OPEN ACCESS
PAPER

Mongolian Journal of Geography and Geoecology - MJGG

Received: 08 May 2025; Accepted: 27 June 2025; Published online: 1 September 2025
https://doi.org/10.5564/mjgg.v62i46.4102

Soil carbon management index under different land use

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CITATION
Zoljargal Kh, Ikhbayar D, Purevdorj Ts (2025) Soil Carbon Management Index Under Different Land Use. *Mongolian Journal of Geograhy and Geoecology,* 62(46), 1–7. https://doi.org/10.5564/mjgg.v62i46.4102

ABSTRACT

This study evaluates the Carbon Management Index (CMI) across various land uses: settlement, pasture, forest, wheat cropland, abandoned cropland, and potato cropland in Jargalant soum, Central province, Mongolia. We assessed soil quality and carbon dynamics using permanganate oxidizable carbon (POXC) as an indicator of labile carbon. Soil samples from 0–15 cm and 15–30 cm depths revealed POXC ranging from 0.36 to 1.68 g kg^{-1}, highest in forest soils and lowest in abandoned cropland. The results of the study showed that at the 0-15 cm depth, CMI varied from 22.3 (settlement) and 28.4 (abandoned cropland) to 60.6 (wheat cropland), 60.9 (potato cropland), and 76 (pasture), indicating degradation in settlement and abandoned soils and rehabilitation in pasture and croplands soil. 15-30 cm depth, CMI varied from 67 (settlement) and 78 (abandoned cropland) to 131 (wheat cropland), 138 (pasture), and 198 (potato cropland), indicating degradation in settlement and abandoned soils and rehabilitation in pasture and cropland soils. POXC strongly correlated with soil organic carbon (SOC; r = 0.908, 0.841). These findings highlight POXC and CMI as sensitive tools for monitoring soil health and informing sustainable land management practices.

KEYWORDS

Soil organic carbon, Permanganate oxidizable organic carbon, Carbon management index

1. INTRODUCTION

Soil carbon is a vital component of healthy soils and plays an important role in agriculture, ecosystem health, and climate change mitigation. Soil labile carbon is a small fraction of soil organic carbon, but it is an active fraction that affects soil biological and dynamic properties and participates in the soil food chain [1].Soil labile carbon is the fraction of soil organic carbon with most rapid turnover times, and its oxidation drives the flux of CO_2 between soils and atmosphere [2]. This fraction, which accounts for 1-5% of the total organic carbon in the soil, is characterized by a decomposition period of several weeks to a year or faster [3].

Permanganate oxidized organic carbon (POXC) is also called active carbon. Although it accounts for a small percentage of soil organic carbon, it is important for soil carbon growth, soil structure, and the fertility cycle and movement [4].

In our previous study, we used a modified version of this method to determine POXC in some types of soils in Mongolia, such as cropland, pastures, and forest soils in the central agricultural region [4], [5]. Recently, interest in the POXC method has grown due to its cost-effectiveness, rapid analysis, and lack of requirement for sample density, and reliability through a standardised approach. POXC serves as an indicator of soil health and is determined via permanganate oxidation. A lighter color of the solution indicates more active carbon POXC [6].

CMI is an evaluation model used to assess the impact of specific land uses on soil quality compared to a reference land use soil [7]. Higher CMI values signify better soil carbon buildup, while lower values indicate carbon degradation.

Therefore, the objective of this study is to investigate the dynamics of labile carbon in different land use types and to calculate the CMI using this POXC to assess the soil quality.

2. RESEARCH METHODS

Jargalant soum of Central province is situated on 48°31' North Latitude and 105°52' East Longitude (**Figure 1.**). In this study area, the mean annual average temperature is -2°C. The average air temperature in the coldest month of January fluctuates from -35 °C to -40°C and the average air temperature in July, the warmest month, ranges from +30 °C to +35 °C. The study area has an annual average precipitation of 285 mm. Elevation at a height of roughly 1200 meters above average sea level. It has an area of 186800 hectares. Of which: 99000 hectares are pasture land, 38,000 hectares are agricultural land, and 33,800 hectares are forests, mostly pine forest. Since its establishment in the southern part of Mongolia's forest-steppe region, with its convenient geographical location and fertile soil, agriculture has been carried out stably and successfully for over 90 years. In this study site, Kastanozem soil is the main representative soil type. Main crops are wheat and potatoes. Jargalant soum has an agriculturally based economy.

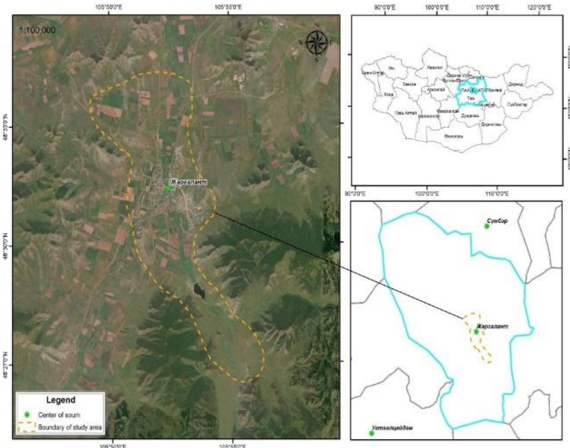

Figure 1. Location of the study site

In June 2024, we collected a total of 42 soil samples with depths of 0-15 cm and 15-30 cm from settlement, pasture, forest, wheat cropland, abandoned, and potato cropland sites. These soil samples were analyzed in the soil laboratory of the Institute of Geography and Geoecology, Mongolian Academy of Sciences, to determine the contents of physico-chemical properties and labile carbon. POXC was determined based on Weil et al (2003) as modified by Culman (2012) using 0.02 mol $L^{-}1$ $KMnO_4$ [1], [10]. Briefly, 2.5 g of air-dried soil was treated with 0.2M KMnO4 by shaking for 2 minutes and allowed to settle for exactly 10 minutes. The absorbance was measured with a spectrometer at 550 nm of light and compared to an absorbance reading on a standard curve. Non-reduced Mn+7 was quantified assuming the oxidation of 9000 mg C per mol Mn+7 reduced [8].

Carbon management index (CMI)

The CMI value is a suitable indicator for evaluating soil quality and carbon changes in the topsoil and subsoil. The formula provided by Blair [8] was used to calculate CMI, with uncultivated soils considered as a reference sample. Carbon pool index (CPI) is the ratio of the total organic carbon of the sample to the total organic carbon of the reference soil, while Lability (L) is the ratio of soil labile C or POXC to the difference between total organic carbon and POXC. CPI, lability index (LI), L, and CMI are calculated by the following formula.

$$CPI = \frac{Total\ organic\ C\ content\ in\ the\ sample\ (\frac{g}{kg})}{Total\ organic\ C\ content\ in\ the\ reference\ sample\ (\frac{g}{kg})} \quad (1)$$

$$LI = \frac{Lability\ of\ C\ in\ the\ sample}{Lability\ of\ C\ \ in\ the\ reference\ sample} \quad (2)$$

$$L = \frac{POXC\ content}{Total\ organic\ C - POXC\ content} \quad (3)$$

$$CMI = CPI \times LI \times 100 \quad (4)$$

In this study, forest land use soil was chosen as a reference land use because it has remained undisturbed and preserved in its natural state since its establishment.

Pearson’s correlation coefficients were computed to assess the strength and direction of linear relationships among the selected soil physicochemical and textural variables. The significance of the correlations was evaluated at the 0.05 and 0.01 probability levels. All statistical analyses were performed using Microsoft Excel.

3. RESULT AND DISCUSSION

The pH of the soils ranged from alkaline (8.50-8.73) in the Forest subsoil and Settlement, and slightly alkaline (7.19-7.88) in pasture, wheat cropland, abandoned, and potato cropland soils. The SOM of the pasture was the highest (7.41%), followed by forest, wheat cropland, potato cropland, abandoned, and lowest (2.01%) in the settlement. Soils were nonsaline, available phosphorus values were low to high, available potassium values were low to high, and soil textures were in forest and abandoned croplands were sandy loam, while other land use type soils were loam and silty loam (Table 1).

Soil organic carbon concentrations in the 0-15 cm of the pasture were highest (42.9g kg^{-1}), followed by that of the forest (36.2g kg^{-1}), wheat cropland (29.5g kg^{-1}), potato cropland (25.9g kg^{-1}), abandoned (12.2g kg-1), and settlement was the lowest (11.7g kg^{-1}), in the 15-30 cm of the wheat cropland was highest (25.2g kg^{-1}), followed by that of potato cropland (22.9g kg^{-1}), pasture (20.9g kg^{-1}), forest (13.2g kg^{-1}), settlement (10.7g kg^{-1}), and that of abondoned was the lowest (9.7g kg^{-1}) (Figure 2).

Table 1. Soil physical-chemical properties

Depth,	pH 1:2.5	SOM	$EC_{1:2.5}$	P_2O_5	K_2O	Sand	Silt	Clay
cm		%	dS/m	mg/100g		%		
Settlement								
0-15	8.57	2.01	0.153	4.78	46.8	50.9	39.2	9.9
15-30	8.73	1.84	0.190	3.59	30.7	38.8	41.2	10.0
Pasture								
0-15	7.48	7.41	0.033	1.90	38.6	40.2	51.8	8.0
15-30	7.55	3.60	0.031	0.78	11.8	24.8	56.5	18.6
Forest								
0-15	7.19	6.24	0.031	2.31	10.7	52.8	36.6	10.6
15-30	8.50	2.75	0.123	1.47	1.7	56.8	31.9	11.3
Wheat cropland								
0-15	7.65	5.08	0.061	2.67	53.8	28.9	55.8	15.3
15-30	7.57	4.34	0.045	1.63	14	29.2	54.8	15.9
Abandoned								
0-15	7.63	2.10	0.03	1.92	6.8	52.5	33.9	13.6
15-30	7.75	1.67	0.026	1.44	2.9	57.1	31.3	11.6
Potato cropland								
0-15	7.73	4.48	0.106	3.97	48.4	29.2	53.5	17.3
15-30	7.88	3.94	0.055	2.13	16.6	22.8	58.6	18.7

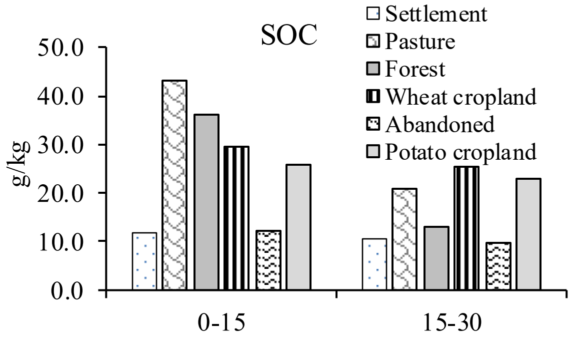

Figure 2. SOC values of different land use types at 2 depths

At the 0–15 cm soil depth, POXC concentrations were highest in forest soils (1.68 g kg⁻¹), followed by pasture (1.30 g kg⁻¹), wheat cropland (1.03 g kg⁻¹), and potato cropland (1.03 g kg⁻¹). Abandoned cropland and settlement soils exhibited considerably lower POXC levels, with concentrations of 0.48 g kg⁻¹ and 0.38 g kg⁻¹, respectively. At the 15–30 cm depth, the highest POXC concentration was observed in potato cropland soils (0.91 g kg⁻¹), followed by pasture (0.64 g kg⁻¹), wheat cropland (0.61 g kg⁻¹), and forest soils (0.46 g kg⁻¹). Abandoned cropland (0.36 g kg⁻¹) and settlement soils (0.31 g kg⁻¹) again recorded the lowest values (Figure 3).

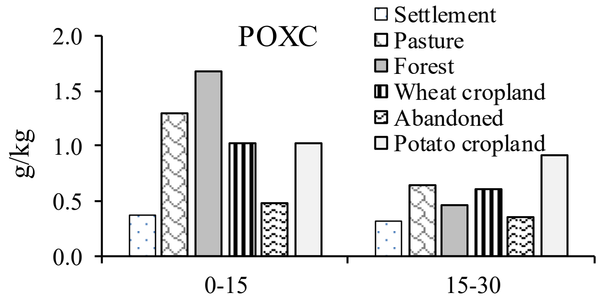

Figure 3. POXC values of different land use types at 2 depths

In the 0-15 cm settlement, pasture, forest, wheat cropland, abandoned, and potato cropland soils, POXC accounted for 3.2%, 3.0%, 4.6%, 3.5%, 3.9%, and 4% of the total SOC, respectively. In the 15-30 cm settlement, pasture, forest, wheat cropland, abandoned cropland, and potato cropland soils, POXC accounted for 2.9%, 3%, 3.5%, 2.4%, 3.7%, and 3.9% of the total SOC, respectively.

Table 2. Correlation coefficient matrix between POXC and physicochemical properties in the 0-15 cm soils

0-15 cm	pH	EC	SOC, g/kg	POXC, g/kg	P_2O_5	K_2O	Sand	Silt	Clay
pH	1								
EC	.894*	1							
SOC, g/kg	-0.70	-0.53	1						
POXC g/kg	-0.80	-0.54	.908*	1					
P_2O_5	.825*	.988**	-0.50	-0.46	1				
K_2O	0.50	0.63	0.08	-0.14	0.59	1			
Sand	0.08	-0.13	-0.33	-0.18	-0.13	-0.76	1		
Silt	-0.08	0.10	0.50	0.27	0.08	0.81	-.956**	1	
Clay	-0.05	0.14	-0.29	-0.16	0.20	0.24	-0.61	0.35	1

**Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed*

The correlation matrix reveals significant relationships among the measured soil properties. In the 0-15 cm layer, soil pH exhibited a strong positive correlation with electrical conductivity (EC) and available phosphorus (P_2O_5) ($p < 0.05$), indicating that higher pH is associated with increased salinity and phosphorus availability. EC also showed a highly significant positive correlation with P_2O_5 ($p < 0.01$), suggesting a potential interaction between salinity and nutrient mobility.

Soil organic carbon (SOC) was strongly positively correlated with permanganate oxidizable carbon (POXC) ($p < 0.05$), reflecting the consistency between total and labile carbon fractions. However, SOC and POXC were negatively correlated with pH and EC, indicating that higher organic matter content is associated with more acidic and less saline soils (Table 2).

Table 3. Correlation coefficient matrix between POXC and physicochemical properties in the 15-30 cm soils

15-30 cm	pH	EC	SOC, g/kg	POXC, g/kg	P_2O_5	K_2O	Sand	Silt	Clay
pH	1								
EC	.958**	1							
SOC, g/kg	-0.64	-0.50	1						
POXC, g/kg	-0.51	-0.50	.841*	1					
P_2O_5	0.72	0.80	-0.34	-0.30	1				
K_2O	0.36	0.57	0.08	-0.01	.814*	1			
Sand	0.43	0.24	-.826*	-0.74	-0.02	-0.54	1		
Silt	-0.54	-0.36	.902*	.813*	-0.11	0.40	-.986**	1	
Clay	-0.73	-0.66	.878*	.908*	-0.48	-0.01	-.829*	.895*	1

**Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed)*

In the 15-30 cm, Pearson correlation analysis revealed several significant relationships among soil physicochemical and textural properties. Soil pH exhibited a very strong positive correlation with EC ($p<0.01$), and a moderate positive correlation with available phosphorus (P_2O_5), suggesting that higher pH levels are associated with greater salinity and phosphorus content. Soil organic carbon (SOC) was positively and significantly correlated with permanganate oxidizable carbon (POXC), silt, and clay ($p<0.05$), indicating that finer-textured soils tend to retain more organic matter. Similarly, POXC showed strong positive correlations with silt and clay ($p<0.05$). Conversely, SOC and POXC were negatively correlated with sand content ($p<0.05$), highlighting the inverse relationship between organic matter content and coarser soil fractions. A highly significant negative correlation was observed between sand and silt ($p<0.01$), confirming the expected textural balance (Table 3).

The CPI ranged from 0.32 to 1.91 for the five land use types, highest in wheat cropland and lowest in settlement. LI ranged from 0.64 to 1.15, highest in potato cropland soil and lowest in settlement soils. CMI ranged from 22.3 to 198.9, highest in potato cropland soil at 15-30 cm depth, and lowest in settlement soils (Table 4).

Table 4. CPI, LI, and CMI under different land use types

Land use	0-15 cm			15-30 cm		
	CPI	LI	CMI	CPI	LI	CMI
Settlement	0.32	0.69	22.3	0.81	0.83	67.0
Pasture	1.19	0.64	76.1	1.58	0.88	138.5
Wheat	0.82	0.74	60.6	1.91	0.69	131.2
Abandoned	0.34	0.84	28.4	0.74	1.06	78.4
Potato	0.72	0.85	60.9	1.74	1.15	198.8
Forest	1	1	100	1	1	100

The Lability Index (LI) gauges are relative lability of soil organic matter (SOM) in altered land use compared to reference soil. In contrast, the carbon pool index (CPI) quantifies changes in total organic carbon resulting from land use changes, with lower CPI values indicating greater carbon loss. A higher CMI value signifies system rehabilitation, improvement, and sustainability, whereas a lower value suggests decline.

The pasture and forest had high SOC (Figure 2). This is attributed to the recovery of above- and below-ground biomass. Forest increases SOC due to high carbon inputs. In addition, vegetation cover protects against the loss of SOC from the surface compared to other land use types. For all land uses, POXC decreases with depth. SOC is high in forest soils due to the large amount of organic matter added each year by leaf fall [9].

POXC accounted for 2.4–4.6% of total organic carbon in our study. These results are in agreement with a previous study [10], which observed that a similar proportion of POXC (1-4%). POXC was found to be strongly correlated with soil SOC (R^2=0.84) [11]. In our study, these correlations were R^2=0.908 and

R^2=0.841. Researchers further emphasise that a high CMI value indicates positive impacts on total organic carbon content and soil quality, suggesting that a CMI value exceeding 100 reflects beneficial effects, while values below 100 indicate adverse impacts. [12]. A high soil CMI means good quality, and our research confirms this, with pasture, wheat cropland, and potato cropland soils having a CMI greater than 100. In other words, it can be said that CMI detects changes in soil organic carbon dynamics.

4. CONCLUSION

This study demonstrates that land use significantly affects soil carbon dynamics in Jargalant soum, Central province, Mongolia. A study shows that different land use types have an influence on POXC and consequently CMI. The POXC method is more standardized, requires less specialized equipment, therefore, POXC is considered a simple, rapid assessment of labile organic carbon. POXC concentrations in forest and pasture were the highest, followed by those of the wheat cropland and potato cropland, while the abandoned cropland and settlement had the lowest concentrations. POXC, strongly correlated with SOC, serves as a sensitive indicator of soil quality. High CMI values in potato cropland (198) and pasture (138) at 15–30 cm depth indicate soil rehabilitation, while low values in settlement (22.3) and abandoned cropland (28.4) suggest degradation. CMI is a metric used to assess the quality of soil and its ability to store and manage carbon. Active or labile carbon responds rapidly to any environmental changes thus considered an early or sensitive indicator of soil quality. Consequently, the application of POXC analysis for investigation presents significant potential for improving and refining current soil quality assessment methodologies. These findings advocate for the integration of POXC and CMI in soil monitoring to guide sustainable land management practices.

ACKNOWLEDGMENTS

This research work was carried out within the framework of the regional “Assessing and Mitigating Agro-Contaminants to Improve Water Quality and Soil Productivity in Catchments Using Integrated Isotopic Approaches-RAS5091, IAEA project". I would like to thank the staff of the Division of Soil Research for their help in carrying out this study.

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