OPEN ACCESS
PAPER

Mongolian Journal of Geography and Geoecology - MJGG

Received: 08 May 2025; Accepted: 02 June 2025; Published online: 1 September 2025
https://doi.org/10.5564/mjgg.v62i46.4098

The effect of tree species on soil organic carbon stock in Mongolian forest

***CORRESPONDING AUTHOR**
Byambaa Ganbat
byambaag@mas.ac.mn
ORCID
0000-0002-4680-5619

CITATION
Byambaa G, Batkhishig O, Bat-Erdene Kh, Nyamdavaa B (2025) The Effect of Tree Species on Soil Organic Carbon Stock in Mongolian Forest. *Mongolian Journal of Geograhy and Geoecology,* 62(46), 1–7. https://doi.org/10.5564/mjgg.v62i46.4098

Byambaa Ganbat[1,2,*], Batkhishig Ochirbat[2], Bat-Erdene Khatanbaatar[2], Nyamdavaa Batsaikhan[1]

[1] *School of Arts & Sciences, National University of Mongolia, Ulaanbaatar, 210646, Mongolia.*
[2] *Institute of Geography and Geoecology, Mongolian Academy of Sciences, Ulaanbaatar 15170, Mongolia.*

ABSTRACT

Forest ecosystems in Mongolia play a critical role in storing soil organic carbon (SOC), a key component in mitigating climate change. However, little is known about how SOC stocks vary with dominant tree species in these forests. This study investigates the impact of tree species on SOC stocks in Mongolia's boreal forests, focusing on four commonly found species: Larix sibirica, Pinus sylvestris, Pinus sibirica, and Betula platyphylla. Data were compiled from 885 soil samples across 177 soil profiles, representing diverse forest ecosystems. SOC stocks were standardized to two depth intervals (0–30 cm and 30–60 cm) using a weighted averaging method. Statistical analyses, including as ANOVA and Principal Component Analysis (PCA), were conducted to determine species-level differences and the influence of environmental factors. Results show significant variation in SOC stocks among species ($F = 8.79$, $p < 0.001$), with Betula platyphylla exhibiting the highest mean SOC stock (110.1 Mg C ha^{-1}) and *Pinus sylvestris* the lowest (64.2 Mg C ha^{-1}). SOC stocks generally decreased with depth across all species, though Pinus sylvestris showed higher subsurface SOC than in surface layers, likely due to deeper root systems in sandy Arenic Podzols. PCA revealed that SOC in surface layers is positively influenced by slope, temperature, and precipitation, while subsurface SOC is more closely associated with latitude and elevation. The study highlights the role of tree species and site-specific conditions in shaping SOC dynamics, emphasizing the need to consider forest composition in carbon management and climate adaptation strategies in Mongolia.

KEYWORDS

SOC stock, SOC, Organic carbon, Forest soil, Soil, Tree species, Mongolia

1. INTRODUCTION

Soil organic carbon (SOC) stored in forest ecosystems plays a crucial role in climate change mitigation [1]. Tree species composition significantly influences SOC stocks. Coniferous species generally accumulate higher amounts of SOC in the forest floor, whereas deciduous species tend to contribute more to SOC stock in mineral soils. Overall, deciduous tree species are associated with greater SOC stocks in mineral soil layers compared to coniferous species [1], [2], [3], [4].

Mongolia's taiga region represents about 2% of the global boreal forest ecosystem [5]. Northern Mongolia's boreal forests, forming the southernmost extension of the vast Siberian Taiga. These forests, covering approximately 17.5 million hectares or about 8.1% of Mongolia's territory [6]. The boreal forests are integral to the livelihoods of local communities, offering resources like fuelwood, timber, nuts, berries, and honey. They play a crucial role in preventing soil erosion, regulating water cycles, and acting as a barrier against desertification. However, these forests face threats from climate change, illegal logging, and frequent fires, which can alter forest composition and reduce biodiversity.

The forests are primarily composed of coniferous and deciduous species, forming distinct forest types. Siberian Larch (*Larix sibirica* L.), dominates approximately 81% of the forested area, adapted to cold climates and fire-prone environments. Scots Pine (*Pinus sylvestris*) 5% and Siberian Pine (*Pinus sibirica*) 7%: Occupy about 10–12% of the forest area, often found in mixed stands. Birch (*Betula platyphylla*) 6%: A pioneer species, commonly found in disturbed areas and mixed forests [7].

Several studies have examined the distribution, classification, and properties of forest soils in Mongolia [8], [9], [10], [11], [12], [13]. While these earlier works provide useful information on organic matter in forest and taiga soils, detailed investigations of SOC stocks and dynamics remain limited. In particular, there is a lack of research on how forest type and tree species composition influence in SOC stock in Mongolian forests. The objective of the study is to address this gap the examining the variation in SOC stocks among forest types characterized by different dominant tree species in Mongolia. To achieve this, a review of forest soil studies conducted in Mongolia prior to 2024 was undertaken to compile relevant data. The compiled data were analyzed then to enable a comparative assessment of SOC storage across the various forest types.

2. RESEARCH METHODS

Study area. The study was conducted to examine the variation in SOC stocks across different tree species in the taiga and forested regions of northern Mongolia, and located between 46.30°–52.00°N latitude and 98.00°–113.00°E longitude (Figure 1). This region contains approximately 98.8% of Mongolia's forest soils, making it highly representative of the country's forested ecosystems. The area experiences a harsh continental climate, and characterized by long, cold winters with short time, and warm summers. Annual precipitation ranges from 200 to 400 mm, with higher amounts typically occurring in mountainous regions [14]. Permafrost is widespread, particularly in shaded and high-elevation areas, significantly influencing soil moisture dynamics and vegetation distribution [15]. The upper treeline reaches elevations of 2450–2500 meters in the Khangai and Mongol Altai mountain ranges, while the lower limit descends to 600–800 meters in the Orkhon–Selenge basin. These diverse topographic and climatic conditions reflect the wide ecological variability under which forest soils are distributed in Mongolia [9].

Data sources and soil sampling. In our study, we utilized data from several key sources. These include the works of Soviet-era researchers such as Krasnoshchekov [2013], Ogorodnikov [1981], and Khudyakov [2009], based on field studies conducted in Mongolia between 1970 and 1990, as well as a thematic monographs by Undral [1978]. Additionally, we incorporated results from more recent research conducted since 2000 by Division of the Soil Science in the Institute of Geography and Geoecology, Mongolian Academy of Sciences. This includes data from 885 soil samples were collected from 177 soil profiles across various forest regions.

Estimation of SOC stocks. The following equation was used to estimate SOC stock using soil variables, including gravel, bulk density, organic carbon concentrate, and depth. Forest soil organic carbon by volume (SOC, Mg C m^{-2}) was measured as following equition:

$$\text{Td} = \sum_{i=1}^{k} pi\ Pi\ Di\ (1 - S_i) \qquad (1)$$

Where Td is the total amount of organic carbon (Mg m^{-2}) above depth d, d in Td refers to the sum of thickness of layers from $i = 1$ to k, pi is the bulk density (Mg m^{-3}) of active soil (<2 mm) of layer i, Pi is the proportion of organic carbon (g C g^{-1}) in layer i,

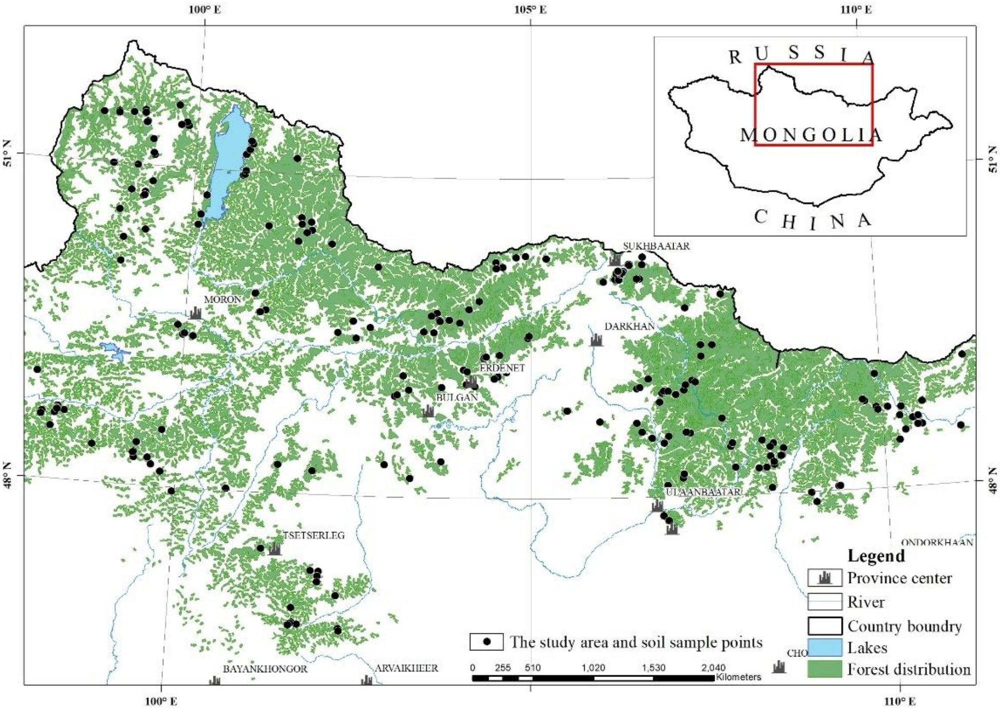

Figure 1. Location of Study area

Di is the thickness of this layer (m), and S_i is the proportion of volume of fragments >2 mm [16].

The soil samples used in these studies were collected from each genetic horizon of the soil profile (O, A, AB, B, BC). To enable consistent comparison and analysis across a large number of soil profiles, it was necessary to standardize the depth intervals. Therefore, laboratory results from genetic horizons were converted into fixed depth layers (0–30 cm and 30–60 cm) using a weighted average method.

Statistical analysis. The estimation of SOC stocks was carried out for forest stands dominated by four tree species that are widely distributed in Mongolia: *Larix sibirica, Pinus sylvestris, Pinus sibirica,* and *Betula platyphylla.* The data of the Mongolian forest soil survey were statistically analyzed. An analysis of variance was used to identify differences in soil organic carbon stocks by tree species *(Larix sibirica, Pinus sylvestris, Pinus sibirica, Betula platyphylla).* All data analyses were done with R version 4.0.3 [17].

3. RESULT AND DISCUSSION

Forest science literature provides extensive insights into the influence of tree species on soil properties. Differences in SOC stocks are largely driven by species-specific growth rates and the allocation of photosynthates to above- and below-ground biomass [1]. In this study, SOC stocks varied significantly among the examined tree species, as confirmed by the statistical analysis ($F = 8.79$, $p < 0.001$).

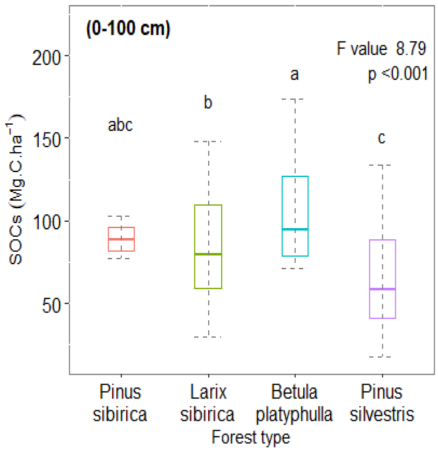

Figure 2. Soc stocks in forest by tree species (0-100cm) soc stocks by soil depths

Although coniferous forests are often reported to store higher SOC stocks than mixed or broadleaf forests [1], [18], our results showed that *Betula platyphylla*, a broadleaf species, had the highest mean SOC stock (110.1 Mg C ha^{-1}), with a wide range from 70.9 to 220.2 Mg C ha^{-1} (Figure 2). This finding aligns with recent studies suggesting that broadleaf forests may contain more SOC than coniferous counterparts [2]. In coniferous forests, SOC tends to accumulate

Table 1. SOC stock in forest area by depth and tree species, SE – standard error, SD – standard division

Tree species	Count	Mean	SE	Median	SD	Max	Min
0 - 30 cm							
Pinus sibirica	4	70.8	4.09	74.2	8.18	76.2	58.6
Larix sibirica	84	64.8	2.35	64.3	21.5	112	25.2
Betula platyphulla	15	80.2	7.36	66.7	28.5	161	52.9
Pinus silvestris	50	39.9	2.51	35.3	17.7	79.3	12.9
30 – 60 cm							
Pinus sibirica	6	17.0	2.78	15.7	6.82	24.9	8.36
Larix sibirica	105	15.7	0.95	15.0	9.78	42.8	1.53
Betula platyphulla	17	18.6	2.87	14.2	11.8	45	6.32
Pinus silvestris	49	23.3	1.86	21.3	13	52.6	4.98

more in the forest floor, while in broadleaf forests, SOC is more prominent in the mineral soil layer [2], [18]. Although the total leaf litter input does not vary substantially between species [19], the decomposition rate of broadleaf litter is generally higher than that of conifers [20].

Among the species assessed, *Larix sibirica* which dominates approximately 81% of Mongolia's forest area—had a mean SOC stock of 83.5 Mg C ha⁻¹. *Pinus sylvestris* showed the lowest mean SOC stock at 64.2 Mg C ha⁻¹, and also exhibited the highest variability. These interspecific differences likely reflect variations in litter quality, root biomass, and site conditions.

The mean SOC stocks across the 0–30 cm and 30–60 cm soil depths for each tree species are presented in Table 1. *Betula platyphylla* showed the highest SOC stock in the topsoil (80.2 Mg C ha⁻¹). For comparison, Cha et al. [2019] reported that deciduous trees contained approximately 66 Mg C ha⁻¹ in the 0–30 cm layer of mineral soils, whereas pine species contained around 49.5 Mg C ha⁻¹. Our findings support the general observation that deciduous forests tend to store more SOC in the soil than coniferous forests.

Interestingly, *Pinus sylvestris* exhibited the highest SOC stock in the subsoil (30–60 cm), with a mean of 23.3 Mg C ha⁻¹, despite its relatively low SOC concentration in the topsoil. In Mongolia, *Pinus sylvestris* predominantly grows in *Arenic Podzols*, which are sandy soils that promote deep root development. Notably, in the 30–60 cm layer, gravel content ranged from 22.3% to 39.2%, excluding Arenic Podzols. These factors may explain the elevated SOC stocks observed in the deeper soil layers beneath *Pinus sylvestris* stands.

SOC stocks consistently decreased with depth for all species. *Pinus sibirica* and *Betula platyphylla* had similar subsoil SOC means (17.0 and 18.6 Mg C ha⁻¹, respectively). These patterns highlight the influence of root architecture and litter input on vertical SOC distribution.

Previous research has shown that coniferous litter is more resistant to decomposition than broadleaf litter, resulting in a thicker organic horizon composed of partially decomposed material [21]. In contrast, broadleaf forests typically form thinner organic layers with higher turnover rates. Broadleaf tree species also tend to develop deeper root systems, which may enhance carbon input into deeper soil layers [22], [23], [24]. Overall, these results underscore that SOC dynamics are shaped by complex interactions between species-specific traits and local soil conditions.

Principal Component Analysis (PCA) of Environmental Drivers

Principal Component Analysis (PCA) was conducted to assess the influence of environmental variables (slope, elevation, permafrost, temperature, and precipitation) on SOC stocks across five tree species (*Betula platyphylla, Larix sibirica, Pinus sibirica,* and *Pinus sylvestris*) at two soil depths.

At 0–30 cm depth, SOC showed positive correlations with slope, surface temperature, and precipitation, while elevation and permafrost were negatively associated. *Betula platyphylla* and *Larix sibirica* samples clustered near vectors for slope and SOC, indicating that these species tend to store more SOC on steeper slopes. *Pinus sylvestris* formed a distinct cluster, suggesting different environmental controls.

At 30–60 cm depth, SOC was strongly negatively correlated with latitude, elevation, and permafrost. Positive associations with precipitation and temperature persisted but were weaker. *Betula platyphylla* again aligned closely with the SOC vector, indicating higher subsurface SOC, while *Pinus*

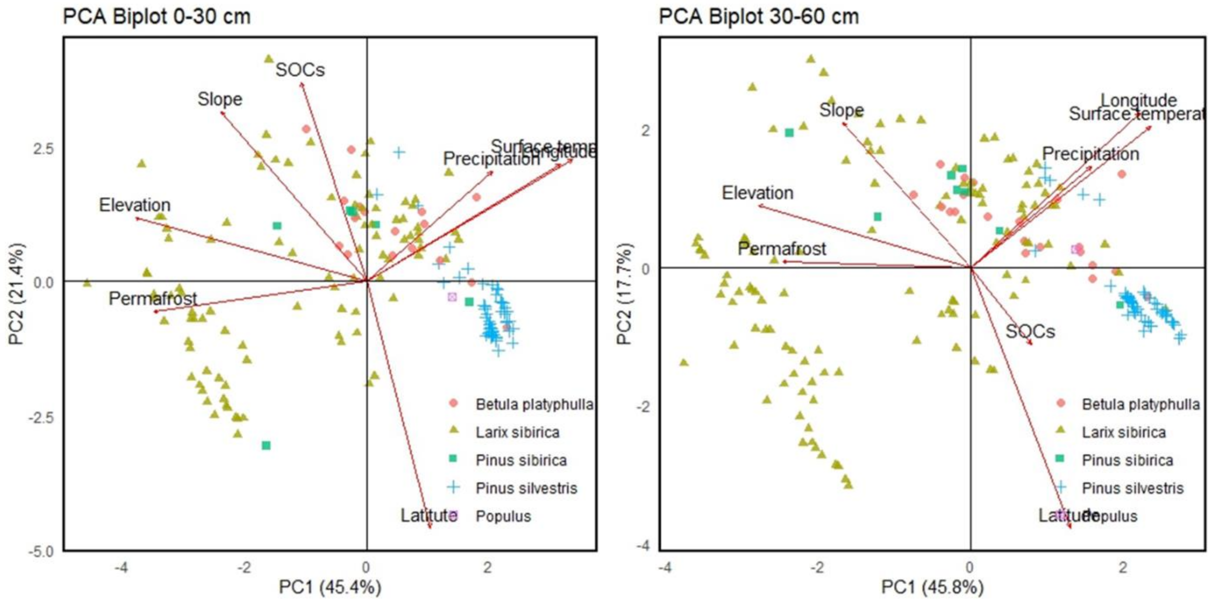

Figure 3.Principal Component Analysis (PCA) of Environmental Drivers

sylvestris was associated with colder, higher-latitude sites where SOC stocks were generally lower.

These PCA results confirm that SOC distribution is driven by both environmental gradients and species specific characteristics. In surface soils, climatic factors like precipitation and temperature exert greater influence, whereas in deeper soils, geographic factors such as latitude and elevation play a more dominant role (Figure 3).

4. CONCLUSION

This study demonstrates that tree species composition has a significant influence on SOC stocks in Mongolian forest ecosystems. Among the four dominant species evaluated, *Betula platyphylla* stored the highest SOC stock, particularly in the topsoil (0–30 cm), while *Pinus sylvestris* generally exhibited the lowest values. These differences are attributed to species specific traits such as litter quality, decomposition rates, and root distribution patterns. SOC stocks were found to decrease with soil depth across all species, although *Pinus sylvestris* maintained relatively higher carbon stocks in subsoil layers due to its adaptation to sandy soils. PCA further revealed that environmental factors such as slope, temperature, precipitation, and permafrost distribution differentially affect SOC distribution at various soil depths. The findings underscore the importance of tree species selection and site characteristics in managing forest carbon stocks. These insights are valuable for forest management and climate change mitigation strategies, particularly in boreal and permafrost-influenced regions like northern Mongolia.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Science and Technology Foundation of Mongolia for its generous support, and to the staff of the Institute of Geography and Geoecology, Mongolian Academy of Sciences, for their invaluable assistance and collaboration throughout this study.

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