Soil organic carbon pools and carbon management index under different land use systems in North Western Himalayas

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Current study was conducted to evaluate the effect of important land uses and soil depth on soil organic carbon pools viz. total organic carbon, Walkley and black carbon, labile organic carbon, particulate organic carbon, microbial biomass carbon and carbon management index (CMI) in the north Western Himalayas, India. Soil samples from five different land uses viz. forest, pasture, apple, saffron and paddy-oilseed were collected up to a depth of 1 m (0-30, 30-60, 60-90 cm). The results revealed that regardless of soil depth, all the carbon pools differed significantly ($p < 0.05$) among studied land use systems with maximum values observed under forest soils and lowest under paddy-oilseed soils. Further, upon evaluating the impact of soil depth, a significant ($p < 0.05$) decline and variation in all the carbon pools was observed with maximum values recorded in surface (0-30 cm) soils and least in sub-surface (60-90 cm) layers. CMI was higher in forest soils and lowest in paddy-oilseed. From regression analysis, a positive significant association (high R-squared values) between CMI and soil organic carbon pools was also observed at all three depths. Therefore, land use changes and soil depth had a significant impact on soil organic carbon pools and eventually on CMI, which is used as deterioration indicator or soil carbon rehabilitation that influences the universal goal of sustainability in the long run.

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2   **use systems in North Western Himalayas**

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22 # ABSTRACT

23 A current study was undertaken to examine the impact of important land use systems (LUSs) and

24 depth on soil organic carbon (SOC) pools viz. total organic carbon, Walkley-Black carbon, labile

25 organic carbon, particulate organic carbon, microbial biomass carbon, and carbon management

26 index (CMI) in the north Western Himalayas, India. Soil samples from five different land use

27 viz. forest, pasture, apple, saffron, and paddy-oilseed were collected up to a depth of 90 cm (0-

28 30, 30-60, 60-90 cm). The results revealed that regardless of soil depth, all the carbon pools

29 differed significantly ($p < 0.05$) among studied LUSs with maximum values observed under

30 forest soils and lowest under paddy-oilseed soils. Further, upon evaluating the impact of soil

31 depth, a significant ($p < 0.05$) decline and variation in all the carbon pools was observed with

32 maximum values recorded in surface (0-30 cm) soils and least in sub-surface (60-90 cm) layers.

33 CMI was higher in forest soils and lowest in paddy-oilseed. From the regression analysis, a
34 positive significant association (high R-squared values) between CMI and SOC pools was also
35 observed at all three depths. Therefore, land use changes and soil depth had substantial impact on
36 SOC pools and eventually on CMI, which is used as a deterioration indicator or soil carbon
37 rehabilitation that influences the universal goal of sustainability in the long run.

38 **Keywords:** carbon management index, SOC pools, soil quality, soil depth, sustainability.

39 **1. Introduction**
40 SOC is a substantial fertility attribute that affects various soil properties, thus influencing the
41 quality of soil and ecological functions (Benbi et al. 2015; Yadav et al. 2018). It tends to
42 sequester carbon and performs a significant function in the global carbon cycle (Lal 2018) and
43 climate change (Zhang et al. 2017). However, anthropogenic disturbances have been a
44 significant reason for soil loss and degeneration of carbon stocks, which is a grieve concern to
45 ecosystem sustainability (Yadav et al. 2018). Soils have undergone unabated degradation at a
46 formidable rate owing to wind and water erosion, desertification, and salinization resulting from
47 abuse and inapt agricultural practices. Therefore, it becomes critical to protect them from further
48 deterioration as there is a corresponding depletion in soil quality to produce nutritious crops. Soil
49 organic matter (SOM) is fundamental for agricultural sustainability and its compositional
50 alterations could eventuate in both total and active carbon pools (Blair et al. 1995) where labile
51 fraction includes microbial biomass carbon (MBC), particulate organic matter (POM), easily
52 extractable carbon, readily mineralizable carbon and carbohydrates (Haynes 2005). Among the
53 fractions, labile organic carbon (LOC) is quite susceptible to the alterations in vegetation and
54 microenvironment of soil and management practices (Sahoo et al. 2019; Cheng et al. 2008;
55 Sainepo et al. 2018). Soil carbon is substantially impacted by climate, and land use changes (Lal
56 2018), and the transition from natural to the managed system causes SOC pool depletion (Yigini
57 and Panagos, 2016; Somasundaram et al. 2018; Meena et al. 2018). In Kashmir Himalayas, a
58 significant impact of cropping sequences on carbon sequestration has been observed, resulting in
59 the alteration of soil physical, chemical, and biological properties (Kalambukattu et al. 2013). In
60 addition, conservation tillage and agro-forestry system have been found to have a greater ability
61 for SOC storage among the different management practices in agricultural soils (Babu et al.
62 2020; Luo et al. 2010; Lal 2002; Nath and Lal 2017). Soil stores four times more carbon than the

63 biosphere up to 2 meters (Lal 2001) and fewer alterations in SOC can aid in significant variation

64 in atmospheric carbon dioxide stock (Babu et al. 2020). Thus sustaining SOM is of paramount

65 significance for conserving the quality of soil and ecological balance.

66 The physical, chemical, and biological properties of soil and the self-organization capacity are

67 directly impacted by organic carbon (OC) pools and carbon lability (Addiscott 1995; Blair and

68 Crocker 2000). As a result, their integration into CMI, could serve as a vital metric for assessing

69 the potential of management systems for improving soil quality (Blair et al. 1995, 2006 a, b;

70 Diekow et al. 2005). Greenhouse effect could also be reduced by sequestering carbon through

71 suitable land-use systems (Sofi et al. 2016; Han et al. 2013). Forest land use has a maximum

72 potential to sequester soil carbon compared to other land uses (Kooch et al. 2012). However, the

73 prominent land uses of Kashmir valley are under constant stress caused by land conversions

74 owing to cultivation and infrastructural activities (Fayaz et al. 2020), thus reducing carbon

75 sequestration and threatening sustainability. Moreover, most of the studies are concerned with

76 fertility evaluation and crop yields, water, and fertilizer management, however, the impact of

77 LUSs and soil depth on SOC fractions and CMI in the Kashmir Himalayas has not been well

78 studied. Pertaining to the significance of related work, proper comprehension and consideration

79 of research regarding carbon pools and carbon sequestration are needed. Hence, this study was

80 carried out to (i) determine the influence of different LUSs and soil depth on SOC pools, (ii) to

81 evaluate the CMI among LUSs at different depths, and (iii) to identify the relationships between

82 various C fractions and CMI. The outcome is expected to be substantial in order to develop

83 strategies for better soil carbon management and carbon rehabilitation to serve the purpose of

84 global sustainability.

85 **2. Materials and methods**

86 **2.1. Study area**

87 A study was carried out across Kashmir valley in India with an altitude range from 1587-

88 2640 meters. Kashmir valley lies between the coordinates of 33° 20' to 34° 54' N and 73° 55' to

89 75° 35' E occupying a total area of 1.5948 million hectares, which includes the net sown area

90 (3.31 lakh hectares), forest (5.24 thousand hectares), permanent pastures (34.92 thousand

91 hectares) and other grazing lands. The soils in the study area are of different groups including

92 hapludalfs, hapludolls, ochraualfs, eutrochrepts, croboralfs, argiudolls, ustifluvents, udifluvents,

93 fluviatile and lacustrine. Five different land uses were selected based on the land use system

94 being followed over the last 30-40 years viz., forest, pasture, apple, saffron, and paddy-oilseed.

95 A purposive random method of sampling was used for the collection of geo-referenced soil

96 samples from preferred LUSs prevailing in the study area. In the forest, soil samples were taken

97 in between the tree rows, in pasture lands, soil samples were taken in the moderately grazed area.

98 However, in Apple, soil samples were taken just outside the drip line and in saffron, samples

99 were taken inside corm beds while in the paddy-oilseed cropping system samples were taken

100 inside crop fields. All the samples were collected in the summer season at 0-30, 30-60, and 60-90

101 cm soil depth. Each soil sample was a composite of four sub-samples, and three soil samples

102 from different locations were collected, for each land use system.

103 **2.2. Physico-chemical properties**

104 Soil samples collected from different locations were air dried, ground and passed through a 2

105 mm sieve to analyze different parameters. Particle size distribution was assessed by the

106 hydrometer method in line with Bouyoucos (1927).

107 Soil reaction (pH) was assessed using a glass electrode pH meter as described by Jackson (1973).

108 Bulk density (BD) was evaluated by employing the protocols described by Blake and Hartge

109 (1986). Soil cores were taken from each location and from each land use system. The weight of

110 soil + core sampler (Wt_{sc}) was recorded and the volume of core sampler (V) was determined, and

111 substituted in the equation:

112
$$BD = \frac{Wt_{sc}}{V}$$

113 Available nitrogen (N) was assessed by employing the respective standard method described in

114 Subbiah and Asija (1956), where 5 g soil sample (< 2mm) was treated with 20 ml of 0.32%

115 $KMnO_4$, 25 ml of 2.5% sodium hydroxide solution and 10 ml of distilled water followed by

116 distillation. To determine the nitrogen content of the sample, a distillate was collected in a boric

117 acid mixture, and absorbed ammonia was titrated with 0.2 N H_2SO_4.

118 **2.3. Soil organic carbon pools**

119 Total organic carbon represents the carbon stocks in the soil which was determined by the wet

120 oxidation as previously described in Snyder and Trofymow (1984). The calculation is as follows:

121   Mg C trapped = (mean meq H^+ used in titrating blanks – meq H^+ used in

122   sample) x 12 mg C/2 meq +

123   When 1.0 N HCL is used in titrating, this formula reduces to:

124   Mg C trapped = (ml HCL Blank – ml HCL sample) x 6

125   Walkley Black carbon (WBC) represents readily oxidizable OC which was evaluated by

126   oxidizing OM using chromic acid, followed by back titration of unconsumed potassium

127   dichromate with ferrous sulfate (Walkley and Black 1934).

128   For labile carbon determination, the soil was oxidized with 333 mM $KMnO_4$ followed by shaking

129   and centrifugation, and the concentration of $KMnO_4$ was quantified at 565 nm wavelength using

130   a spectrophotometer (Blair *et al*. 1997).

131   Particulate organic carbon was determined by shaking a suspension (soil+ 0.5% sodium

132   hexametaphosphate) for 24 hours followed by sieving through 0.053 mm and the retained

133   material was subjected to the wet oxidation method (Camberdella and Elliot 1992).

134   MBC was determined using the fumigation extraction method as previously described in

135   Jenkinson and Powelson (1976), where one set was fumigated with fresh ethanol-free chloroform

136   while another set was un-fumigated and extraction with 0.5 M K_2SO_4 followed by oxidation with

137    $K_2Cr_2O_7$ and titration with ferrous ammonium sulfate.

138   **2.4. Carbon management index**

139   CMI is an evaluation methodology that indicates how a certain land type alters the quality of soil

140   in contrast to a reference land use. The CMI was computed from the following relationships:

141   i)   Carbon pool index (CPI) = $\dfrac{Sample\ total\ C\ (mg/g)}{Reference\ total\ C\ (mg/g)}$

142

143   ii)   Carbon lability index was calculated as follows:

144   a)   Lability of Carbon = $\dfrac{C\ in\ fraction\ oxidized\ by\ KMnO4}{C\ remaining\ un-oxidized\ by\ KMnO4}$

145   The lability of carbon was estimated from the difference between labile carbon content and non-

146   labile carbon content (difference between TOC and LOC) of samples.

147   b) Lability index (LI) = $\dfrac{\textit{Lability of C in sample soil}}{\textit{Lability of C in reference soil}}$

148   iii)   Then, CMI was calculated as follows;

149   CMI = CPI x LI x 100

150   CMI was computed for all the land uses; taking native forest soil as a reference with a known

151   CMI of 100.

152   **2.5. Statistical analysis**

153   A two-way ANOVA was employed to evaluate the influence of land use and soil depth on SOC

154   pools. The statistical difference was determined at $P < 0.05$. A correlation coefficient was

155   performed to evaluate the association among physico-chemical characteristics and SOC pools. A

156   simple linear regression was employed to comprehend the relation between CMI and SOC

157   fractions.

158   **3. Results and discussion**

159   **3.1. Physico-chemical properties of soils under different land use systems**

160   The mean sand percentage at the surface (0-30 cm) and sub-surface (30-60 and 60-90 cm) soils

161   varied from 19.33 – 54.20, 17.10 – 50.30, and 15.46 – 46.37%, respectively, with the minimum

162   content in paddy-oilseed soils and maximum in forest soils (Figure 1). The silt percentage at the

163   surface (0-30 cm) and sub-surfaces (30-60 and 60-90 cm) varied from 34.20 – 50.53, 35.43 –

164   51.13, and 36.90 – 52.76% with the least in paddy-oilseed soils and higher in apple (Figure 1).

165   The clay percentage varied between 11.60 – 33.70, 14.26 – 35.00, and 16.73 – 38.10% with the

166   maximum in paddy-oilseed soils and minimum in forest soils. The studied land uses were

167   categorized as sandy loam, loam, silt loam, clay loam, and silty clay loam. This is aligned with

168   the reports of Maqbool et al. (2017) and Mahapatra et al. (2000). The sand percentage exhibited

169   a declining pattern along the soil depth while silt and clay percentage depicted an increasing

170   pattern along the soil depth, which might be ascribed to illuviation and translocation of clay from

171   upper soil layers (Najar et al. 2009; Mohamed et al. 2017). Forest soils exhibited coarse texture

172   with more percentage of sand and a low percentage of clay owing to steep slopes, reduced soil

173   development, higher altitudes, less infiltration, and vice versa in cultivated soils (Abad et al.,

174   2014; Kiflu & Beyene 2013; Maqbool et al., 2017). The N levels in surface (0-30 cm) and sub-

175 surfaces (30-60 and 60-90 cm) varied from 279.30 − 417.52, 237.04 − 313.85, and 167.67 −

176 235.40 kg ha^{-1}, respectively, with maximum values in forest soils and minimum in cultivated

177 land uses (Figure 2). A decline was observed in N levels along the soil depth with a significant (p

178 < 0.05) difference across the depths (Table 1, Figure 1). These findings are in line with the

179 previous reports of scientists (Pal et al. 2013; Maqbool et al. 2017). The mean values of BD in

180 surface (0-30 cm) and sub-surface (30-60 and 60-90 cm) soils varied from 1.18 − 1.38, 1.25 −

181 1.42, and 1.31 − 1.51 Mgm^{-3}, respectively, with the minimum values observed under forest soils

182 and maximum under paddy-oilseed soils (Figure 2). Further, while evaluating the impact of soil

183 depth, an increment was observed and all the examined depths differed significantly (p < 0.05)

184 (Table 1, Figure 2). This could be attributed to the absence of anthropogenic disturbances, and

185 higher organic matter content in forest soils and vice versa in cultivated soils. These are further

186 consistent with the previous reports (Sofi et al. 2012; Chemeda et al. 2017). The mean values of

187 soil pH in the surface (0-30 cm) and sub-surface (30-60 and 60-90 cm) layer varied from 6.13 −

188 7.17, 6.37 − 7.30, and 7.33 − 7.50, respectively, with minimum values observed in forest soil and

189 maximum in paddy-oilseed soils (Figure 2). Moreover, an increment was observed along the soil

190 depth, and all the examined soil depths differed significantly (p < 0.05) (Table 1, Figure 2). In

191 general, soils were slightly acidic to slightly alkaline in reaction. This might be ascribed to the

192 absorption of bases by tree biomass, the acidic character of litter following its degradation, the

193 accumulation of organic matter in forest soils, and rapid oxidation owing to tillage practices in

194 cultivated soils. Our results agree with the prior reports (Muche et al. 2015; Kiflu and Beyene

195 2013).

196 **3.2. Distribution of SOC pools across studied LUSs**

197 Statistical analysis adopting two factor completely randomized design with interaction was

198 employed for the data obtained from investigated LUSs at different depths (Table 2 − 6). Table 2

199 depicts a two-way ANOVA, reflecting the LUS and soil depth influence on TOC. The mean

200 values of TOC under surface (0-30 cm) soils varied from 36.12 - 64.32 Mg ha^{-1} and in sub-

201 surface (30-60 and 60-90 cm) layers from 27.48 - 55.66 Mg ha^{-1} and 18.90 - 44.54 Mg ha^{-1},

202 respectively across studied LUSs. The amount of TOC differed significantly (p < 0.05) among

203 studied LUSs with maximum content under forest soils and minimum under paddy-oilseed soils.

204 Furthermore, a significant decline has been observed in TOC content along the soil depth (p <

205 0.05). The increased amounts of TOC in the forest soils might be associated with a significant

206   annual inclusion of organic materials as plant litter that persists in the soil because of no
207   intrusion and seasonal tillage (Smith 2007; Baker et al. 2007). The rate of decomposition is
208   impeded by the lower temperature conditions in high altitudes which accounts for increased
209   carbon values. The smaller level of TOC in croplands could be because of the negligible surface
210   cover, removal of biomass in harvested products, elimination of crop residue, and increased
211   tillage which enhances the loss of carbon (Smith 2007). Moreover, increased TOC levels in the
212   upper layer might be attributed to increased quantities of litter inputs in the surface layer. These
213   findings conform with Haynes (2005), Smith (2007), Baker et al. (2007), Kalambukattu et al.
214   (2013), Sofi et al. (2016), and Giannetta et al. (2018, 2019).

215   Table 3 depicts the mean values of WBC under surface (0-30 cm) soils varied from 11.70 - 22.00
216   g kg^{-1} and in sub-surface (30-60 and 60-90 cm) layers from 11.46 - 18.86 and 10.36 - 16.36 g kg^{-1}
217   ^{1}, respectively across studied land use systems. The amount of WBC differed significantly ($p <$
218   0.05) among studied LUSs with maximum content under forest soils and minimum under paddy-
219   oilseed soils, while saffron and paddy-oilseed were at par. Further, a significant ($p < 0.05$)
220   reduction in WBC was recorded along the soil depth. Higher organic carbon in surface soils of
221   forests has also been recorded by Miller and Gardiner (2001), Kaleem et al. (2005), Yimer et al.
222   (2007), Jamala and Oke (2013), Yihenew et al. (2015). The low organic carbon in cultivated
223   lands might be due to the rapid mineralization and loss of carbon from soil (Chauhan et al.
224   2014), long-term cultivation under submerged conditions resulting in stable aggregate
225   breakdown and SOM degradation (Yang et al. 2005), eventually deteriorates soil quality. The
226   reports are further supported by the results of Liding et al. (2011), Mojiri et al. (2012),
227   Wiesmeier et al. (2012), Poeplau and Don (2013), Chemeda et al. (2017), Kaur and Bhat (2017).

228   The mean values of LOC under surface (0-30 cm) soils varied from 2.33 - 7.20 g kg^{-1} and in sub-
229   surface (30-60 and 60-90 cm) layers from 2.09 - 4.74 and 1.86 - 3.28 g kg^{-1}, respectively across
230   studied land use systems (Table 4). The amount of LOC differed significantly ($p < 0.05$) among
231   studied LUSs with maximum content under forest soils and minimum under paddy-oilseed soils,
232   following a trend; forest > pasture > apple > saffron > paddy-oilseed. Furthermore, while
233   evaluating the effect of soil depth, a significant decline in LOC content was observed and all
234   depths differed significantly ($p < 0.05$). The continuous annual inclusion of rapidly
235   decomposable plant litter and increased MBC levels justifies the elevated amount of LOC in

236   forest soils. Whereas the lower values of labile carbon among studied land uses can be attributed

237   to the destabilization of aggregates and accelerated oxidation of SOM in plow and harrow-based

238   traditional cultivation systems (Bayer et al. 2006). These observations are concordant with those

239   of Garten et al. (1999), McLauchlan and Hobbie (2004), Cheng et al. (2008), and Sofi et al.

240   (2016).

241   The mean values of POC under surface (0-30 cm) soils ranged from 756.31 – 1380.24 mg kg^{-1}

242   and in sub-surface (30-60 and 60-90 cm) layers from 569.12 – 1122.11 mg kg^{-1} and 390.74 –

243   971.11 mg kg^{-1}, respectively across studied LUSs (Table 5). The amount of POC differed

244   significantly ($p < 0.05$) among studied LUSs with maximum content under forest soils and

245   minimum under paddy-oilseed soils, following a trend; forest > pasture > apple > saffron >

246   paddy-oilseed. Further, a reduction in POC was recorded along the soil depth and all depths

247   differed significantly ($p < 0.05$). The elevated POC levels in forest soils can be linked to larger

248   litter deposits, which contain additional labile carbon (Laik et al. 2009; Barreto et al. 2011) thus,

249   promote microbial vitality and quantity. In addition, it could also be linked to negligible

250   anthropogenic disturbances, surface cover, and mechanical soil maintenance to decrease erosion.

251   Comparable findings were documented in the central Himalayan range by Kalambukattu et al.

252   (2013), who found that undisturbed land use categories exhibited greater POC owing to carbon

253   buildup that is preserved by soil aggregates. The lowest POC under cultivated soils might be

254   attributed to the deterioration of soil aggregates through tillage that exposes POC to increased

255   breakdown and mineralization resulting in decreased POC levels (Bayer et al. 2006).

256   Furthermore, this fraction does not establish organo-complexes with minerals, thereby making it

257   prone to mineralization (Christensen 1988). These observations are further in agreement with Six

258   et al. (1998), Figueiredo et al. (2010), Liu et al. (2014), Sofi et al. (2016), and Poeplau and Don

259   (2013).

260   The mean values of MBC under surface (0-30 cm) soils ranged from 830.21 – 1458.12 mg kg^{-1}

261   and in sub-surface (30-60 and 60-90 cm) layers from 546.38 – 1232.53 and 365.50 – 1004.14 mg

262   kg^{-1}, respectively across studied LUSs (Table 6). The amount of MBC differed significantly ($p <$

263   0.05) among studied LUSs with maximum content under forest soils and minimum under paddy-

264   oilseed soils. MBC content decreased significantly with soil depth and all depths differed

265   significantly ($p < 0.05$). The size of the microbial reservoir is influenced by LUSs and the

266   management activities of soil. In addition to the above-mentioned reasons, the elevated MBC

267   values recorded under forests could be ascribed to the synthesis of biomass in the rhizosphere

268   and to a lesser extent, reduced soil tillage. The biomass activity of soil might have been enhanced

269   by organic matter inclusion and improved nutrient cycling in forests (Min et al. 2003). The

270   lowest MBC under cultivated soils might be attributed to low vegetation, tillage operations,

271   oxidation of OM and microbial OC declines steadily with a distance from the rhizosphere (Paul

272   and Clark 1996). These observations are concordant with those of Beare et al. (1994),

273   Purakayastha et al. (2009), Huang and Song (2010), Singh et al. (2011), and Sofi et al. (2016).

274   **3.3 Carbon management index (CMI)**

275   The evaluation of CMI was performed for studied LUSs while taking forest surface soil as a

276   reference for calculation. A significant influence of LUSs and soil depth on CMI values was

277   observed. In this study, the highest CMI values were observed under forest followed by pasture

278   and lowest in paddy-oilseed with the following trend: forest (100) > pasture (95.46) > apple

279   (61.16) > saffron (47.44) > paddy-oilseed (28.29) at surface soils, whereas, CMI showed a

280   significant decline in lower depths across studied land use systems (Figure 3). This reflects that

281   CMI serves as reliable metrics for estimating variations in SOC pools as well as soil quality.

282   Forest soils had the highest CMI value, which was different from other land uses (Figure 3),

283   since forest provides a less oxidative environment for the breakdown of POC and POC build-up

284   has been enabled by the prevalence of the thicket awning, a preventive pattern of the macro-

285   aggregates and lesser erodability. These observations are similar to those noticed by (Blair et al.

286   1995). The periodic organic matter preservation and reduced depletion concerning forest and

287   pasture have proven to augment the values of CMI (Blair and Crocker 2000). The lower level of

288   CMI in paddy-oilseed soils indicates that this land use type has lower inputs of carbon and raised

289   turnover levels because of increased temperature and SOC depletion. Similar reports have been

290   noticed by Cao et al. (2013). The usage of nitrogen-based fertilizer has improved biomass

291   thereby aggrandizing SOM. These observations are similar to Vieira et al. (2007) who noticed

292   fertilization and residue inclusion aggrandize the SOM's lability by 12-46%, thus raising CMI.

293   There exists no definite norm for CMI since it relies on the indigenous LUS of the region;

294   therefore, greater values of CMI signify carbon restoration whereas the least CMI levels denote

295   the depletion of carbon. This is further consistent with reports of Benbi et al. 2015.

3.4. Relationship matrix of physico-chemical characteristics, SOC pools and CMI

A correlation was performed between the physico-chemical characteristics and SOC pools which revealed a positive significant association of N with carbon pools, whereas pH and BD showed a negative significant association with SOC pools (Figure 4). From regression analysis (Figures 5, 6, and 7), a positive significant association (high R-squared values) was marked between CMI and different organic carbon pools in surface (0-30 cm) as well as sub-surface (30-60 and 60-90 cm) layers.

Conclusion

The study concluded that various LUSs and soil depth had an impact on SOC pools and, eventually, the CMI. Soil carbon pool dynamics were better in the case of forest and pasture soils while agricultural perturbations including stubble elimination, tillage, and increased erosion could be a substantial driver of carbon depletion from cultivated soils. However, among cultivated land uses, apple soils showed a better carbon management index. So, land use conversions must be checked to impede carbon depletion. A decrease in organic carbon fractions with change in management practices and soil depth has been observed. So, minimizing erosion, the addition of more organic matter, diversifying cropping systems, and minimum or zero tillage operations are important steps in reversing soil depletion and improving soil quality. Therefore, we must adopt best management practices to sequester more carbon which eventually improves the quality of soil and ecological balance and ultimately serve the purpose of global sustainability.

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Two-way ANOVA for the effect of land use system (LUS) and soil depth on Sand, Silt, Clay, BD, pH, and N.

1   **Table 1:** Two-way ANOVA for the effect of land use system (LUS) and soil depth on Sand, Silt,

2   Clay, BD, pH, and N.

Treatment	df	Sand	Silt	Clay	BD	pH	N
		p	*p*	*p*	*p*	*p*	*p*
LUS	4	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
SD	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LUS x SD	8	0.02	0.33	0.94	0.99	<0.001	0.06

Effect of LUSs on TOC (Mg ha^{-1}) at different depths

1   **Table 2: Effect of LUSs on TOC (Mg ha^{-1}) at different depths**

Depth/ Land Use	Depth-1	Depth-2	Depth-3	Factor Mean
Forest	64.32 ±0.63	55.66 ±0.81	44.54 ±0.93	**54.84^a**
Pasture	59.33 ±0.34	52.58 ±0.52	42.14 ±0.57	**51.35^b**
Apple	48.24 ±0.21	39.97 ±0.10	31.00 ±0.10	**39.73^c**
Saffron	41.28 ±0.36	30.62 ±0.33	21.73 ±0.48	**31.21^d**
Paddy-Oilseed	36.12 ±0.22	27.48 ±0.28	18.90 ±0.16	**27.50^e**
Factor Mean	**49.85^a**	**41.26^b**	**31.66^c**	
C.D (p < 0.05)	**Land Use =0.79**	**Depth =0.61**	**Land Use x Depth =1.37**	

2   Depth-1 = 0-30 cm   Depth-2 = 30-60 cm   Depth-3 = 60-90 cm
3   Mean values possessing different letters are significantly different at probability level of α 0.05

Effect of LUSs on WBC (g kg^{-1}) at different depths

1 **Table 3: Effect of LUSs on WBC (g kg⁻¹) at different depths**

Depth/ Land Use	Depth-1	Depth-2	Depth-3	Factor Mean
Forest	22.00 ±0.11	18.86 ±0.52	16.36 ±0.50	**19.07ᵃ**
Pasture	16.90 ±0.52	14.73 ±0.44	13.33 ±0.53	**14.99ᵇ**
Apple	16.86 ±0.06	13.96 ±0.87	11.73 ±0.18	**14.18ᶜ**
Saffron	12.36 ±0.06	11.50 ±0.30	10.80 ±0.36	**11.56ᵈ**
Paddy-Oilseed	11.70 ±0.23	11.46 ±0.32	10.36 ±0.24	**11.17ᵈ**
Factor Mean	**15.96ᵃ**	**14.10ᵇ**	**12.52ᶜ**	
C.D (p < 0.05)	**Land Use =0.69**	**Depth =0.53**	**Land Use x Depth =1.19**	

2 Depth-1 = 0-30 cm   Depth-2 = 30-60 cm   Depth-3 = 60-90 cm
3 Mean values possessing different letters are significantly different at probability level of α 0.05

Effect of LUSs on LOC (g kg^{-1}) at different depths

1 **Table 4: Effect of LUSs on LOC (g kg⁻¹) at different depths**

Depth/ Land Use	Depth-1	Depth-2	Depth-3	Factor Mean
Forest	7.20 ±0.38	4.74 ±0.03	3.28 ±0.02	**5.07ᵃ**
Pasture	6.82 ±0.32	4.06 ±0.18	3.01 ±0.04	**4.62ᵇ**
Apple	4.62 ±0.24	3.87 ±0.04	2.12 ±0.04	**3.53ᶜ**
Saffron	3.66 ±0.32	3.16 ±0.16	2.05 ±0.05	**2.95ᵈ**
Paddy-Oilseed	2.33 ±0.07	2.09 ±0.02	1.86 ±0.06	**2.09ᵉ**
Factor Mean	**4.92ᵃ**	**3.58ᵇ**	**2.46ᶜ**	
C.D (p < 0.05)	**Land Use =0.30**	**Depth =0.23**	**Land Use x Depth =0.53**	

2 Depth-1 = 0-30 cm   Depth-2 = 30-60 cm   Depth-3 = 60-90 cm
3 Mean values possessing different letters are significantly different at probability level of α 0.05

Effect of LUSs on POC (mg kg^{-1}) at different depths

1   **Table 5: Effect of LUSs on POC (mg kg⁻¹) at different depths**

Depth/ Land Use	Depth-1	Depth-2	Depth-3	Factor Mean
Forest	1380.24 ±60.01	1122.11 ±15.30	971.11 ±6.74	**1157.82ᵃ**
Pasture	1290.34 ±35.38	1091.36 ±5.76	894.14 ±6.48	**1091.95ᵇ**
Apple	910.52 ±9.28	788.47 ±3.68	693.13 ±3.18	**797.37ᶜ**
Saffron	870.44 ±14.84	673.65 ±7.87	492.42 ±1.38	**678.84ᵈ**
Paddy-Oilseed	756.31 ±19.13	569.12 ±1.41	390.74 ±1.37	**572.06ᵉ**
Factor Mean	**1041.57ᵃ**	**848.94ᵇ**	**688.30ᶜ**	
C.D ($p < 0.05$)	**Land Use =33.44**	**Depth =25.90**	**Land Use x Depth =57.92**	

2   Depth-1 = 0-30 cm   Depth-2 = 30-60 cm   Depth-3 = 60-90 cm
3   Mean values possessing different letters are significantly different at probability level of α 0.05

Effect of LUSs on MBC (mg kg^{-1}) at different depths

1 **Table 6: Effect of LUSs on MBC (mg kg^{-1}) at different depths**

Depth/ Land Use	Depth-1	Depth-2	Depth-3	Factor Mean
Forest	1458.12 ±33.51	1232.53 ±6.08	1004.14 ±2.76	1232.59[a]
Pasture	1370.32 ±108.48	1189.52 ±115.43	993.21 ±102.83	1184.35[b]
Apple	1105.16 ±96.40	933.38 ±102.01	771.37 ±90.86	936.64[c]
Saffron	968.26 ±139.23	703.61 ±130.18	515.30 ±124.80	729.05[d]
Paddy-Oilseed	830.21 ±141.18	546.38 ±136.36	365.50 ±128.10	581.03[e]
Factor Mean	1146.42[a]	921.28[b]	729.90[c]	
C.D ($p < 0.05$)	Land Use =20.23	Depth =15.67	Land Use x Depth =35.05	

2 Depth-1 = 0-30 cm   Depth-2 = 30-60 cm   Depth-3 = 60-90 cm

3 Mean values possessing different letters are significantly different at probability level of α 0.05

Figure 1

Particle size distribution and nitrogen content under different LUSs and soil depth
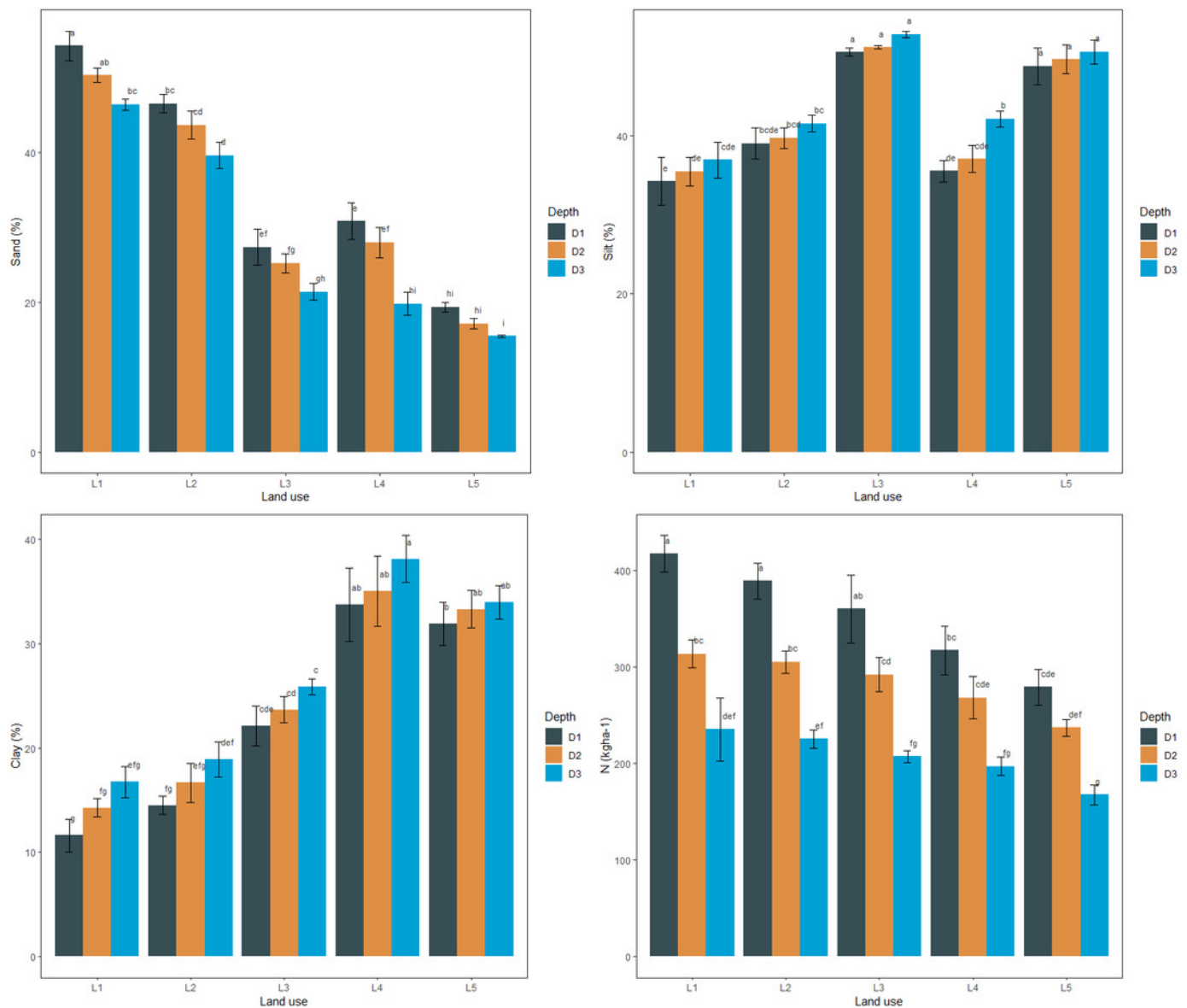
Figure 2

Soil reaction (pH) and bulk density under different LUSs and soil depth
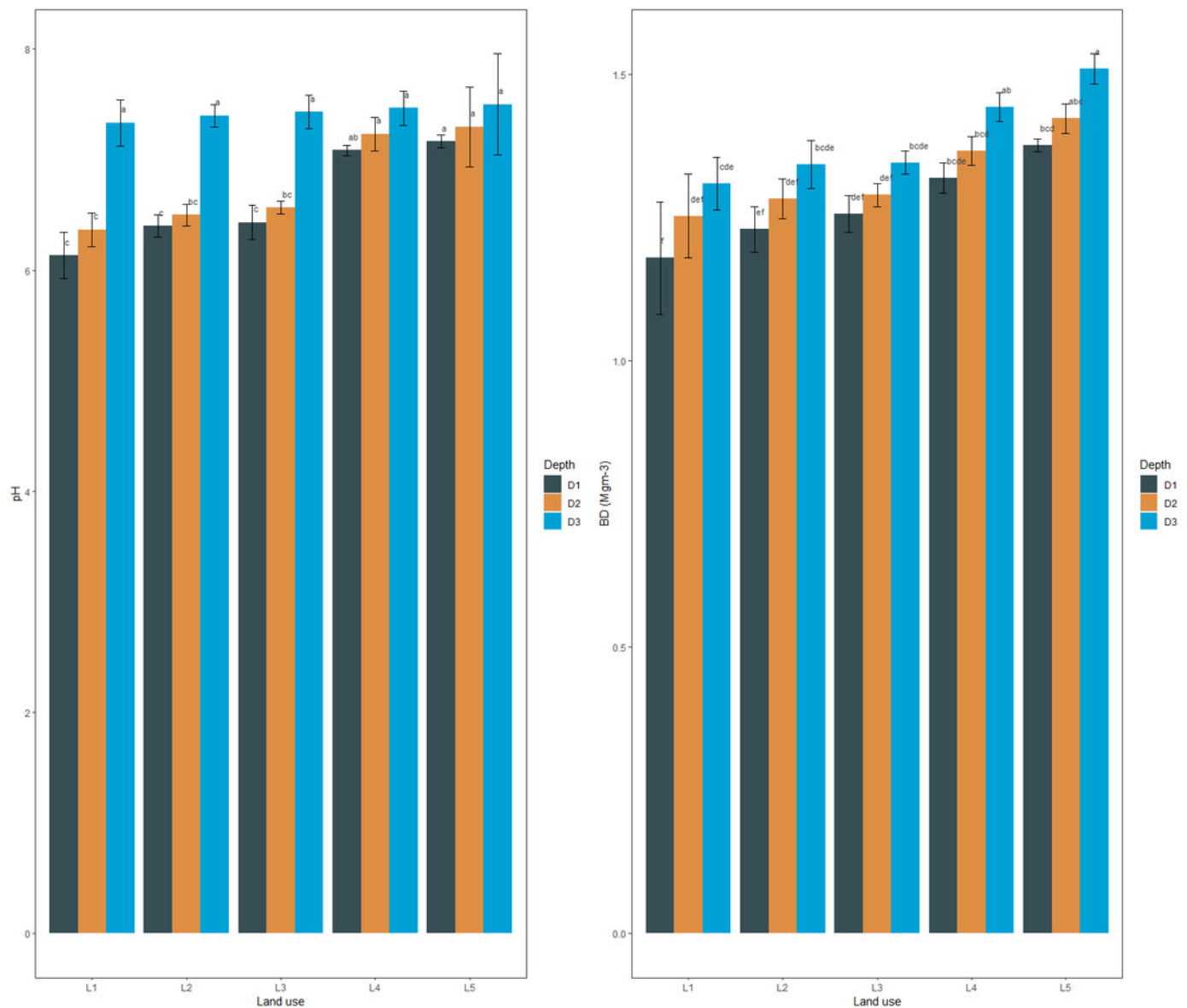
Figure 3

CMI values of different LUSs at varying depths (Reference Land Use: Forest)
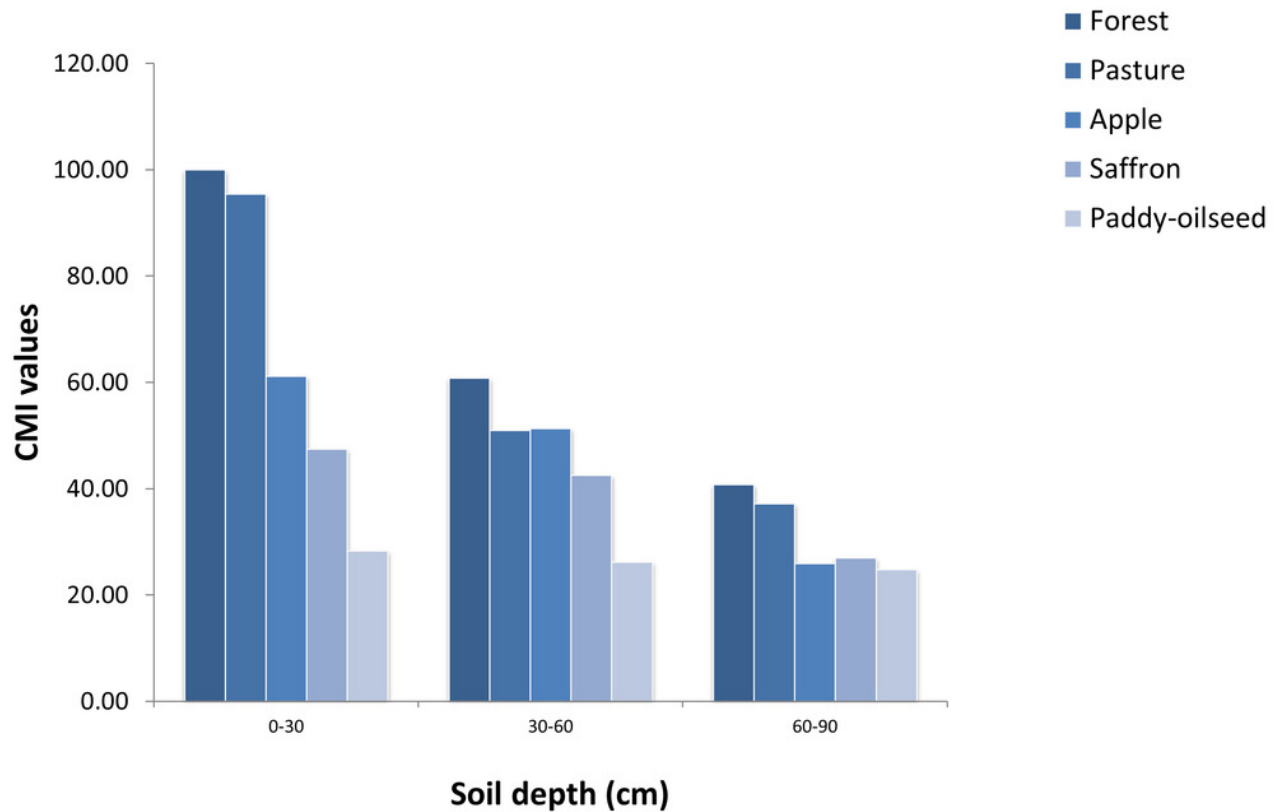
Figure 4

Correlation between physico-chemical characteristics and SOC pools
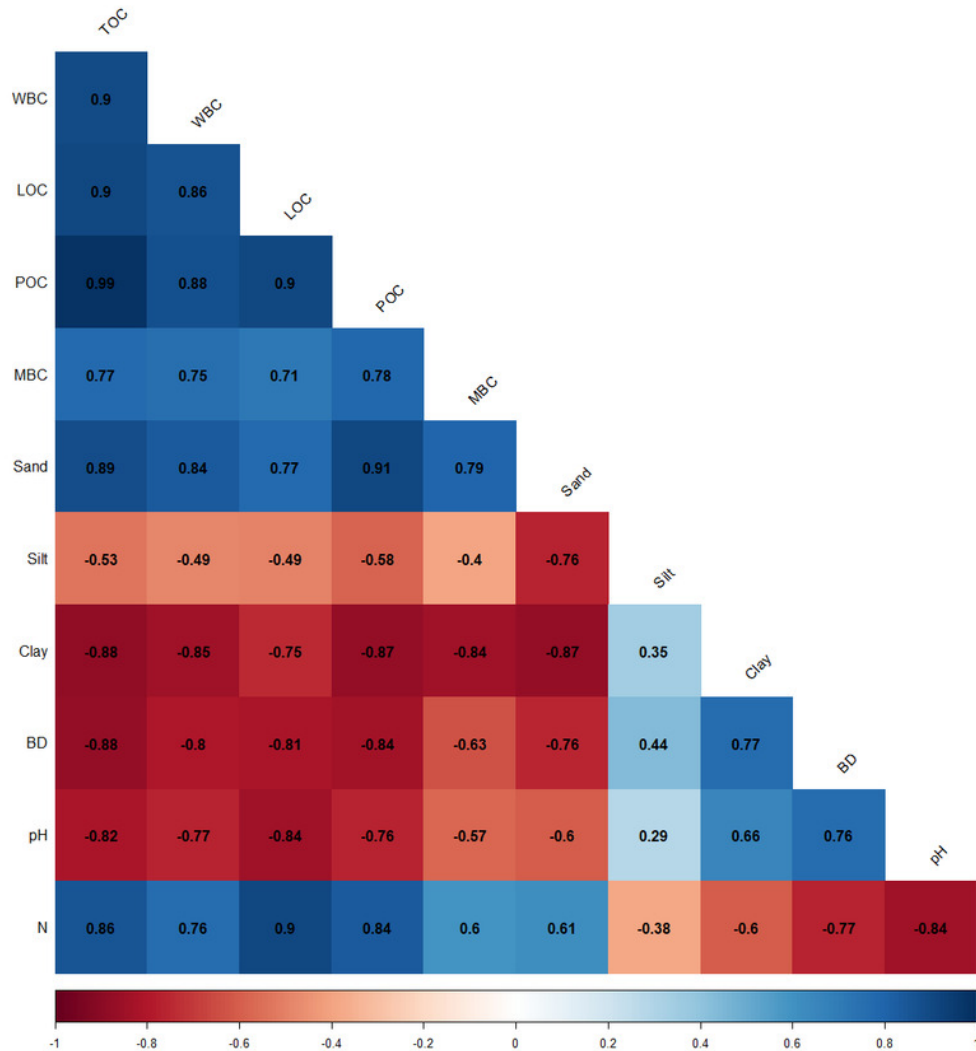
Figure 5

Relationship among SOC pools and CMI at 0-30 cm depth.
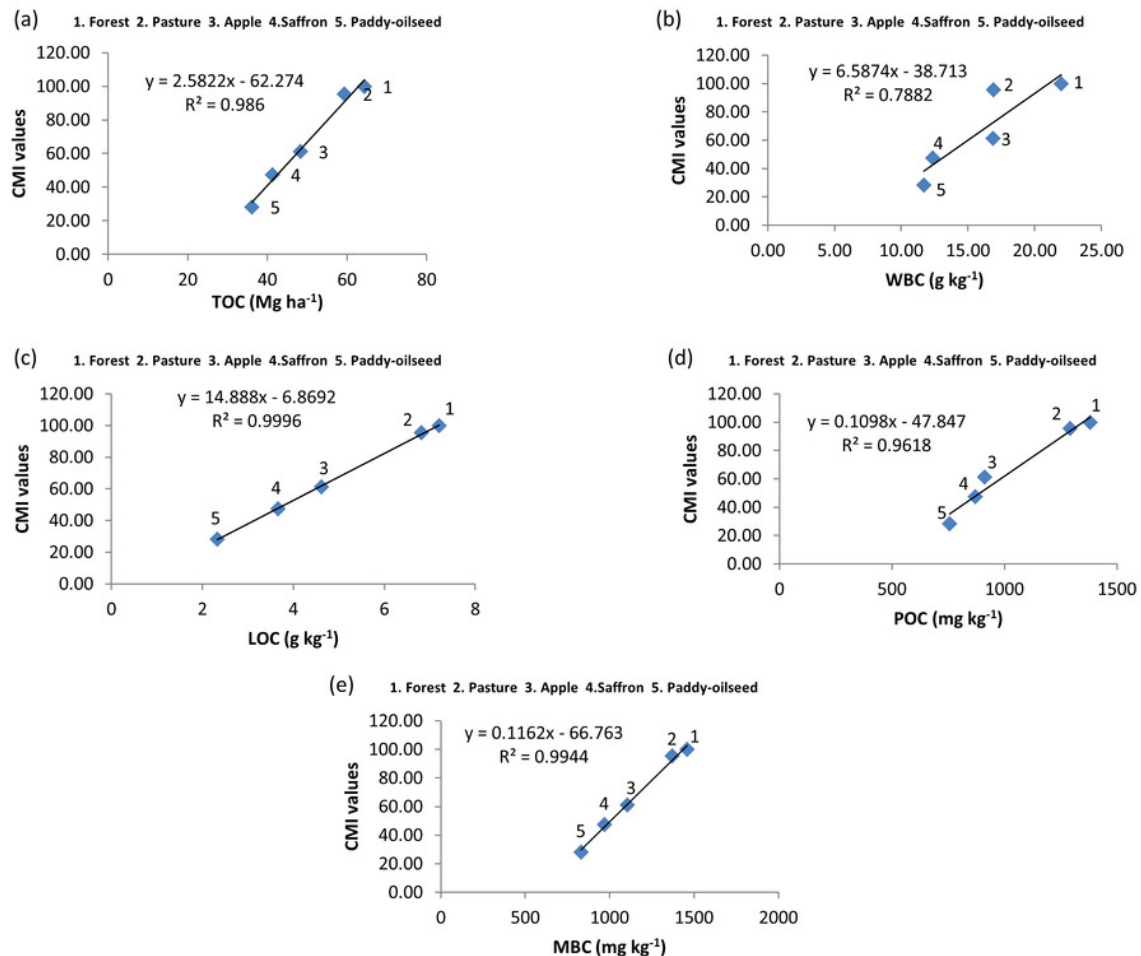
Figure 6

Relationship among SOC pools and CMI at 30-60 cm depth.
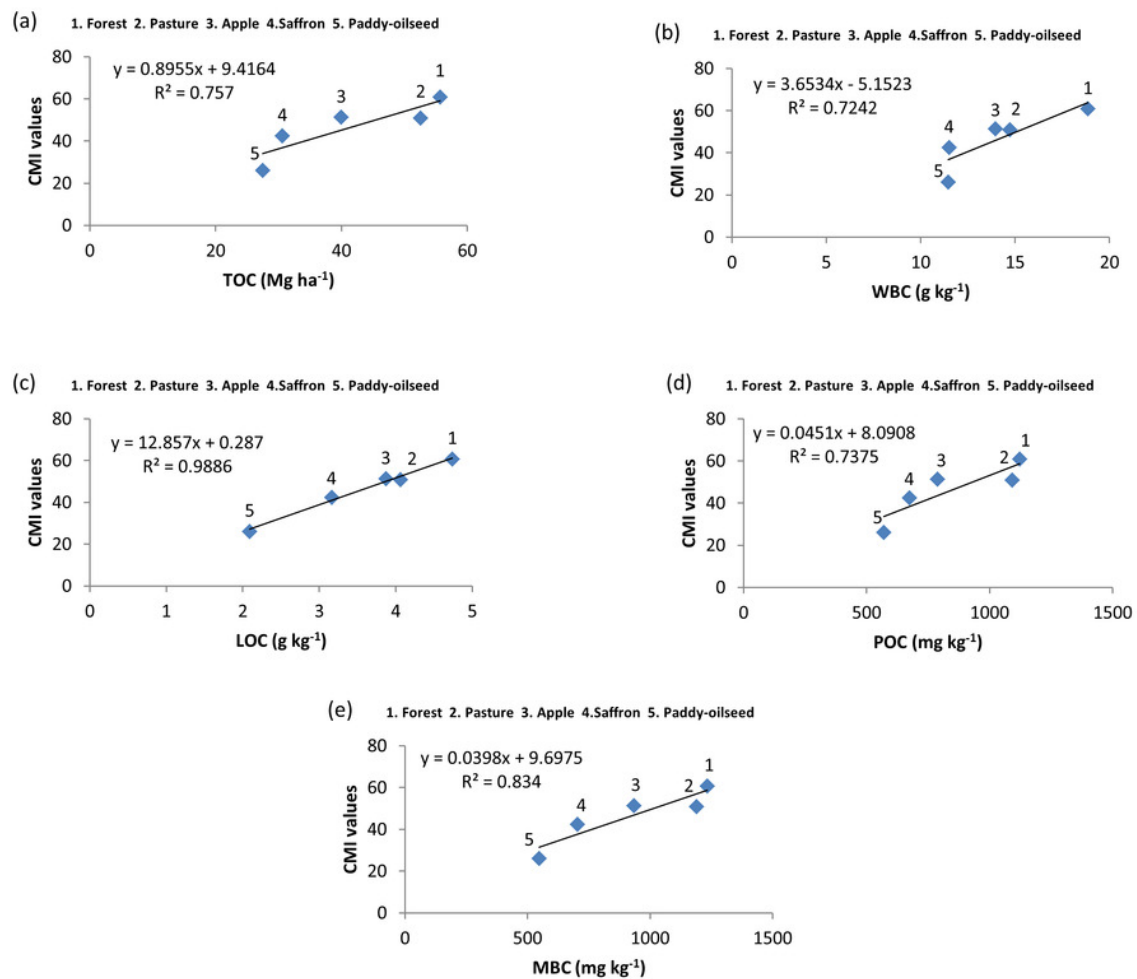
Figure 7

Relationship among SOC pools and CMI at 60-90 cm depth.