CL (6.0%), and HL (5.0%) but found non-significant changes for GL (1.1%) and PL (4.1%) over the FL, which is considered as control for this study. Soil pH showed positive effects for other LUs over the FL for depth-wise data (**Figure 3A**). In the 0–15 cm soil depth, pH increased significantly in CL (6.4%) and HL (5.6%) over the FL, but no significant changes were found for BL, GL, and PL. In the 15–30 cm soil depth, pH increased significantly in CL (6.3%) and HL (4.3%) over the FL but was non-significant for BL, GL, and PL, whereas in soil depth 30–45 cm, pH increased significantly in BL (8.1%), CL (3.7%), and HL (5.2%) over the FL and was non-significant for GL and PL (**Figure 3A**). The depth-wise results of pH were in concurrence to the findings of overall pH except for BL and similarly indicated that conversion of FL towards other LUs could result into increase in soil pH (**Figure 3A**).

3.2 Impacts on Bulk Density and Cation Exchange Capacity

BD was found to be significantly and positively affected in LUs CL and HL over the FL. The percent increase of BD in BL, CL, GL, HL, and PL was 2.7%, 5.9%, 1.0%, 4.9%, and 5.8%, respectively, when compared with FL (**Figure 3B**); however, the increase was lower in the GL system. BD improved with soil depths, particularly at 0–15 cm; a significant increase of 4.2% (BL), 4.1% (CL), 1.6% (GL), and 4.2% (HL) was observed over the FL. CL and HL showed a consistent increase in BD with increased depth, 6.8% and 4.5% (15–30 cm) and 11.8% and 9.1% (30–45 cm), respectively, which was significant over

FIGURE 4 | Comparisons of soil properties. **(A)** Soil organic carbon (SOC), and **(B)** total carbon (TC) under various land uses (BL, CL, GL, HL, and PL) with FL based on soil depths (0–15 cm, 15–30 cm, and 30–45 cm). The error bars show 95% confidence intervals (CI) and the difference is significant if it does not pass zero. *indicates significant difference at p-value is less than 0.05. Here, Forest land (FL) is used as control, BL—Barren land, CL—Cultivated land, GL—Grassland, HL—Horticulture land, and PL—Plantation land.

FL (**Figure 3B**). Others showed a non-significant change. Conversion of FL to GL reduced CEC significantly in particular in the 15–30 cm depth. For example, the percent decrease for GL in CEC was 8.8% over the FL (**Figure 3C**).

3.3 Impacts on Soil Organic Carbon
Negative effects of LUC on SOC were found for LUs like BL, CL, GL, HL, and PL when compared to FL (**Figure 4A**). The SOC decreased significantly for BL (−27.3%), CL (−31.1%), GL (−36.1%), and PL (−35.5%) over the FL considered as control for this study, but changes were non-significant for HL (−11.5%). SOC decreased with soil depth in LUs when compared to FL (**Figure 4A**). In the soil depth 0–15 cm, SOC decreased significantly in BL (−25.5%) and GL (−27.5%) over the FL but changed non-significantly for CL (−21.0%), HL (−17.5%), and PL (−31.1%) in comparison to FL. In soil depth 15–30 cm, SOC decreased significantly in BL (−29.6%), CL (−46.5%), GL (−41.3%), and PL (−40.5%) over the FL. The reduction was higher in soil depth 30–45 cm where SOC decreased significantly in BL (−27.7%), CL (−54.9%), GL (−63.7%), and PL (−36.4%) over the FL. In both soil depths, the observed changes for HL were −12.4% (15–30 cm) and 1.8% (30–45 cm), respectively, and were non-significant. The depth-wise results of SOC were in concurrence to the findings of overall SOC and similarly indicated that conversion of FL towards other LUs would cause a decline in SOC content.
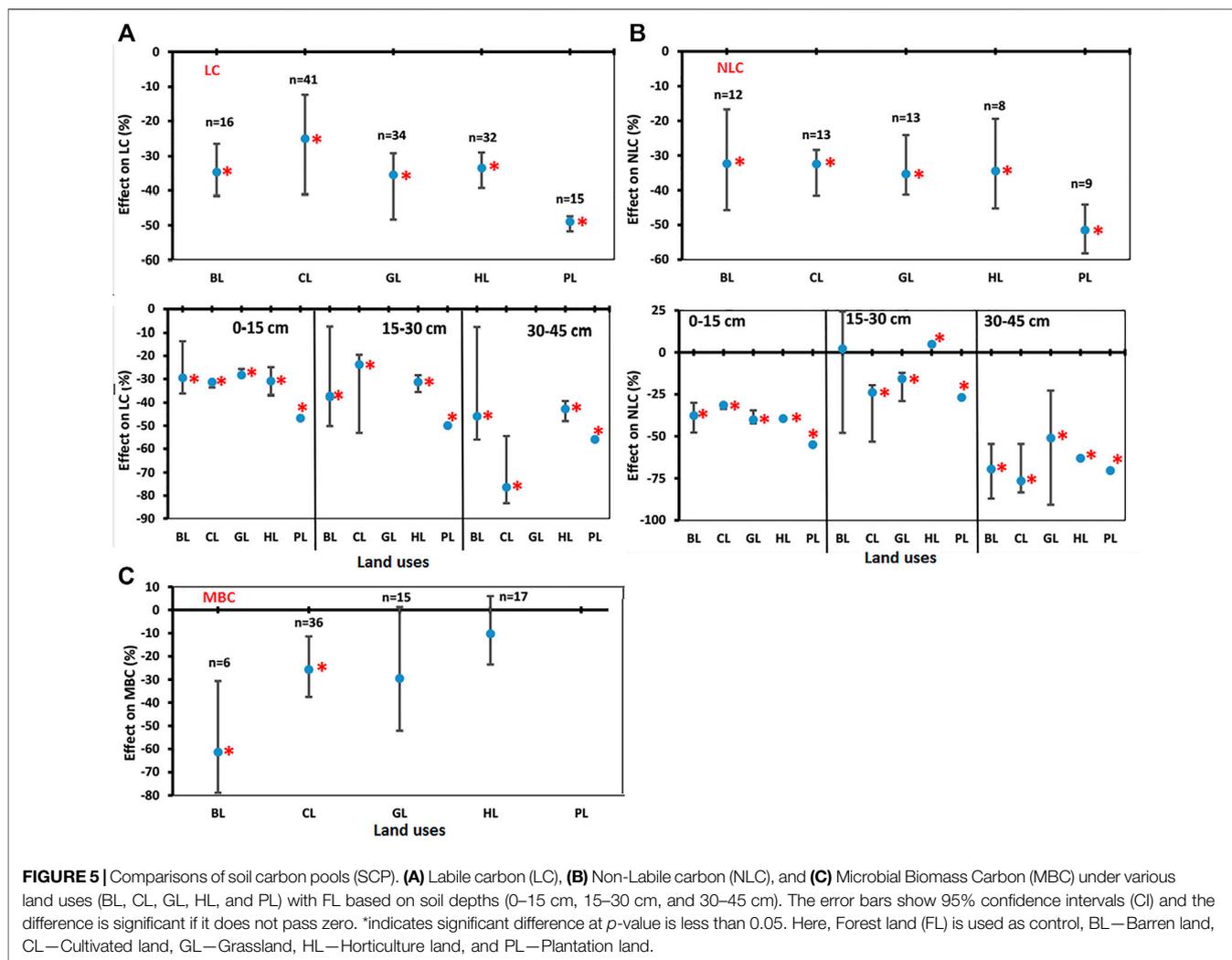
3.4 Impacts on Total Carbon
Negative effects of LUC on total carbon (TC) were found for LUs like BL, CL, GL, HL, and PL when compared to FL (**Figure 4B**).

TC decreased significantly for BL (−54.3%), CL (−20.8%), GL (−35.0%), HL (−39.6%), and PL (−8.7%) over the FL. Total C decreased with soil depth for other LUs over the FL (**Figure 4B**). In soil depth 0–15 cm, TC decreased significantly in BL (−57.8%), CL (−30.5%), GL (−41.4%), HL (−31.2%), and PL (−20.2%) over the FL. In soil depth 15–30 cm, TC decreased significantly in BL (−39.5%) and GL (−31.6%) over the FL and increased significantly in PL (16.6%). However, TC for CL was not significantly different as compared to FL. In soil depth 30–45 cm, TC decreased significantly in HL (−40.0%) over the FL and increased significantly in PL (14.7%) over the FL (**Figure 4B**).

3.5 Impacts on Labile Carbon and Non-Labile Carbon
Labile carbon (LC) decreased significantly for BL (−34.7%), CL (−24.9%), GL (−35.5%), HL (−33.5%), and PL (−48.9%) over the FL (**Figure 5A**). These results indicated that conversion of FL towards other LUs could readily result into decline in LC content under most conditions. Labile C decreased significantly in the soil depth 0–15 cm in BL (−29.6%), CL (−9.7%), GL (−28.4%), HL (−31.0%), and PL (−46.8%) over the FL. Also, in soil depth 15–30 cm, LC decreased significantly in BL (−37.6%), CL (−45.6%), GL (−55.6%), HL (−31.4%), and PL (−50.0%) over the FL. In soil depth 30–45 cm, LC decreased significantly in BL (−45.9%), CL (−53.8%), GL (−64.6%), HL (−42.8%), and PL (−56.0%) over the FL (**Figure 5A**).

Non-labile carbon (NLC) decreased significantly for BL (−32.3%), CL (−32.4%), GL (−35.3%), HL (−34.5%), and PL

FIGURE 5 | Comparisons of soil carbon pools (SCP). **(A)** Labile carbon (LC), **(B)** Non-Labile carbon (NLC), and **(C)** Microbial Biomass Carbon (MBC) under various land uses (BL, CL, GL, HL, and PL) with FL based on soil depths (0–15 cm, 15–30 cm, and 30–45 cm). The error bars show 95% confidence intervals (CI) and the difference is significant if it does not pass zero. *indicates significant difference at p-value is less than 0.05. Here, Forest land (FL) is used as control, BL—Barren land, CL—Cultivated land, GL—Grassland, HL—Horticulture land, and PL—Plantation land.

(−51.5%) over the FL (**Figure 5B**). These results indicated that conversion of FL into other LUs could result into decline in NLC content under most conditions in all soil depths. In soil depth 0–15 cm, NLC decreased significantly in BL (−37.6%), CL (−31.4%), GL (−40.0%), HL (−39.44%), and PL (−54.9%) over the FL. In soil depth 15–30 cm, NLC decreased significantly in CL (−23.8%), GL (−15.6%), and PL (−26.8%) over the FL and increased significantly in HL (4.9%) as compared to FL. The BL was non-significantly changed in this depth. In soil depth 30–45 cm, NLC decreased significantly in BL (−69.5%), CL (−76.4%), GL (−51.0%), HL (−63.0%), and PL (−70.4%) over the FL (**Figure 5B**). In general, the percent decrease in 30–45 cm soil depth was greater than that in 15–30 cm followed by 0–15 cm (**Figure 5B**).

3.6 Impacts on Microbial Biomass Carbon (MBC)
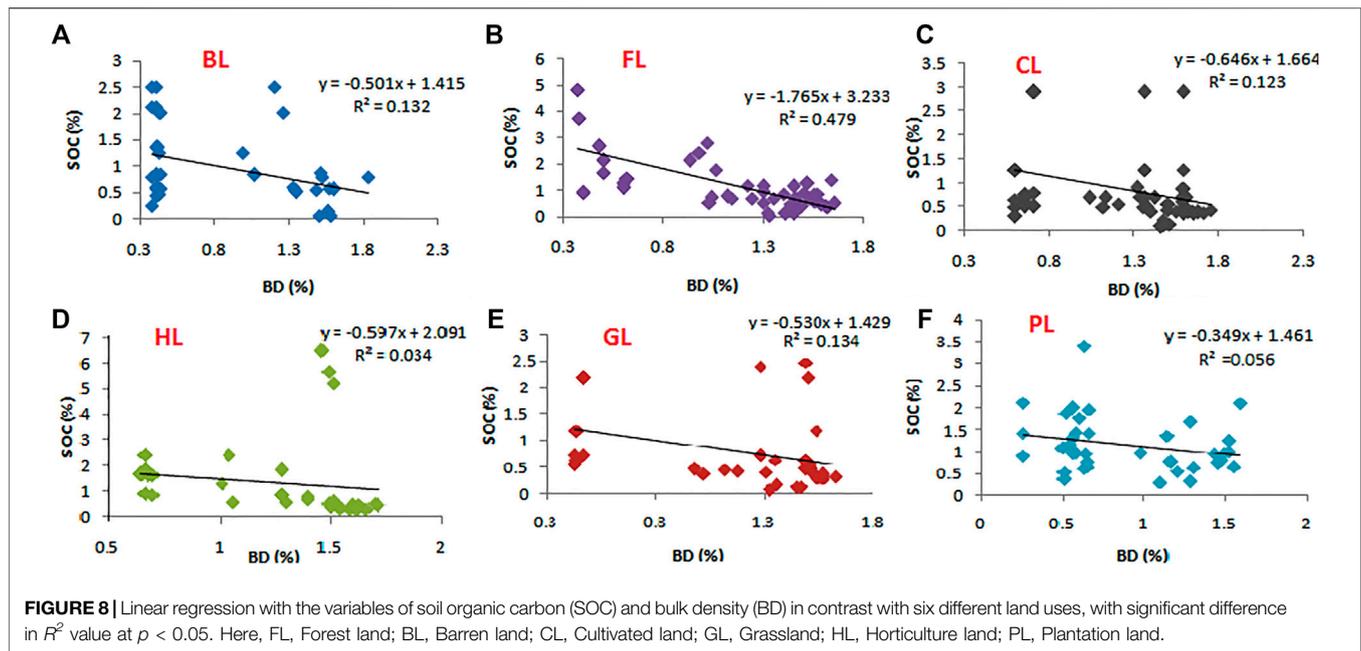Negative effects of LUC on soil MBC were found for LUs like BL, CL, GL, and HL (**Figure 5C**). For example, MBC levels decreased significantly for BL (−61.3%) and CL (−25.7%) over the FL but changes in GL (−29.5%) and HL (−10.3%) were non-significant. These results indicate that the conversion of FL to other LUs (BL/ CL/GL/HL) could result in the decline of MBC content in soils (**Supplementary Figure S2**).

3.7 Changes in Soil Carbon Stocks (SOC Stocks) by Land-Use Change
LUC impacts on the SOC stocks were seen in all the regions of the country. For example, conversion of FL into LUs such as BL, CL, HL, and PL significantly reduced SOC stocks, whereas no significant change was observed under GL (**Figure 6**). The percent reduction of SOC stocks in BL, CL, GL, HL, and PL was 34.0%, 41.2%, 1.5%, 33.5%, and 47.9%, respectively, as compared with FL (**Figure 6**). There was a general trend of reduction in SOC stocks in all LUs. In soil depth 0–15 cm, SOC stocks decreased significantly in BL (−31.9%), CL (−38.3%), HL (−38.0%), and PL (−30.2%) over the FL but no significant change was observed for GL (5.7%) (**Figure 6**). Similarly, in soil depth
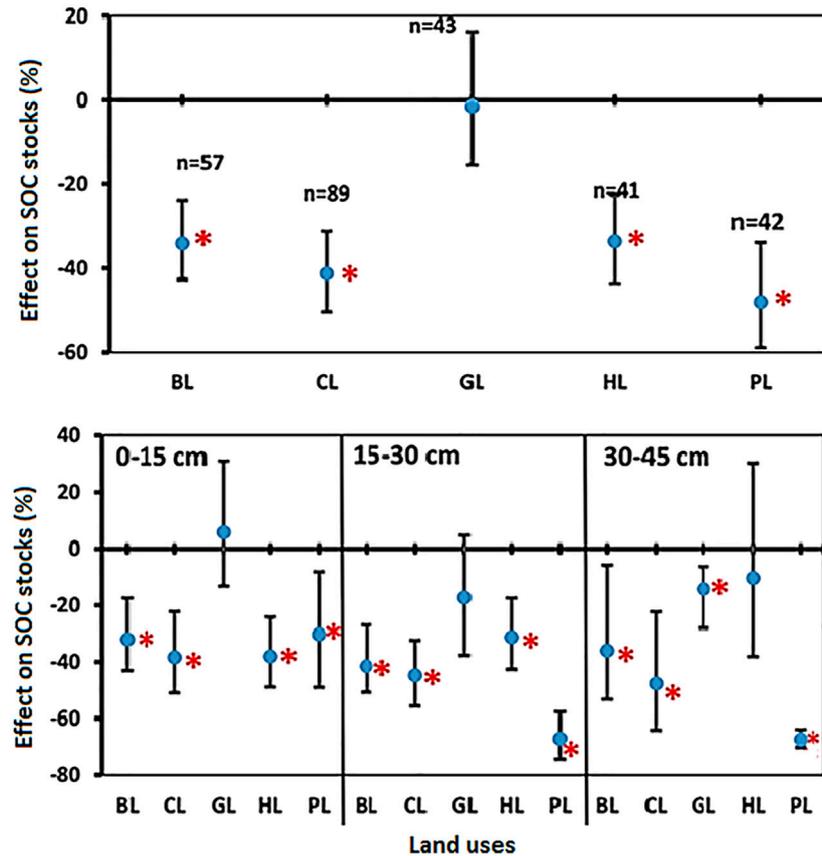
FIGURE 6 | Comparisons of soil carbon stocks (SOC stocks) under various land uses (BL, CL, GL, HL, and PL) with FL based on soil depths (0–15 cm, 15–30 cm, and 30–45 cm). The error bars show 95% confidence intervals (CI) and the difference is significant if it does not pass zero. *indicates significant difference at *p*-value is less than 0.05. Here, Forest land (FL) is used as control, BL—Barren land, CL—Cultivated land, GL—Grassland, HL—Horticulture land, and PL—Plantation land.
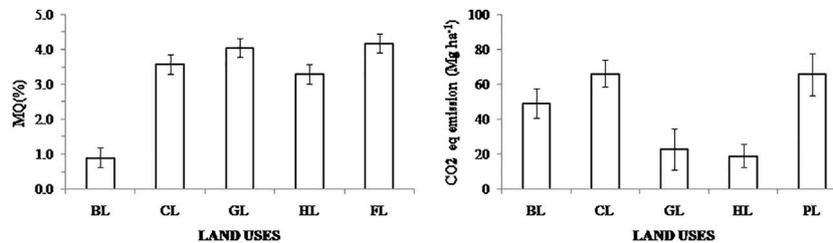
FIGURE 7 | Comparison of microbial quotient (MQ) and CO_2 eq. emissions in various land uses from the collected studies (mean ± standard error). Here, Forest land (FL) is used as control, BL—Barren land, CL—Cultivated land, GL—Grassland, HL—Horticulture land, and PL—Plantation land. Note: PL has no sufficient data for MQ analysis.

15–30 cm, SOC stocks decreased significantly in BL (−41.4%), CL (−44.6%), HL (−31.2%), and PL (−67.1%) over the FL, but the small change observed for GL (−17.3%) was not significant. Unlike the two top soil depths, in the soil depth 30–45 cm, SOC in GL decreased significantly (−14.2%), whereas the change in HL (−10.3%) was non-significant. There was a significant change in SOC in BL (−35.9%), CL (−47.6%), and PL (−67.2%) over the FL (**Figure 6**).

3.8 Effect of LUC on Microbial Quotient (MQ) and CO_2 Equivalent Emission

Results for MQ and CO_2 equivalent emission showed significant differences in all LUs compared to FL systems (**Figure 7**; **Supplementary Figure S2**). MQ values in BL were lowest (0.91 ± 0.28) compared with those observed in other LUs (ranging from 3.31 ± 0.45 to 4.19 ± 0.49), whereas CO_2 equivalent emissions were lower in GL and HL (23 ± 11 and

FIGURE 8 | Linear regression with the variables of soil organic carbon (SOC) and bulk density (BD) in contrast with six different land uses, with significant difference in R^2 value at $p < 0.05$. Here, FL, Forest land; BL, Barren land; CL, Cultivated land; GL, Grassland; HL, Horticulture land; PL, Plantation land.

19 ± 8 Mg ha^{-1}, respectively) and highest in CL and PL systems (66 ± 12 Mg ha^{-1}) compared to FL (**Figure 7**).

3.9 Correlation of SOC With BD in Land Uses

Bulk density (BD) was found to be significant and negatively correlated with SOC in all the LUs at $p < 0.05$ (**Figure 8**). The maximum correlation was observed in FL ($R^2 = 0.48**$).

4 DISCUSSION

4.1 Changes in Soil Properties Following Land-Use Change

Deforestation and LUC from FL to different LU production systems with varying anthropogenic activities has been suggested to increase CO_2 and other GHG emissions contributing to climate change (Lal, 2004; Wang et al., 2021). Through meta-analysis, this study attempted to determine the impact of LUC on soil properties, particularly SOC and microbial biomass, in the Indian context using datasets representing different agroecological regions. Appropriate number of datasets was used for conducting meta-analysis of soil parameters: soil pH ($n = 155$), SOC ($n = 333$), BD ($n = 303$), and TC ($n = 163$). A positive change in soil pH due to changes of LU as observed in our study resonates the earlier work done (Rabbi et al., 2016; Malik et al., 2018). The higher positive impact on soil pH in CL followed by HL, BL, PL, and GL could be due to the management practices including application of fertilizers and other soil amendments, irrigation practices, etc. It has been reported that LU intensification in lower pH soils positively affects the pH and leads to SOC loss through increased rate of decomposition from improved microbial growth and activity (Malik et al., 2018). Sharma et al. (2014) recorded higher soil pH in CL than the FL in Indian Himalaya's foot hill. LUC have an impact on soil properties such as BD. A positive change in BD due to changes of LU was recorded in

our study similar to previous reports (Vidya et al., 2002; Meena et al., 2018). Lower BD in FL than other LUs could be partly attributed to the higher organic matter (OM) content in the soil, better aggregation resulting in an increase in the volume of micropores, and overall better soil structure (Materechera and Mkhabela, 1995). The highest BD was found in soil depths of 30–45 cm, while the lowest was found in surface soil (0–15 cm), indicating that BD increased with soil depth due to the effects of the overlying soil's weight (Vidya et al., 2002; Meena et al., 2018).

A better understanding of the dynamics and responses in SOC content is vital for detecting and forecasting changes in response to global climate change (Negi and Gupta, 2010). The evidence from the meta-analysis of experimental findings from different agroecological regions indicates a general trend of decline in SOC from the conversion of FL into different LUs. Similar findings for the reduction in SOC when native forest systems were converted into managed agroecosystems have been reported from other regions of the world (Mayer et al., 2020). The heterogeneity associated with various studies considered in this meta-analysis, in terms of environmental, edaphic, and specific management practices, contributed to the differences in the magnitude of effect seen for different LUs. Similar results were reported in the central Himalayan region of Uttarakhand, India (Kalambukattu et al., 2013).

Large annual additions of OM in the form of leaf litter, which are potentially highest in the FL, coupled with lack of tillage/disturbance activities and a slow rate of decomposition would have contributed to higher soil carbon values (Haynes, 2005; Baker et al., 2007; Kalambukattu et al., 2013). Whereas the lower SOC in other LUs compared to FL could be attributed to the tillage and other disturbance activities, removal of crop residues through burning, grazing, irrigation, etc. affects higher OM decomposition and nutrient mineralization (Batjes, 1999; Ogle et al., 2014). Decomposition of OM releases CO_2 into the environment, resulting in a decrease in SOC (Ramzan et al., 2019). In the case

of CL systems, crop residue removal, intensive cultivation practices, and increased microbial carbon turnover can increase carbon losses from the soil system (Lal and Kimble, 1997; Yang et al., 2004; Baker et al., 2007; Smith et al., 2008; Sharma et al., 2014). The loss of SOC through increased CO_2 levels into the environment is suggested to contribute significantly to the global warming and climate change (Lal 2004; Sanderman et al., 2017). Therefore, there is a widespread belief that it is important to store SOC in the terrestrial environment through increased SOC sequestration and reduced losses in order to manage climate change and associated effects on overall ecosystem health. Any attempts to reduce SOC losses through changes in the management in different LUs would help sequester more carbon in terrestrial ecosystems. The study shows that there is scope for improvement of SOC in different LUs (BL/CL/GL/PL/HL) to become carbon equivalent to that in FL systems, i.e., a potential to increase SOC by 27.3% in BL, 31.1% in CL, 36.1% in GL, 35.5% in PL, and 11.5% in HL. This change could be possible through proper management strategies that promote C sequestration in soil. As with our findings, several studies have found a strong and negative association between SOC and BD over the LUC (Hati et al., 2007; Wang et al., 2011; Padbhushan et al., 2016a; Padbhushan et al., 2016b; Meena et al., 2018).

TC content is one of the key indicators of soil quality that has been linked to the long-term addition of organic residues to the soil (Lemke et al., 2010; Yang et al., 2012; Padbhushan et al., 2016b), and it plays an important role in improving other physico-chemical properties of soils. Total C includes all carbon pools, i.e., inorganic carbon, charcoal carbon, and organic carbon (which includes labile carbon pools). While the changes in TC reflect the overall changes in SOC stocks, it may not give true reflection of changes in SOC components that may differentially respond or change due to management in different LUs. Measuring changes in TC content due to LUC has been shown to take longer periods, i.e., decades, compared to the changes that can be seen in the more labile components of SOC (Lal, 2004; Sanderman et al., 2017). Over the FL, the TC trend changed from BL < HL < GL < CL < PL (higher negative value to lower negative value). In terms of soil depths, the 0–15 cm soil depth showed the greatest difference in negative value, indicating that changes in TC were greater in the surface soil than the other soil depths due to more litter addition on the undisturbed soil.

It is now well accepted that changes in TC may not be a sensitive indicator for short-term responses on SOC stocks, and carbon sequestration and measurement of SOM composition or soil carbon pools have been suggested as better indicators of changes in soil quality due to LUC (Gregorich et al., 1994; Leifeld and Kögel-Knabner, 2005).

4.2 Changes in Soil Carbon Pools and Microbial Quotient (MQ) Following Land-Use Change

Soil carbon pools such as LC, NLC, and MBC were shown to give more useful information about carbon cycling and loss through CO_2 emissions and more sensitive soil-quality parameters for carbon dynamics under different management practices (Yang et al., 2012). PL showed greater loss both for LC and NLC than other LUs used in

our study over the FL. This could be due to post burn cultivation in the PL system. Similar results were corroborated by Sahoo et al. (2019) in Mizoram, Northeast India who reported lower LC and NLC in PL than other LUs compared to FL. The negative effects of LUC from FL extended to all the SOC pools including LC pool. Thus, FL systems showed the highest values for SOC pools compared to all the LUs considered in this study. High soil carbon pools (for all the three soil quality parameters) in FL could be attributed to undisturbed litter additions for long periods. In contrast, disturbances caused by cultivation and low additions of OM are reasons for low LC in CL. Consequences are nutrient loss and impacting macroaggregate formation, which result in lowering in soil fertility and quality, including higher BD and soil compaction. In general, LC was more in surface soil than the subsurface soil potentially due to higher amounts of added root biomass and exudation coupled with surface crop residues (Padre et al., 2007; Brar et al., 2013; Padbhushan et al., 2015).

MBC represents the living component of SOC and is considered to reflect LC levels in soil systems (Gonzalez-Quiñones et al., 2011; Mendoza et al., 2020). Soils from FL systems showed the highest amount of MBC levels mostly from the larger amounts of aboveground residues and root biomass (Holden and Treseder, 2013; Kumar et al., 2021). MBC can be a sensitive indicator of SOC changes as it has a much faster rate of turnover; hence, trends in MBC have been suggested to predict longer-term trends in SOC (Gupta et al., 1994; Lal, 2004; Haynes 2005; Padbhushan et al., 2020). The lack of carbon inputs from plants would be the primary reason for the lowest MBC in the BL systems. It is well known that the practice of fallowing in cropping lands can cause a significant reduction in MBC and microbial activities (Sarkar et al., 2020). Similarly, the lower value of MBC in CL is attributed to the intensive tillage practice promoting microbial turnover of biologically available soil OM and crop residues and the loss of carbon as CO_2 emissions (Gougoulias et al., 2014; Tiefenbacher et al., 2021). There are several individual and meta-analysis studies that reported significant reductions in MBC from conventional tillage practices, in particular when compared to no-till practices (Roper et al., 2010; Zuber and Villamil, 2016).

MQ is one of the important derived measures to indicate changes in MBC, potential for microbial carbon turnover, and the general soil quality in different LU systems (Anderson and Domsch, 1993). Unlike the absolute values of microbial biomass, MQ being a ratio avoids the problems from comparing values across soils and systems with different total SOM levels. Results in this study indicate that MQ showed greater effect in BL followed by PL, CL, and GL. The lowest values for MQ coupled with lower SOC in BL suggest that changing FL systems to BL not only reduced the overall SOC stocks but also affected microbial carbon turnover, with an overall decline in soil quality. The general trend of higher MQ values in LUs such as FL and GL suggests the presence of perennial vegetation and/or lower disturbance supporting higher biological activity and associated ecosystem functions. It is suggested that a greater decrease in MQ values, in particular LUs, indicates that soil is being used in an exploitative manner and microbial pools are declining faster than changes in the total SOC (Sparling, 1997).

4.3 Changes in SOC Stocks Following Land-Use Change

LUC-associated fluctuations in SOC stocks have been reported in many agroecological regions from different parts of the world (Chatterjee et al., 2018; Pellikka et al., 2018). Also, the conversion of LUs from FL to other LUs leading in lower SOC stocks can result in a decrease in soil quality (De Blécourt et al., 2013; Guillaume et al., 2015; Fan et al., 2016; Iqbal and Tiwari, 2016). Changes in LU from FL to other LUs can serve as a carbon source while also affecting soil characteristics (Abera and Wolde-Meskel, 2013). According to a report, about 350 mha of FL has been transferred to other LUs (ITTO, 2002), resulting in biodiversity loss (Ahrends et al., 2015) and 20–40% SOC storage losses (De Blécourt et al., 2013; Guillaume et al., 2015). According to a meta-analysis, when native FL was transformed to PL and CL, SOC stocks decreased by 13%–42% (Guo and Gifford, 2002). Similarly, in this study, LUs had a negative effect on SOC stocks. The absence of deep-rooted trees and fewer canopy covers in this study resulted in lower SOC stocks for PL and HL as compared to FL. Also, SOC content is an indicator of the influence of nature of crops and its management practice. These PL use types undergo regular intercultural operations, which thereby reduces the input of carbon to the soil (Sahoo et al., 2019). The equilibrium between the rate of deposition of photosynthetic materials and the rate of respiration by decomposer microorganisms influences the ability for soils to sequester carbon from the atmosphere (Mathieu et al., 2015). In addition, since root tissue is more resistant to decomposition and mineralization than top soil litters, root-derived carbon has a longer residence period (Rasse et al., 2005).

This meta-analysis study shows that the scope of improvement of SOC stocks in other LUs (BL/CL/GL/PL/HL) to become carbon equivalent to FL can be possible by increasing SOC stocks by 33.5%–41.2% in BL, CL, and HL systems. The level of increase in SOC stocks required was lowest in GL (1.47%) systems and highest in PL. The general trend for the required increase of SOC stocks with depth was similar to the total SOC. However, this change being more in lower depths as compared to surface soil is due to the differences in SOC stocks brought out by LUCs in the subsurface soil over the surface soil. As restoring the lost SOC stocks under different LUs is a difficult job, it is worthwhile to make it possible through management practices. A large amount of atmospheric CO_2 can be restored into the soil, which may help mitigate the problems of climate change. Integration of organic inputs with chemical fertilizer in cultivated soil can be one of the better LU management strategies for restoring carbon in the soil and improving the crop productivity and thus managing soil health and ensuring food security (Padbhushan et al., 2020).

4.4 Effects of SOC on Soil Health and Food Security

Greenhouse gases (GHGs) are the main players to maintain the Earth's habitable temperature. A small change in their amount in the atmosphere can affect the climatic conditions on Earth. Anthropogenic emissions of CO_2 are likely to increase with increase in human population (Lelieveld et al., 2019). Human led LUC can result in significant exchanges of CO_2 between the soil and air (Lal, 2004). Carbon dioxide equivalent (CO_2 eq) emissions in our study were found to be affected in all the LUs over the FL, suggesting loss in SOC stocks. CL and PL had more SOC stocks lost and added more CO_2 in the atmosphere (Sahoo et al., 2019). Therefore, restoration of carbon in the soil can be one of the options to counteract the effect of climate change and the problems created due to climate change. Since OM plays a multifaceted role in several soil processes (Gregorich et al., 1994), SOC is one of the essential components for sustaining soil health and food security by the maintenance of the production system (Anantha et al., 2018).

The findings in this study show that changes in LU have an effect on not only SOC but also other soil resources. Some studies have found links between SOC and total nitrogen and other parameters, implying that OM turnover has an effect on these variables (Xu et al., 2019). The importance of soil management and carbon storage is becoming more widely recognized. However, due to continued LUC to meet the ever-growing food production needs, maintaining or improving low levels of SOC stocks is a major challenge. This issue can be mitigated by employing proper crop production management strategies that include systems with lower disturbance/tillage practices, retention of crop residues, application of organic manures, and inclusion of perennial crops as part of an integrated system approach.

5 CONCLUSION

Our study found that LUC had a positive effect on soil pH and BD, while SOC, TC, and soil carbon pools were negatively affected, in comparison with FL systems. The conversion of FL to other LUs resulted in losses of overall SOC stocks and the trends were similar in all the soil carbon pools such as LC, NLC, and MBC. LUC, in general, affected soil carbon pools and soil properties in surface as well as subsurface layers. SOC stocks declined by a minimum of 2% in GL, 42% in CL, and 48% in PL. There was a negative association between SOC and BD in several LUs. Similarly, when compared to FL, MQ and CO_2 eq emissions were negatively impacted in all LUs (BL/CL/GL/HL/PL). Overall, in view of the evidence for the potential impact of LUC on SOC stocks, C turnover, and soil quality, there is an urgent need for sustainable management of current production systems and natural resources that reduce CO_2 emissions and increase soil carbon in LU systems in India.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

ACKNOWLEDGMENTS

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.794866/full#supplementary-material

Supplementary Figure S1 | Trend of share of forest land (FL) in Y1-axis and cultivated land (CL) in Y2-axis area of total land (1990–2017) of India, FAO (http://faostat.fao.org/).

Supplementary Figure S2 | Relationship between microbial biomass carbon (MBC, mg carbon/kg soil) and soil organic carbon (SOC, g carbon/kg soil) from the studies used in the study. Dotted lines indicate microbial quotient (MQ) of 2.5% and 5%.

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