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GRÓ Land Restoration Training Programme
Árleynir 22, 112 Reykjavik, Iceland

Final project 2021

SOIL ORGANIC AND INORGANIC CARBON DIFFERENCE ALONG ECOLOGICAL ZONES IN MONGOLIA

Ganzorig Ulgiichimeg
Institute of Geography and Geoecology, Mongolian Academy of Sciences
Baruun selbe 15-4, Chingeltei district, Ulaanbaatar, Mongolia
Ulgiichimeg.ganzoo@gmail.com

Supervisors
Dr Ólafur Arnalds
Agricultural University of Iceland
oa@lbhi.is

Dr Erla Sturludóttir
Agricultural University of Iceland
erla@lbhi.is

ABSTRACT

Soil carbon is the key part of terrestrial carbon storage and cycling. It consists of soil organic carbon (SOC) and soil inorganic carbon (SIC). There is limited information available on Mongolia's regional soil carbon stock. The study's aims were to quantify current regional soil carbon stocks and to investigate the interaction between SOC and relevant environmental variables such as latitude gradient, elevation, precipitation, and temperature. Soil samples were collected at 0-5 and 5-30 cm soil depth at 134 sampling sites within the six ecological zones in Mongolia. The mean soil organic carbon contents were 9.53 kg/m² in the meadow steppe zone, 9.6 kg/m² in steppe zones, 5.58 kg/m² in the dry steppe zone, 4.67 kg/m² in the arid steppe zone, 2.02 kg/m² in the desert steppe zone, and 1.57 kg/m² in the steppe desert zone. Soil inorganic carbon stocks ranged from 0.2 to 4.6 kg/m² within the ecological zones. Soil organic carbon was 25-98% of the carbon along the northern ecological zones. Soil inorganic carbon dominated the soil in southern zones, especially in the desert steppe and steppe desert zones (70-75% of the soil carbon). Soil organic carbon and soil inorganic carbon in Mongolian soils for the depth of 0-30 cm were estimated to be 4.8 Pg and 1.8 Pg, respectively. Elevation, latitude gradient, precipitation, and temperature parameters have a significant effect on soil carbon content and stocks. This study provides a general overview of current stocks of soil carbon, as well as the effect of climatic parameters and landscape on soil carbon content, along the ecological zones in southern Mongolia.

Key words: soil, soil carbon, ecological zone, organic carbon, inorganic carbon

This paper should be cited as:

Ulgiichimeg G (2021) Soil organic and inorganic carbon difference along ecological zones in Mongolia. GRÓ Land Restoration Training Programme [Final project] https://www.grocentre.is/static/gro/publication/827/document/ulgiichimeg2021.pdf

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ABBREVIATIONS

BD	Bulk density
C	Carbon
CF	Coarse fragments
CO_2	Carbon dioxide
EC	Electric conductivity
IPCC	Intergovernmental Panel on Climate Change
MAT	Mean annual temperature
MAP	Mean annual precipitation
SC	Soil carbon
SIC	Soil inorganic carbon
SOC	Soil organic carbon
STC	Soil total carbon
Pg	Peta gram

1. INTRODUCTION

Carbon studies have become a diverse topic in ecology, oceanography, and geochemistry because of the documented increase in CO_2 levels in the atmosphere (Raven et al. 2005). With the signing of the Paris Agreement, countries are obligated to analyse their contributions to global CO_2 sources and sinks, as well as the processes that regulate CO_2 build-up in the atmosphere (Delbeke et al. 2019). Over the last decades, our knowledge about carbon has improved with numerous studies at a global level. Recently, attention has focused on organic carbon pools in soils because soil carbon is a major element of the global carbon cycle, with important implications for climate change (Lal 2004; Zhang et al. 2015).

Soil carbon is a crucial part of the terrestrial carbon pool (Lal 2004), which comprises soil organic carbon (SOC) and soil inorganic carbon (SIC). The global carbon stock has been estimated to be about 2296–2500 Pg C in the upper 100 cm soil layer (Batjes 1996; Lal 2004). The soil carbon pool is now generally lower than before the rise of widespread human disturbance (Smith 2006). It is estimated that soils have historically lost between 40 and 124 Pg C worldwide due to agriculture and other human disturbance (Schimel 1995; Houghton 1999).

The global SOC pool in the 0–1 m layer is estimated to be 1462–1548 Pg (Batjes 1996) and 1550 Pg (Lal 2004). SOC is one of the largest pools of terrestrial carbon (Batjes 1996) compared to other sources of organic carbon and is about twice the amount of carbon in the atmosphere and three times the amount stored in terrestrial vegetation (IPCC 2000). SOC components are indicators of soil quality that affect essential biological, physical, and chemical activity such as nutrient cycling, water retention and soil formation (Blanco-Canqui & Lal 2010). Soil organic carbon is therefore, in addition to atmospheric and climate effects, essential for ecosystem fertility and human well-being. There have been many studies focusing on SOC stocks and change, ranging from field plots to national estimates (Batjes 1996; Lal et al. 2000; Eswaran et al. 2001; Blanco-Canqui & Lal 2010).

However, much less attention has been given to SIC than SOC even though it plays a vital role in carbon sequestration and climate mitigation (Lal et al. 2000). Researchers estimated the SIC pool at the first 1 m depth from 695-745 Pg (Batjes 1996) to 950 Pg (Lal 2004) at a global level. Soil inorganic carbon is found in various forms such as gaseous CO_2 (g), dissolved CO_2 (aq), carbonic acid H_2CO_3 (aq), bicarbonate HCO^{3-}(aq), and carbonate CO_3^{2-}(aq) (Monger et al. 2015). Soil inorganic carbon (SIC) is mainly in two solid forms, calcium carbonate ($CaCO_3$), and dolomite ($MgCO_3$) (Batjes 1996). In arid and semi-arid regions, SIC storage and accumulation are generally considered to be greater than SOC storage and accumulation (Lal 2008). However, the carbonatic soil carbon does not readily interact with the atmosphere, hence more attention should be put on the more reactive or unstable forms of soil carbon, such as soil organic carbon (Clara et al. 2017).

Mongolia is an arid and semi-arid country of 1,566 thousand km^2 in east central Asia. The main ecological zones of Mongolia are defined as “desert” and “desert steppe”. The Gobi Desert and the desert steppe regions constitute about 60% of the country’s territory (Yembuu 2020), around 900,000 km^2. In Mongolia, desertification has become one of the critical environmental issues due to changing climate, land degradation, and overgrazing (Ochirbat 2013). Desertification processes drastically reduce soil fertility (Lu et al. 2014) and the carbon contents of soils. Researchers estimate that 77 to 90% of Mongolia is affected by desertification (Batjargal 1997; Tamura et al. 2013; Nyamtseren et al. 2018). Soils of arid and semi-arid areas of Mongolia contain significant amounts of SIC (Wu et al. 2009). Climate variables, notably precipitation and temperature, are widely recognized as the most important drivers of SOC and SIC content (Alvarez & Lavado 1998). Precipitation is expected to influence SOC content because increased precipitation is frequently linked with more rapid rates of plant growth, which increases the content of SOC and sometimes SIC accumulation (Raheb et al. 2017).

Several studies of soil organic matter and other soil studies have been conducted in the Gobi Desert and surrounding zones. Several studies investigated soil chemical characteristics in the northern part of the Gobi Desert in 1926 (Polynov & Krashennikov 1926; Polynov & Lisovskii 1926). Other studies have involved chemical and physical characteristics, classification (Bespalov 1951; Gerasimov & Lavrenko 1952; Sokolovskii 1960; Kokorin 1968; Rubtsova 1978; Umarov & Yakunin 1978), soil mapping, soil classification, and specialized studies (Oros 2001; Dechingungaa 2003; Ochirbat 2011, 2013, 2016; Pankova & Lebedeva 2015; Purevsuren & Gankhuyag 2016; Ochirbat et al. 2019) in the Gobi Desert. However, only few have investigated soil carbon in the Gobi Desert (Ochirbat & Ulgiichimeg 2018), according to a study involving the topsoil layer (0-30 cm), soil organic carbon has decreased by 31% over the last 90 years in the Gobi Desert area (Ochirbat & Ulgiichimeg 2018). Recent soil studies have focused on the effect of land management issues, and particularly overgrazing on soil carbon stocks in Mongolia and Inner Mongolia (Zhao et al. 2017). However, due to a lack of soil carbon data, there is limited information about soil carbon stocks at the national level in Mongolia. A more reliable estimation of SOC and SIC storage levels in Mongolia is needed and to improve the understanding of carbon dynamics in Mongolia.

The research focused on identifying and assessing soil carbon, as well as soil organic carbon (SOC) and soil inorganic carbon (SIC) stocks in soils of the Gobi Desert and in soils of the steppes in Mongolia.

1.1 Objectives

The purpose of this research was to quantify soil carbon in Mongolia's dry and semi-arid areas based on field measurements and laboratory results. The specific objectives were to:

1. Investigate the ecological zone differences of soil organic and inorganic carbon contents
2. Calculate the soil organic carbon and inorganic carbon stocks of ecological zones in Mongolia
3. Describe the main factors affecting the soil carbon at different ecological zones.

The results are expected to contribute to a new understanding of soil carbon dynamics in the Gobi Desert and the arid and semi-arid areas in Mongolia.

2. METHODS

2.1 Study area

The main features of Mongolia's distinct ecological zones are defined by the various types of landscape and their geographical distribution induced by latitudinal differences, incoming solar radiation, and climatic factors (Doljin & Yembuu 2020). Mongolia's territorial and geographical differentiation is typified by four main ecological zones: forest steppe, steppe, Gobi, and desert zone. Each zone is divided by sub ecological zones.

The study involved the semi-arid and arid zones (N 44°40’-48°00’; E 99°30’-107°00’) of central and southern Mongolia and focused on identifying the variability in soil carbon and other characteristics in these extensive areas (Fig. 1).

The study area is characterized by a temperate, sub arid and arid continental harsh climate conditions. The mean annual precipitation ranges from 100 to 200 mm with a gradual increase from south to north. Most (80%) of the precipitation falls during the summer season especially in July and August. Mean annual temperatures range from 5°C to 8°C and decreases along the south to north direction (Ministry of Environment and Tourism of Mongolia 2018). Long-term (1980-2020) meteorological data, MAT, and MAP were obtained from the Institute of Meteorology in Mongolia.

Soil samples were obtained from 136 sampling points along the ecological zones, from August to September 2019 (dotted line in Fig. 1). Sampling points were placed at 20 km intervals. At each site, soil samples representing the topsoil layer were collected at 0-5 cm and 5-30 cm depths at three different randomly selected points and sampled according to IPCC recommendations (IPCC 2006). The replication points were 5-10 meters apart, and each replicate consisted of a composite of 2 samples, which were sampled within a 3–5-meter radius. A soil bulk ring sampler with a stainless-steel cutting ring was pushed into the soil, and soil samples were collected from the same depths at all sites.

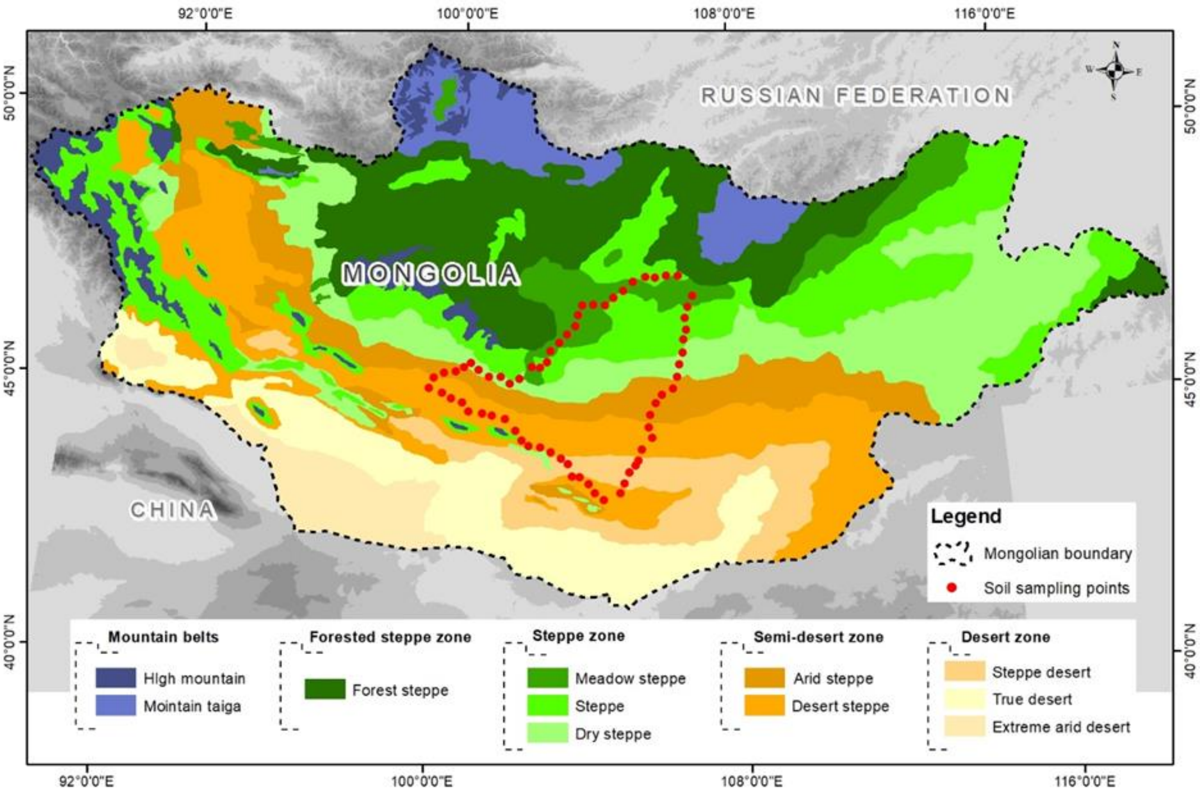

Figure 1. Study area of Ecological zones in Mongolia

2.2 Laboratory methods

The samples were air-dried at room temperature in the laboratory. Soil samples were then oven dried for 24 hours at 105 °C and weighed to determine bulk density (BD). Coarse fragments (CF) were separated from the soil using a 2 mm sieve. The volume and the weight of the coarse fragments were determined, and bulk density was subsequently determined for the volume and weight of the remaining soils (active fraction coarse fragments excluded modified core method; Blake & Hartge 2018).

$$\mathrm{BD} = Ms/Vs \tag{1}$$

where BD is the soil bulk density (g/cm^3); Ms is the dry weight of the soil after removal of CF; (g); Vs is the volume of the active fraction of the soil (<2 mm) after the CF have been excluded.

Soil pH was measured using a 2.5:1 ratio of deionized water/soil mass. Representative sub-samples were crushed to 0.25 mm before the SOC contents were determined by the potassium dichromate sulfuric acid ($K_2Cr_2O_7$-H_2SO_4) oxidation method (Walkley & Black 1934). SIC was determined by dissolving the soil by HCl using the Chittick apparatus (Sherrod et al. 2002). The resulting carbonates refer to the sum of calcium carbonate ($CaCO_3$), magnesium carbonate ($MgCO_3$) and other carbonate minerals. The ratio between the atomic mass of carbon and the molar mass of $CaCO_3$ is 0.12 and converts soil $CaCO_3$ to the soil inorganic carbon (Wu et al. 2009).

I estimated stocks/storage (kg C m^{-2}) of SOC by using the method described in Liu et al. (2011) as follows: Soil organic carbon stock of specific layer ***i*** (SOC_i, kg/m^2) and soil profile is ***t*** (SOC_t, kg/m^2)

$$\boldsymbol{SOCi = C_i \times D_i \times E_i \times (1 - G_i)/10} \qquad (2)$$

$$\boldsymbol{SOC_t = \sum_{i=1}^{k} SOC_t = \sum_{i=1}^{k} \times C_i \times D_i \times E_i \times (1 - G_i)/10} \qquad (3)$$

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where *k* is layers (depth intervals), *Ci* is organic carbon content (%), *Ei* is bulk density (g/cm^3), *Di* is the thickness of the layer and the profile, and *Gi* is the volumetric proportion of the >2mm fraction in the layer *i*.

Similarly, soil inorganic carbon storage of a specific layer *I* (*SI*C*i*, kg/m^2), and soil profile (*SI*C*t*, kg/m^2). The SIC storage of each profile per unit area was calculated using the following equations 4, 5:

$$\boldsymbol{SICi = C_i \times D_i \times E_i \times (1 - G_i)/10} \qquad (4)$$

$$\boldsymbol{SIC_i = \sum_{i=1}^{k} SIC_i = \sum_{i=1}^{k} \times C_i \times D_i \times E_i \times (1 - G_i)/10} \qquad (5)$$

SOCS storage and SICS storage for each ecological zone was calculated using polygon areas in an ecological zone map taken from Yembuu (2020) according to the equation (6):

$$\boldsymbol{SOCS\ or\ SICS = \sum_{i=1}^{n} \times area_i \times SOC_i\ or\ SIC_i} \qquad (6)$$

2.3 Statistical methods

Descriptive statistical values were used to represent soil properties of ecological zones. A Pearson correlation was performed to explore the relationship between soil organic carbon and soil inorganic carbon content. Analysis of variance (ANOVA) was used to assess the effect of latitudinal difference and soil depth, and their interaction on soil carbon content and storage. Therefore, an analysis of covariance standard (ANCOVA) was used to determine soil organic and inorganic carbon (log transformed SOC and SIC to meet the assumption of normality and homogenous variance) changing along the elevation in the ecological zone. R studio environment of R 4.0.4 (RStudio Team 2020) were used for statistical analyses.

3. RESULTS

3.1 Soil properties of difference on the natural zones

According to field survey data for the 134 soil samples, soil pH level ranges from slightly acidic to moderately alkaline (6.5-8.2) for the meadow steppe and dry steppe zones. From the arid steppe zone to the steppe desert zones, pH levels ranged from moderate alkaline to strong alkaline (8.0-9.9). Electric conductivity (EC) varied from 0.01-0.94 dS/m, with salt content increasing in south zones as well as desert steppe and steppe desert. Generally arid and semi-arid region soils accounted for more salt content than other regions (Table 1).

Gravel and stone content (the >2 mm fraction of the soil) ranged from 0 to 62.7%. Gravel content is an important factor for quality and land use in addition to the calculation of total soil carbon contents. Soil texture was mainly coarse sand and sandy soil (sand content 43.9-80.9%), with very high sand content in the arid steppe and dry steppe zones. Sand, silt, and clay are the three major individual fractions that make up soil texture.

Table 1. Mean, maximum and minimum value of soil characteristics for the natural zones.

Ecological zones (n)*	Stats	Elevation (m)	pH	Salt, dS/m	Gravel, %	Sand,%	Silt, %	Clay, %	Bulk density, g/cm^3
Meadow steppe (20)	Mean	1553	7.5	0.05	13.7	61.0	21.0	18.1	1.1
	Max	2041	8.1	0.12	41.0	74.6	39.5	23.8	1.3
	Min	1113	7.1	0.02	0.2	46.9	7.3	13.6	0.7
Steppe (26)	Mean	1364	7.5	0.06	15.9	60.7	20.3	19.0	1.1
	Max	1853	8.2	0.19	57.7	77.5	38.0	25.3	1.3
	Min	1056	6.5	0.02	0.6	44.0	5.9	16.5	0.9
Dry steppe (18)	Mean	1754	7.7	0.07	21.9	69.3	12.4	18.3	1.1
	Max	2011	8.3	0.26	62.7	76.0	19.0	22.3	1.3
	Min	1320	6.1	0.02	1.9	63.0	8.8	15.0	0.9
Arid steppe (16)	Mean	1561	8.1	0.17	8.6	72.1	10.7	17.2	1.2
	Max	1971	8.9	0.63	22.0	80.4	19.0	25.3	1.6
	Min	1346	7.1	0.03	2.0	62.9	5.9	12.2	1.0
Desert steppe (44)	Mean	1362	8.5	0.14	15.6	66.1	13.5	20.4	1.2
	Max	1506	9.9	0.94	42.5	79.1	27.8	32.6	1.3
	Min	1212	8.0	0.01	0.0	49.7	1.5	12.1	0.9
Steppe desert (12)	Mean	1271	8.7	0.19	11.5	59.6	18.4	22.0	1.2
	Max	1571	9.9	0.43	22.3	80.6	33.7	31.1	1.3
	Min	1107	8.0	0.01	0.0	43.9	4.4	13.7	1.0

* *Number of samples*

Soil parameters, such as soil textures, show low correlation with elevation ($r^2=0.12$, $p>0.05$), but other variables do not correlate with elevation. In addition, pH, electric conductivity, gravel content and texture do not correlate with latitude (along the ecological zones). The effect of elevation was indirect and complex, associating with other factors, such us temperature and precipitation as well as along the latitude location.

3.2 The ecological zone difference effect on SOC and SIC distribution

The SOC contents ranged from 0.02 to 3.24% (mean 0.66%) and SIC contents were 0.012-1.42% (mean 0.207%) in 0-30 cm depths along the ecological zones. Comparing zones, SOC contents in the meadow steppe and steppe zones were significantly higher than in other zones ($p<0.001$) (Fig. 2a). The mean SOC content in the meadow zone was 4.2% higher than in the steppe zone; the steppe zone SOC content was 36.5% higher than the dry steppe zone; the dry steppe zone was 36.9% higher than the arid steppe; the arid steppe zone was 57.5% higher than the desert steppe; and the desert steppe zone was 28.9% higher than the steppe desert zone On the other hand, SIC deposition was higher in the steppe desert and desert steppe (Fig. 2Figure 2b). SIC content was significantly higher in the desert steppe and steppe desert zones. A higher amount of SOC contents was observed in the top layer (0-5 cm) than in the 5-30 cm depth interval in all ecological zones.

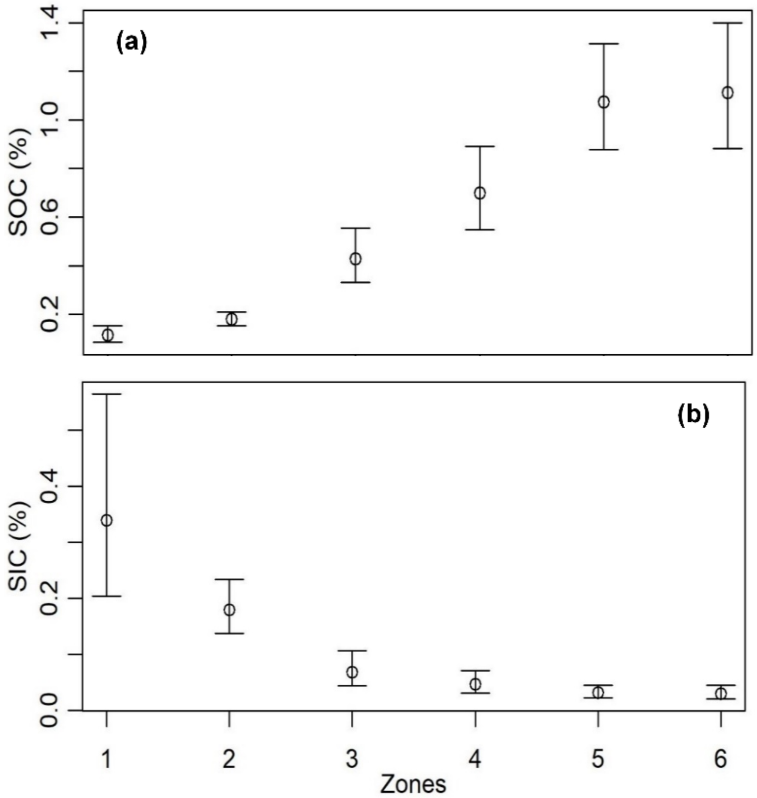

Figure 2. Plot of SOC (a) and SIC (b) content along the ecological zones: 1- steppe desert, 2-desert steppe, 3-dry steppe, 4-arid steppe, 5-steppe, 6-meadow steppe.

There was a significant difference of mean SOC between the zones ($p< 0.001$), even between soil depth and SOC content ($p< 0.01$). This suggests that there is an important difference in soil organic carbon content between ecological zones. Ecological zone and soil depth also significantly influenced the SIC contents with the higher values in the dryer ecological zones ($p < 0.001$).

Pearson correlation coefficients for the sampled layers (n = 134) showed a negative correlation between SOC and SIC content r = -0.60 (95% CI=-0.69 to -0.48). High SOC content in northern zones such as steppe and meadow steppe coincided with low, SIC contents in the top 30 cm depths. The opposite trend in SIC content was observed.

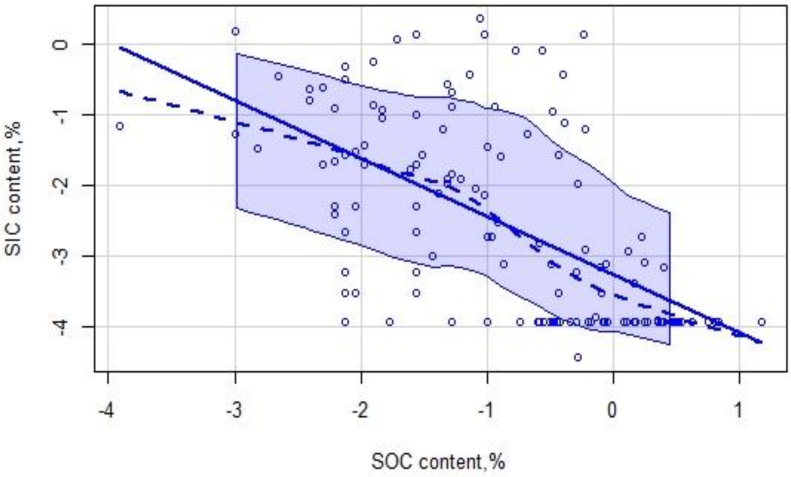

Figure 3. SOC and SIC along the ecological zones.

3.3 Total carbon along the ecological zones

Soil total carbon content (STC) ranged from 0.14% to 3.24% (mean 0.83%). Soil carbon differed significantly between different zones as follows: steppe desert zone 0.58%, desert steppe zone 0.57%, arid steppe zone 0.57%, dry steppe zone 0.85%, steppe 1.21% and meadow steppe zone 1.31%.

The SOC fraction of the total carbon content generally decreased for zones further south (Fig. 4), but the SIC content showed a reverse trend. The ratio of SIC to SOC storage ranged from 25% in steppe desert zones to 98% in steppe zones.

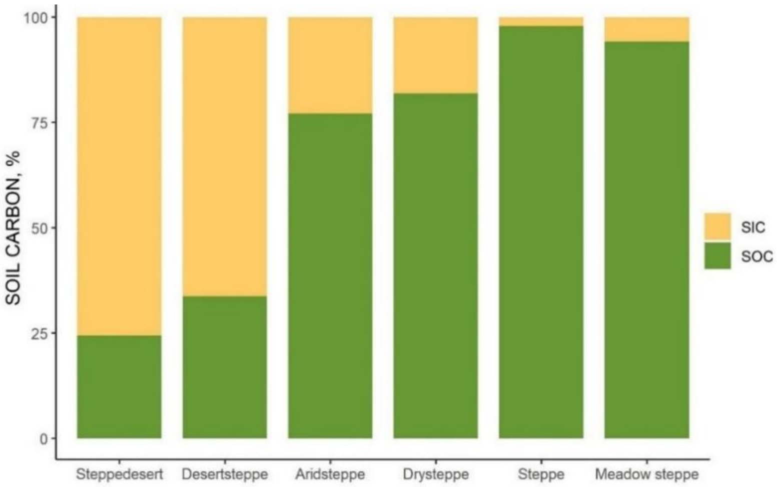

Figure 4. Percentage of SOC and SIC stocks in the 0-30 cm soil layer along the ecological zones.

3.4 The effect of elevation on SOC and SIC content

Soil organic carbon content increases by the elevation within each ecological zone in in addition to showing differences between the zones (Fig. 5). The steppe desert and desert steppes have similar low carbon content values with slight increase with elevation. For instance, soil organic carbon value increases by 0.11% (absolute value) in steppe and meadow steppe zones for each 100 m but in the other zones, such as desert steppe, steppe desert zones SOC increases by a much lower 0.03% for each 100 m elevation increase (Fig. 5).

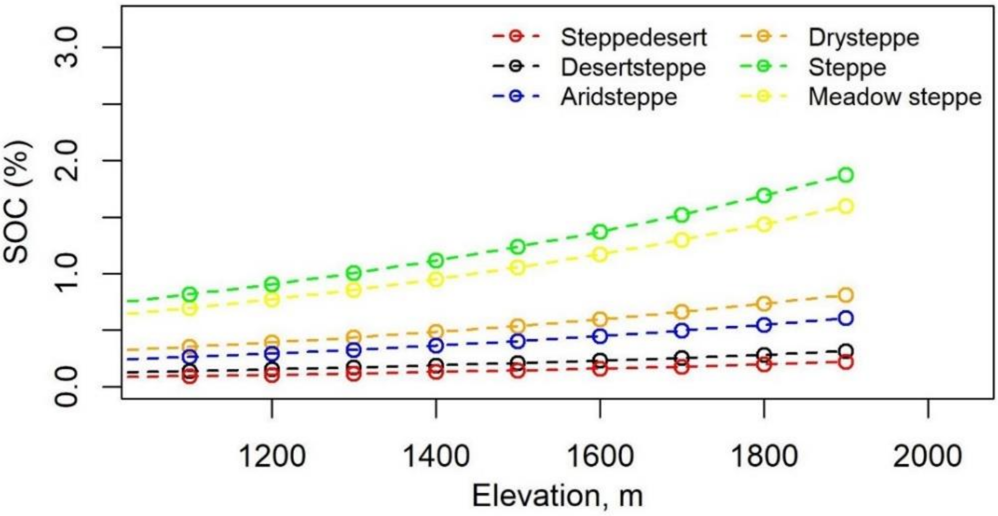

Figure 5. Average SOC content changes in the top 30 cm of soils along the elevation gradients within the ecological zones.

Soil inorganic carbon content decreased with increasing elevation within each ecological zone (Fig. 6). SIC content decreased only slightly with altitude. SIC was rather low in the topmost 30 cm of soil in the northern zones (steppe, arid steppe, meadow steppe). SIC decreases by

0.007% on average with each 100 m increase in elevation within the steppe desert zone, where SIC values were highest among the ecological zones.

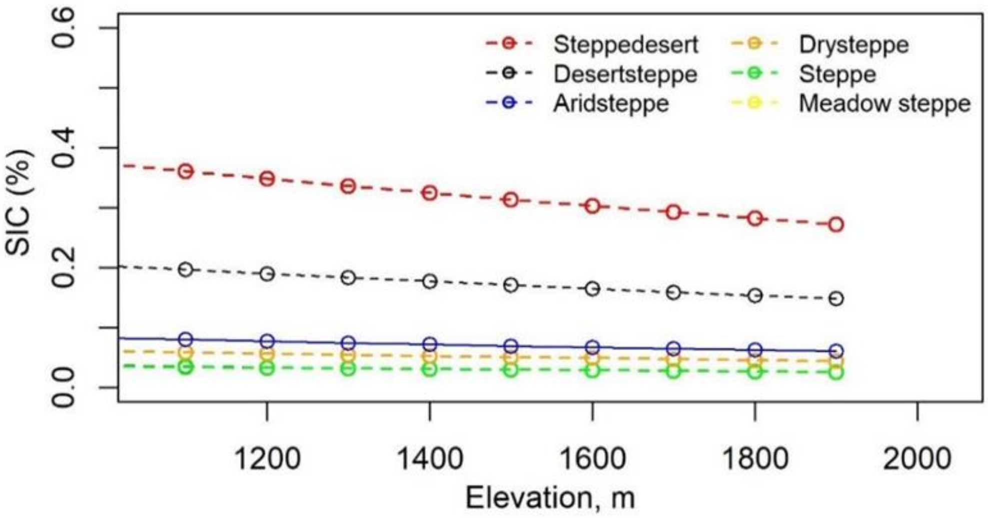

Figure 6. Average SIC content changes in the top 30 cm of soils along elevation gradients within the ecological zones.

The regression analysis for SOC vs elevation was significant ($p<0.001$). A non-significant relationship was found between SIC and elevation ($p>0.05$). Ecological zone ($p<0.001$) and elevation ($p<0.001$) had both significant effects on SOC but only the ecological zone had a significant effect on SIC values ($p <0.001$). Therefore, the value of R^2 is 0.77 for SOC (but as low as 0.28 for SIC R^2), a regression coefficient of 0.77 can be considered high and implies that the fitted regression model captures the majority of variation in response to elevation.

3.5 The relationship between climate variables, SOC and SIC

The annual mean temperature and the average total precipitation interacts with SOC and SIC content within the ecological zones. SOC content was positively correlated with annual precipitation, dropping from 1.25% C on average within the meadow steppe of the highest rainfall (270 mm) to 0.15% in the driest zone, the steppe desert ecological zone. The reverse trend was observed for SIC content and precipitation (Figure 7). SIC content was 3-16 times higher where annual precipitation was lower than 100 mm compared to other more moist zones even though they are considered dry in a broader context (desert steppe and steppe desert). Comparing annual temperature, SIC and SOC suggested reverse effect, with lower SOC and higher SIC with increased temperature (Figure 7).

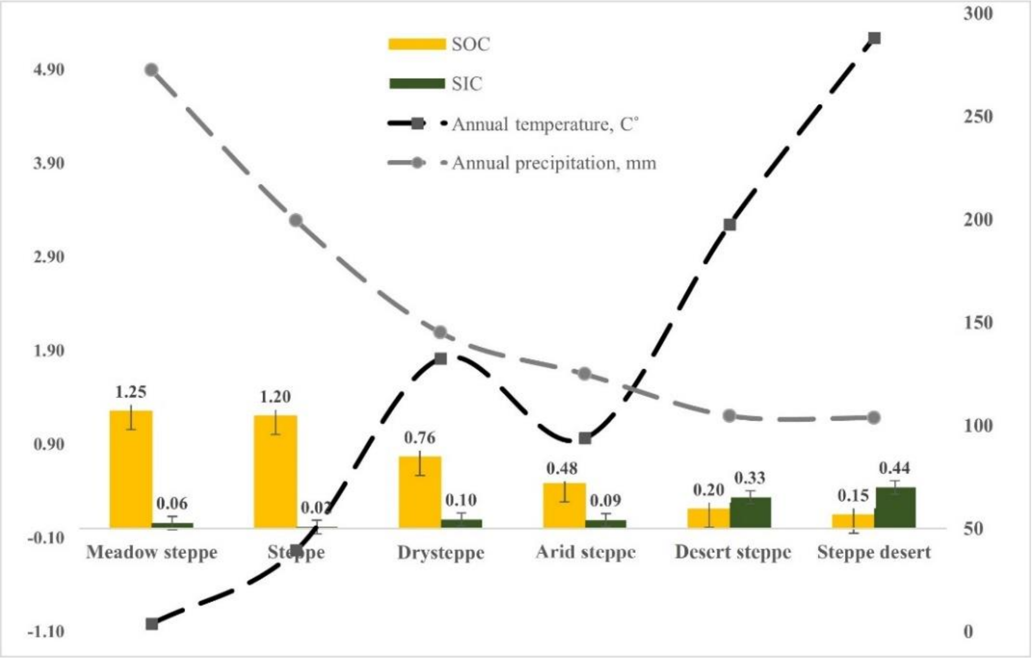

Figure 7. SOC and SIC content changes (average for 0-30 cm soil depth) with annual temperature and precipitation between the ecological zones.

The result from the ANOVA analysis showed that these differences between SOC were significant, i.e. there was a significant effect of temperature F (1, 4) =18.7, $p<0.01$ and annual precipitation F (1, 4) = 23.5 $p<0.001$ on the SOC content. Moreover, differences in SIC were related to variable annual precipitation ($p=0.135$) and temperature ($p<0.01$) within the ecological zones.

3.6 SOC stocks of the ecological zones

Significant differences were found in soil organic carbon stocks in the top 30 cm of soils (kg/m^2) between the ecological zones. The highest amount of SOC stocks was observed in the meadow steppe and the steppe zones (9.60 and 9.53 kg/m^2 respectively), while the lowest carbon stocks were observed in the steppe desert, 1.57 kg/m^2, or about 5 times less than in the meadow steppe. The soil carbon stocks decreased along a line from north to south. SOC stocks in other zones showed intermediate values: the dry steppe zone 5.58 kg/m^2 (max 9.09 kg/m^2, min 2.03 kg/m^2), the arid steppe zone 4.67 kg/m^2 (max 10.36 kg/m^2, min 0.56 kg/m^2) and the desert steppe zone 2.02 kg/m^2 (max 9.09 kg/m^2, min 2.03 kg/m^2) (Figure 8).

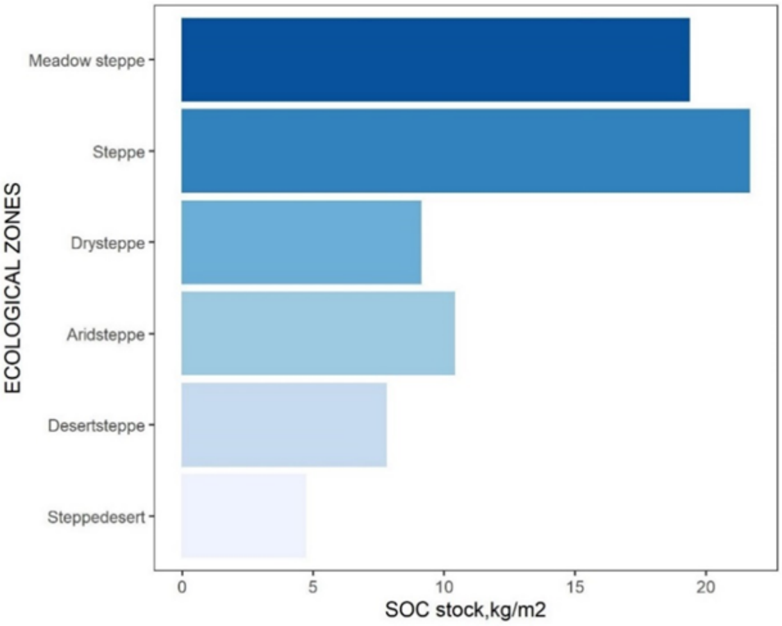

Figure 8. Average SOC stocks in the top 0-30 cm of soils by ecological zones.

3.7 SIC stocks of ecological zones

SIC stocks decreased significantly with more northerly location within the ecological zones in the top 30 cm of soils (Figure 9). Compared with the steppe desert zones (4.58 kg/m^2), SIC stocks were significantly lower in the northern zones, such as steppe and meadow steppe (0.20 kg/m^2 and 0.58 kg/m^2 respectively) at a soil depth of 30 cm.

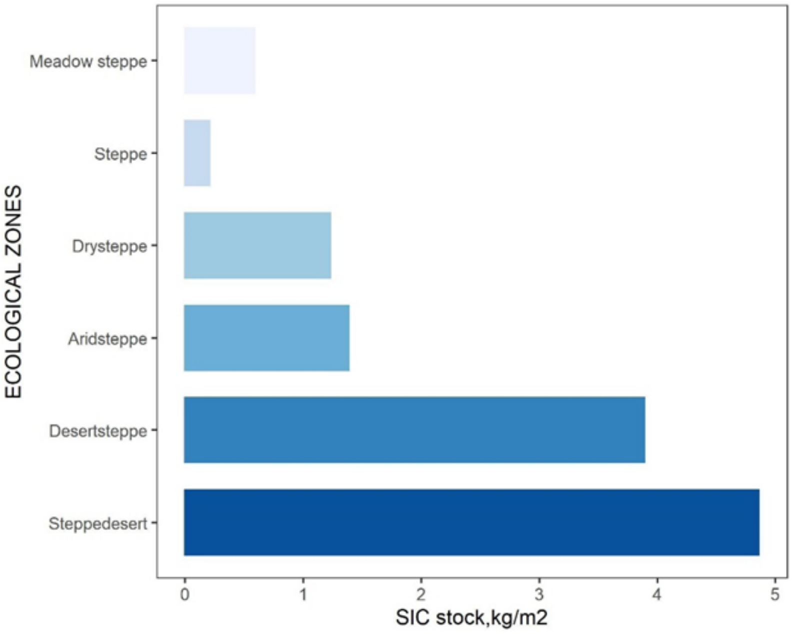

Figure 9. Average SIC stocks in the top 30 cm of soils within the ecological zones.

An analysis of variance (ANOVA) indicated that there was a significant difference in SOC and SIC stocks at 0-30 cm soil depth between the ecological zones ($p<0.001$).

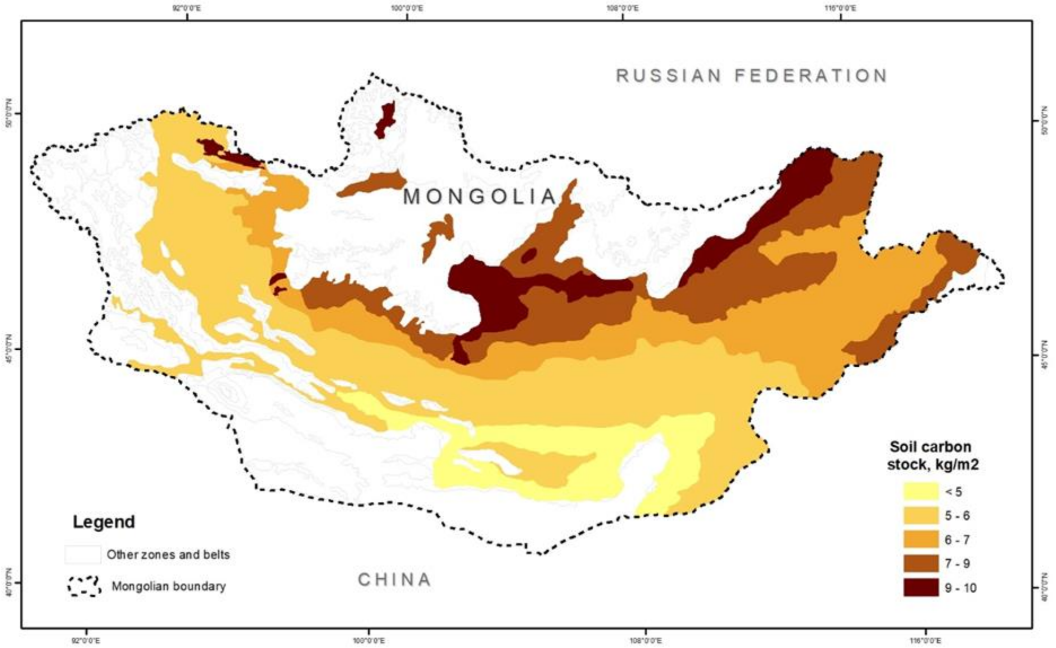

Figure 10. Soil carbon stocks in Mongolia separated by ecological zones (0-30 cm soil depth).

3.8 Carbon pool of meadow steppe to desert steppe zones

The carbon pool of the ecological zones consists of inorganic (SIC) and organic carbon (SOC) which can be combined to obtain the total carbon pool of each area (TC). The aerial extent of the different ecological zones varies considerably, from 74 to about 214 000 km^2 (Table 2) which affects the total carbon pool within the ecological zones. Combining the pools of organic carbon for the all the ecological zones resulted in 4.8 Pg C, but considerably lower totals for inorganic carbon or 1.8 Pg (Table **2**). The largest pool of organic carbon was within the steppe zone, at 1.7 Pg. The largest total carbon pool (SOC+SIC) was found in the steppe (1.774 C Pg), followed by the dry steppe (1.398 C Pg), desert steppe (1.256 C Pg), arid steppe (0.811 C Pg), steppe desert (0.603 C Pg) and meadow steppe (0.753 C Pg) in the top 30 cm soil layer.

Table 2. The soil carbon pool of steppe to desert zones of Mongolia.

№	Zone	Area, km^2	Soil carbon pool, Pg	SOC pool, Pg	SIC pool, Pg
1	Meadow steppe	73,987	0.753	0.710	0.043
2	Steppe	182,158	1.774	1.736	0.037
3	Dry steppe	205,596	1.398	1.147	0.251
4	Arid steppe	134,057	0.811	0.626	0.185
5	Desert steppe	214,389	1.256	0.424	0.832
6	Steppe desert	93,807	0.602	0.147	0.455
7	**Amount**	**903,994**	**6.6**	**4.8**	**1.8**

4. DISCUSSION

4.1 Parameters influencing SOC content

Elevation above sea level affects climatic parameters such as precipitation and temperature (Garten 2004), causing gradients in soils and vegetation types. Generally, air temperature decreases with increasing elevation, with a decreasing rate of 0.58°C each 100 m, and precipitation increases with increasing altitude, with an increasing rate of 18.6 mm for each 100 m (Fu et al. 2004). Temperature and precipitation mainly drive the SOC decomposition rate; lower temperature could reduce SOC output rates, leading to increases or decreases in SOC levels. Leifeld et al. (2015) suggested SOC increases 0.075-0.21% per 100 meter elevation increase in Switzerland. The soil sampling points in this study ranged from 1,056-2,041 m altitude, reflecting common altitude ranges in Mongolia. It was observed that SOC content increased significantly with increasing altitude as was to be expected. However, the effect of elevation presented here is complex and probably indirect. The SOC increase with elevation varied considerably between ecological zones, ranging from 0.007 to 0.1% for each 100 m increase in elevation.

Soil organic carbon content in the top 30 cm soil layer increased from south to north. Differences were greater between ecological zones than within zones. For instance, the difference in SOC was of a factor of 8 between the meadow steppe (1.25% on average) and the steppe desert zone (0.145%), although there was only 230-300 km between zones. The results of this study are similar to results presented for a desert to mountain steppe SOC study in north-western China by Yan et al. (2019) and in a grassland to desert gradient in China (Wang et al. 2004), where SOC in grassland zones was 6 to 7 times higher than in desert zones. It can be concluded that precipitation is the main factor that determines SOC content in the soils in this study, which is in line with the general theory that climatic parameters, particularly precipitation and temperature, are the most important determinants of SOC content (Alvarez & Lavado 1998). Higher precipitation is associated with a higher rate of vegetation growth and litter decomposition and thus with a higher rate of organic carbon input in the soil. This is in agreement with the general conclusions of Schimel 1995, Wang et al. 2004, andXu et al. 2014, stating that environment factors, such as temperature and precipitation parameters, are considered the most effective factors regulating SOC.

4.2 Parameters influencing SIC content

The precipitation and chemical dissolution processes of carbonate are represented by the chemical formulas below (Lal 2008):

$$CO_2 + H_2O \leftrightarrow HCO^{3-} + H^+ \qquad (7)$$

$$Ca^{2+} + 2HCO^{3-} \leftrightarrow CaCO_3 + H_2O + CO_2 \qquad (8)$$

The equation of carbonate precipitation-dissolution are influenced by soil heating and cooling, moisture, CO_2 concentration, and Ca^{2+} and Mg^{2+} concentrations, thus having a direct effect on SIC content (Breecker et al. 2009). Therefore, anything which influences the above-mentioned factors would cause a variation in SIC. There is rather limited information about SIC in the research of carbon soils (Guo et al. 2016).

Soil inorganic carbon (SIC) in this study did not vary as much as SOC along the elevation gradient. However, increase in elevation with increasing precipitation decreased SIC content but increased SOC (Figure 2a). In the southern region, which tends to be more arid and warmer, SIC content was higher, compared to the moist areas (Figure 2b and Figure 9). SIC content was relatively low in the dry steppe, steppe, and meadow steppe in the 0-30 cm soil layers. More SIC was found in the arid steppe with the highest SIC accumulation in the south zones (desert steppe, steppe desert zone). Generally, SIC content was higher in the 5-30 cm depth interval than the 0-5 cm interval in this study; with 80-90% of the SIC found in the 5-30 cm depth interval. This can be explained by carbonates being unstable in more moist surfaces where carbonate in solution migrate, accumulating in layers below the surface horizon (Liu et al. 2014). Therefore, accumulation of SIC in layers below the surface horizon is dependent on leaching processes after intensive, short duration rainfall events (Díaz-Hernández & Barahona Fernández 2008).

4.3 Soil carbon stock and potential carbon sequestration in Mongolia

Most of the soil organic carbon stocks within the top 1 m of soils in dry land areas of Australia and China are found in the top 30 cm of the soils, or about 40-57% of SOC (Orgill et al. 2014; Soussana & Lemaire 2014; Wan et al. 2019). While shorter-term changes in active SOC mostly appear in the top of the profile (Conant & Paustian 2002), stable SOC can accumulate in the deeper soil layers. This carbon fraction may play an important role for global C budgets between the soil and the atmosphere (Batjes 1996).

This study is one of the earliest regarding carbon storage in arid and semi-arid areas in Mongolia. Several studies have calculated SOC stocks in semi-arid and arid zones in north-western China and Iran, as well within similar ecological zones in Mongolia. This study estimated SOC stocks as 1.57-4.57 kg/m^2 in the desert and steppe zones, which is in good agreement with other studies for dry areas in Asia (Table 3) as well in Iran (0.81-0.91 kg/m^2, Raheb et al. 2017). The Intergovernmental Panel for Climate Change (IPCC 2006) estimated soil organic carbon stock of 2.1-2.4 kg/m^2 in boreal and temperate arid regions, and 0.8-5.4 kg/m^2 in desert soils (Yermosols and Xerosols) for the top 30 cm soil layer. Overall, steppe and grassland soils accounted for 5.06-9.06 kg/m^2 in these studies, and the data for more moist areas (meadows and grasslands) in this study are of a similar order (Table 3, upper part).

The analysis variance showed that climate factors as well as mean annual precipitation were the most important factors in determining SOC stocks in the Mongolian steppe and desert regions (Fig. 5), which is consistent with results found in other dry regions in Asia (He et al. 2014; Zhao et al. 2017). As the temperature rises, evaporation rises and plant output decreases, resulting in a decrease in soil organic carbon input (Martin et al. 2011). On the other hand, with increasing temperature, soil microbial decomposition activity increases, resulting in increased soil organic carbon production when enough water is available (Mao et al. 2015). The interaction between temperature and soil moisture is one of the most important factors controlling soil organic carbon storage in general, which is well expressed in this study’s data.

Table 3. Comparison of SOC and SIC stock in several national and regional areas (0-30 cm soil depth).

Region	Natural zone	MAP	SOC, %	SOC, kg/m²
Grassland and Steppe				
China, (Wang et al. 2004)	Grassland	200-400	0.45	7.98
China, (Zhao et al. 2017)	Grassland	300	-	4.11
China, (Mao et al. 2015)	Grassland	500	-	10.19
This study	Grassland	200-300	1.07	5.06-9.6
Desert steppe				
Horqin sand, China (Zhao et al. 2009)	Desert grassland	350-450	0.45	0.19-1.76
Alxa county, China (Zhou et al. 2011)	Desert scrubland	60-160	-	0.21-2.8
Gobi, China, (Zhang & Shao 2014)	Desert	120	0.145	0.68
Urumqi, China (Wang et al. 2014)	Desert	299	-	4.25
Yanqi, China (Wang et al. 2015)	Desert	80	-	4.53
This study	Desert	50-200	0.27	1.57-4.67

Bathes (1996) estimated the organic carbon storage of the world soils level to around 684-724 Pg at 0-30 cm depth. The soil organic carbon storage of desert and steppe areas in Mongolia of 4.8 Pg represented about 0.7 % of the soil organic carbon storage in the top 30 cm of soils. Mongolia makes up about 1.0% of the World's terrestrial area. Steppe, meadow steppe and dry steppe zones are the main storage areas of organic carbon but in the desert steppe and steppe desert zones, SIC storage was 2-4 times higher than the SOC in the top 30 cm soils (Table 2). Although arid and semi-arid areas cover around 80 percent in Mongolia, SIC should not be neglected in dry areas because of the greater amount of SIC compared to SOC. The large amount of SIC could be important in the context of climate change and global environmental change (Yang et al. 2010), particularly in dry areas. Information about SIC is generally very limited at national level and not well studied compared with information about SOC, while such data may become important soon.

Table 4. SOC storage comparison at national and global scales (0-30 cm, unit: Pg).

Author	Region	Area (x10^6 ha)	Pg C in 0-30 cm
(Batjes 1996)	Global		684-724
(Batjes & Dijkshoorn 1999)	Amazon	761.8	36.1
(Wang et al. 2004)	China	901.63	44.48
(Tang et al. 2018)	China: grassland	281.3	24.0
(Tate et al. 2005)	New Zealand	26.8	2.89
(Calvo de Anta et al. 2020)	Spain	50.5	3.33
This study	Mongolia	90.6	4.8

5. CONCLUSIONS

In this research, SOC and SIC content and the effect of altitude, elevation, and climate variables on SOC stocks and storage across the ecological zones of southern Mongolia were studied. The study results can be concluded as follows:

1. The spatial distribution of SOC content within and between the ecological zones exhibited a gradational decreasing trend from north to south zones, while the SIC content decreased from south to north. Furthermore, SOC content increased along an increasing elevation gradient while SIC content showed the reverse with regard to elevation.

2. From an ecological zone study perspective, latitude gradient, elevation, precipitation, and temperature parameters had a significant effect on soil carbon content ($p<0.05$). Generally, SOC was highest in the higher latitudes and higher elevation locations, which have higher precipitation and lower temperatures.

3. Soil carbon was measured for the 0-30 cm depth in six different ecological zones. The largest soil carbon stock was observed in the meadow steppe and the steppe zones, and the lowest carbon stock was observed in the steppe desert.

4. It was estimated that the 0-30 cm soil layer in ecological zones in southern Mongolia currently store about 6.6 Pg of soil carbon. This is about 0.73% of the global soil carbon stocks within this soil depth. Soil organic carbon (SOC) stocks were higher than inorganic carbon stocks (SIC), 70% and 30% respectively.

The study results enhance the understanding of soil carbon storage of the arid and semi-arid regions of Mongolia.

ACKNOWLEDGEMENTS

I would like to thank the GRÓ LRT program for providing me with the chance to study in Iceland. In particular, the GRÓ LRT programme director Sjofn Vilhelmsdottir, deputy programme director Berglind Orradóttir, office manager Halldóra Traustadóttir, and project manager Brita Berglund deserve appreciation.

I express my sincere thanks to my supervisors, Dr. Olafur Arnalds and Dr. Erla Sturludóttir for their continuous guidance and support throughout my land restoration training's report. Also, I would like to thank Berglind Orradottir for her advice that inspired to me make the report better.

I would like to express my sincere gratitude to my colleagues at the Soil Science Department of the Institute of Geography and Geoecology for giving me the opportunity to study here in Iceland.

In addition, I really thank my wife Azjargal Luvsanchultem for taking care of our daughters and boys during the last six months and I also give my gratitude to my father, mother and relatives for their support and assistance.

Finally, I thank my GRÓ LRT fellows for their friendship and help during the training time. I would like to wish them all the best in their future work and life.

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