Saudi Journal of Biological Sciences 28 (2021) 7037–7045

Contents lists available at ScienceDirect

Saudi Journal of Biological Sciences

journal homepage: www.sciencedirect.com

Original article

Soil organic carbon stabilization in permafrost peatlands

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ARTICLE INFO

Article history:
Received 28 May 2021
Revised 27 July 2021
Accepted 28 July 2021
Available online 8 August 2021

Keyword:
Permafrost
Peatland
Degeneration
Carbon
Nitrogen
Iron
Granularity
Microorganism

ABSTRACT

In permafrost peatlands, the degradation of permafrost soil can raise soil temperature and alter moisture conditions, which increases the rate of loss of soil organic carbon (SOC). Here we selected three typical permafrost types that have very different active layer thicknesses but with soil originating from the same vegetation and which exist under comparable climatic conditions in the Da Xing'an mountain range: continuous permafrost, island permafrost, and island melting permafrost. To quantify the relative importance of control elements on SOC stabilization in these different permafrost types, we used correlation analysis to assess the relationship between organic carbon, physical and chemical properties and microorganisms, and explored the contribution of these factors to the accumulation of organic carbon. This study shows that the interaction between clay or silt, iron oxides and microorganisms have an important influence on the stability of organic carbon in permafrost peatlands.

1. Introduction

Affected by the continuous increase in regional temperature, permafrost has degraded significantly over recent years and the active layer has shown a trend of increasing thickness (Cheng et al., 2019). Plaza et al. (2019) found that with the degradation of permafrost, the loss rate of organic carbon could be as high as $4.5\%\cdot a^{-1}$. Schuur et al. (2009) found that the degradation of permafrost in a tundra area in Alaska over the past 15 years had caused a 40% increase in the rate of old carbon loss in permafrost compared with undegraded permafrost in the area. When permafrost thaws, organic carbon from the previously frozen terrestrial repositories is remobilized and transformed through decomposition activities. As microbial communities decompose this newly-available organic matter, GHGs such as CO_2 and CH_4 are produced and emitted (Dutta et al., 2006; Knoblauch et al., 2018; Schuur et al., 2009; Zimov et al., 2006). Compared with permafrost with a high temperature, there is a significantly lower variety and abundance of soil microorganisms in permafrost with a low temperature in the northern permafrost area, and the effect on soil organic carbon decomposition is different (Altshuler et al., 2017; Brown et al., 2002).

The thickness of the permafrost active layer is mainly controlled by temperature, surface water and heat conditions, and has a negative correlation with soil water content (Cheng et al., 2019). The active organic carbon component in the soil is sensitive to hydrothermal changes, and an increase in temperature increases the amount of activated carbon (Wu et al., 2012). An increase in active layer thickness increases the biogeochemical cycling strength of carbon and promotes carbon decomposition (Rui et al., 2011). Soil warming changes the composition of soil organic carbon, by increasing the proportion of alkyl organic carbon, reducing the aromatics of refractory organic carbon (lignin) composition, and increasing the proportion of soil respiration and heterotrophic respiration, which ultimately results in a significant increase in permafrost emissions of carbon into the atmosphere. Soil moisture impacts the degree of increased emissions of greenhouse gas emissions (Natali et al., 2015). There is growing concern about the implications of accelerated thawing of permafrost for regional biogeochemical cycling of carbon and other bio-reactive elements. One such element of concern is mineral Fe. Iron (Fe) oxides have been suggested as important mineral phases for stabilizing soil

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Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.sjbs.2021.07.088
1319-562X/

organic matter (SOM), as SOM can be sorbed onto Fe oxides, which have a high sorption affinity (Kaiser and Guggenberger, 2000; Kaiser and Zech, 2000; Lalonde et al., 2012).

The Da Xing'an mountain range is the only zonal permafrost distribution area in China, which belongs to the cold temperate continental monsoon climate. The microclimate is varied, and the local climate difference is significant. Under the control of the polar continental air mass, the winter is long and cold; under the influence of the subtropical marine air mass, the summer climate is hot and humid, the rainfall is abundant, and the precipitation is concentrated. The annual average temperature in this region is about −4.3 °C, and the annual and diurnal temperature ranges are relatively large. The average annual rainfall in this area is 452 mm, which is mainly concentrated in July and August, accounting for about 45% of the annual rainfall. The winter snow cover lasts for 6 months (January to April), with a snow thickness of 10–30 cm. A natural climate gradient forms across the region with it being warmer in the south and colder in the north, wet in the east, and dry in the west.

Northern peatland is an important soil carbon pool in terrestrial ecosystems (Davidson and Janssens, 2006), which is mainly distributed in high latitudes (Gorham, 1991) and is particularly sensitive to climate change (IPCC, 2007). The Da xing'an mountain range is an important area for the formation and development of peat bogs with high peat content. The environmental conditions within a peat bog are closely related to that of permafrost, and the cryogenic environment of permafrost provides a good basis for the development of peat bogs (Solomon et al., 2007). At present, a large amount of carbon has been found to be accumulated in peatlands, but its carbon source-sink function may change with the increase in air temperature (Breeuwer et al., 2008; Deyn et al., 2008; Ward et al., 2009).

With the gradual warming of the climate, the reserves of SOC in permafrost regions have shown a decreasing trend, and the carbon has been redistributed among other habitats. However, the degradation rate of organic carbon in permafrost is not only affected by the degradability of the permafrost itself, but also controlled by physical and chemical properties, such as organic carbon content, soil particle size, soil water and heat, and pH. Permafrost degradation, therefore, plays an important role in influencing the relationship between SOC and soil properties. In order to compare the relative importance of physical and chemical mechanisms on the stability of soil organic carbon, we chose three typical permafrost soils with different degrees of degeneration and used analysis of regression to assess the relationship between the physical and chemical properties and soil organic carbon (Zhang et al., 2020). The key soil properties that significantly influence the amount of SOC and its stable fraction are identified, and the contribution of these soil habitat on the stability of organic carbon in permafrost are explored.

2. Materials and methods

2.1. Study sites and sampling

The study site was located in the Da Xing'an mountain range (52°20′N, 124°42′E; Fig. 1). The permafrost in the Da Xing'an mountain range extends from the southern boundary to the north, and the type transitions from sporadic island-like permafrost to island-like thawing zone and large continuous permafrost (Jin et al., 2021). The area is characterized by a typical temperate continental climate that has hot and humid summers, long and cold winters, with a mean annual temperature of 2 °C and significant differences in the local climate. The soil and climatic conditions of the selected areas that cover the same vegetation type are shown in Table 1. All study areas have peatland soil and permafrost.

Through on-site sampling and inspection in the study area, we divided the study areas into three levels of permafrost degradation: MoHe (large continuous permafrost) that has a 40 cm thick active layer; TaHe (island-like thawing permafrost) a 60 cm thick active layer; and JaGedaqi (sporadic island-like permafrost) an 80 cm thick active layer. We used the depth of the active layer in these three areas to indicate the different degrees of permafrost degradation as shown in Fig. 1.

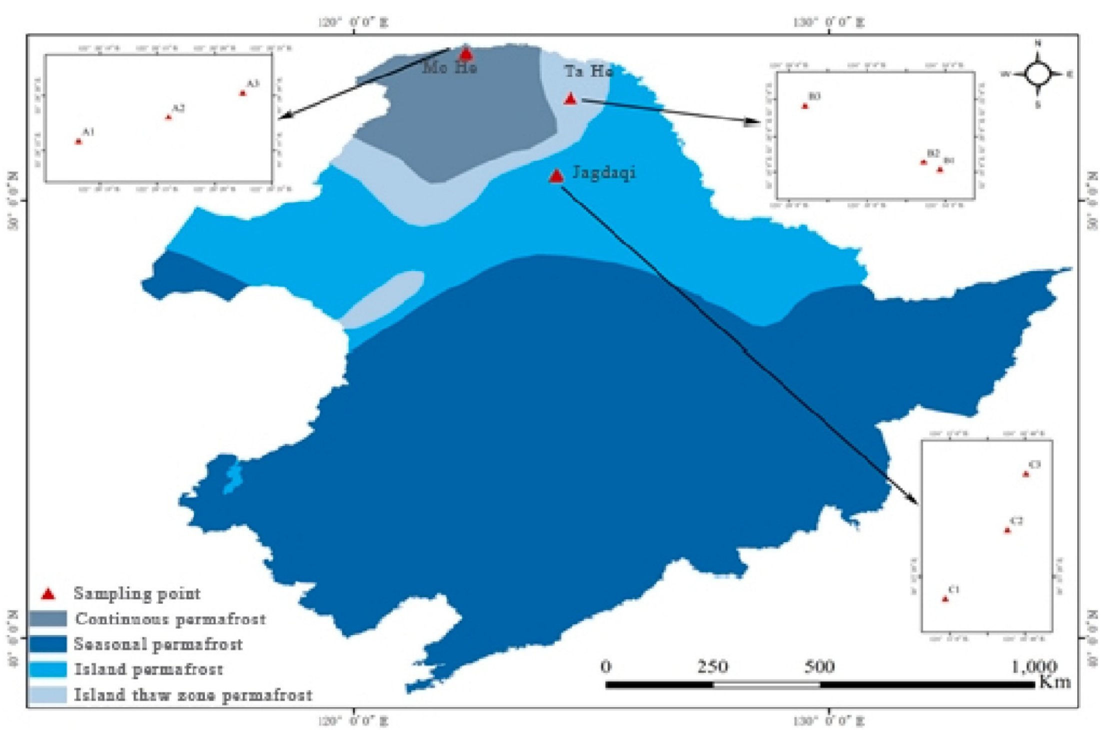

Fig. 1. The location of the permafrost at Da Xing'an Mountains in China.

Table 1
Pearson's coefficient among soil variables.

	Moisture	pH	TOC	Fe-OC	sand	silt	clay	Fe_o	Fe_d	Fe_p
Moisture	1									
pH	−0.90*	1								
TOC	0.92**	−0.88	1							
Fe-OC	0.91*	−0.86	0.983**	1						
sand	0.474	0.087	0.339*	0.338*	1					
silt	0.447*	0.224	0.383*	0.352*	0.074	1				
clay	0.574**	−0.194*	−4.93**	−4.70**	−0.666**	−0.793**	1			
Fe_o	0.660	−0.79	0.406*	0.405*	0.579**	0.182	−0.490**	1		
Fe_d	0.487	−0.42*	0.391*	0.408*	0.487**	0.255	−0.489**	0.953**	1	
Fe_p	0.795	0.064	0.259	0.264	0.12	0.258	−0.2	0.953**	0.823**	1

Note: *, $P < 0.05$; **, $P < 0.01$.

The active layer, also known as the seasonal thaw layer, is the layer between the earth's surface and the permafrost, which can freeze and melt under seasonal influence (Qin et al., 2014; Xu et al., 2021). We collected the soil at the depth between the surface layer and the permafrost. Fieldwork was performed in September 2019, due to that being the time when the active layer is the deepest. Holes were drilled with a soil auger and soil was collected for basic characteristic measurements. In each area, three parallel sample plots along with the sample factor were selected. The distance between each profile was approximately 20 m. In each plot, five soil samples within 1 m * 1 m quadrats were collected (four in the vertexes and 1 in the center) and then mixed to produce a single sample. Within each area, three samples (each sample for one pillar) were collected and stored in an incubator. In order to prevent the nature of the samples from changing during transportation, we carried out soil segmentation at the sampling site and then bagged and stored the samples in a refrigerator at −20 °C. Part of the impurity were removed from soil samples before the soil samples were taken to the laboratory.

2.2. Measurements of soil physical properties

In the determination of soil moisture, the soil samples were dried for 24 h at 105 °C, and the soil moisture content was calculated as the ratio of the total dry weight to the total weight of the soil. For the soil texture measurement, soil samples were natural air-dried, sieved using a 2-mm nylon sieve, and were then pretreated to remove organic materials using 20 ml 5% H_2O_2 for 24 h and excess carbonates using 20 ml 5% HCl for 24 h. Soil clay (particle size < 2 μm), silt (particle size 2–50 μm), and sand (particle size 50–2000 μm) content (Yu et al., 2019) were determined by laser diffraction (Master Sizer 2000, Malvern Corporation).

2.3. Measurements of soil chemical properties

Soil samples were divided into two subsamples. One subsample was used to measure the soil pH, TOC, and Fe-CO. The other subsample was used to measure three forms of Fe-(hydr) oxides to explore the effects of Fe minerals on OC. Soil pH was determined using a pH meter on soil samples that were mixed with distilled water (1:5 soil: water). Three fractions of Fe oxide were extracted: the citrate-bicarbonate- dithionite (CBD) procedure was used to extract Fe (Fe_d), amorphous Fe-(hydr) oxides (Fe_o) was extracted by oxalate-oxalic acid at pH 3.2, and complexed Fe-(hydr) oxides (Fe_p) were extracted using Sodium pyrophosphate. TOC and Fe-OC content were measured by multiN/C analyzer, and Fe concentrations from the extracted solution were determined using ICP-AES. As a complement, based on the CBD method, the organic carbon associated with iron (OC-Fe) and the proportion of OC-Fe to TOC ($f_{OC\text{-}Fe}$) were determined to further quantify the degree of mineral protection. The 16S rRNA v3-v4 region was amplified by PCR, and the general primers used were 308F and 806R.

2.4. Statistical analysis

One-way analyse of variance (ANOVA) were used to determine the significant difference of the TOC and Fe oxide among the three types of permafrost. Relationships between TOC or Fe-CO concentration and soil clay content and iron oxide (Fe_o, Fe_d) concentration were assessed using regression analysis. Alpha diversity was analyzed using Mothur, including OTU number, Coverage, ACE, Chao1, Shannon and Simpson.

3. Results

3.1. Physical and chemical properties of the three permafrost types

The peatlands in the three different permafrost regions all had highly acidic soils with a pH < 4.5. The soil acidity gradually decreased from north to south, however, the pH value of the soil was not significantly different between the three regions. The soil moisture content in JaGedaqi was higher than that in the other two permafrost peatlands, and the moisture content in the three areas gradually decreased from the surface to the bottom of the active layer. The soil particle size in all three peatland soils generally decreased with depth, and the average particle size in JaGedaqi was lower than that in the other two regions.

The concentration of total carbon gradually increased from the large continuous permafrost type to the Islands of permafrost type, and the differences were significant among the three permafrost types. The concentration of carbon decreased with depth, and the differences were significant in the vertical profile. Compared with the concentrations of total carbon, the concentration of total nitrogen was inverse and decreased with depth. The differences in total nitrogen were significant between the first two layers (0–10, 10–30 cm) and the second two layers (30–50, under 50 cm) of soil, and total nitrogen varied significantly between the three permafrost types. For each type, C/N content generally decreased in all horizons, while the C/N content significantly increased from MoHe to JaGedaqi, as shown in Fig. 2.

The concentration of Fe-CO decreased with depth in the three permafrost types. For the active layer, the concentration of Fe-CO increased from the large continuous permafrost to the island permafrost, with the highest value of 22.3% in the islands of permafrost and the lowest value of 12.8% in the continuous permafrost. These differences in Fe-CO were significant between the topsoil of the Islands of permafrost and the other two permafrost types. For the topsoil (0–10 cm), the Fe-CO in JaGedaqi was significantly higher than that of the other two types, and the difference between MoHe and TaHe was not significant. In the second horizon (10–30 cm), the difference was not significant among the three types of permafrost peatlands. For the horizons of the last two layers, there was no significant difference between the two

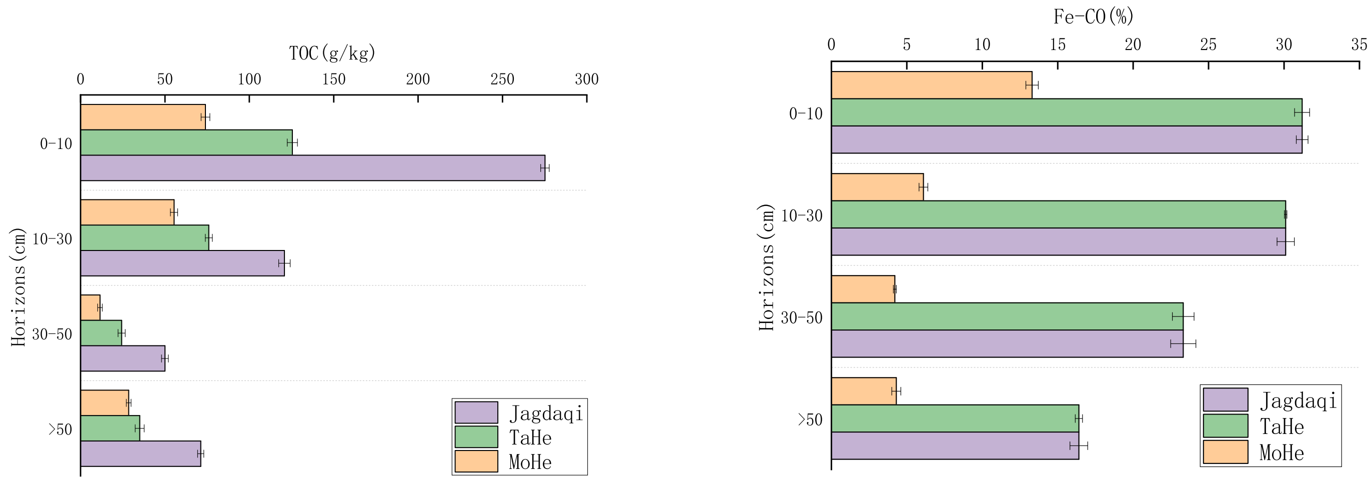

Fig. 2. The concentration of total organic carbon and the Fe-CO in the three types of the permafrost.

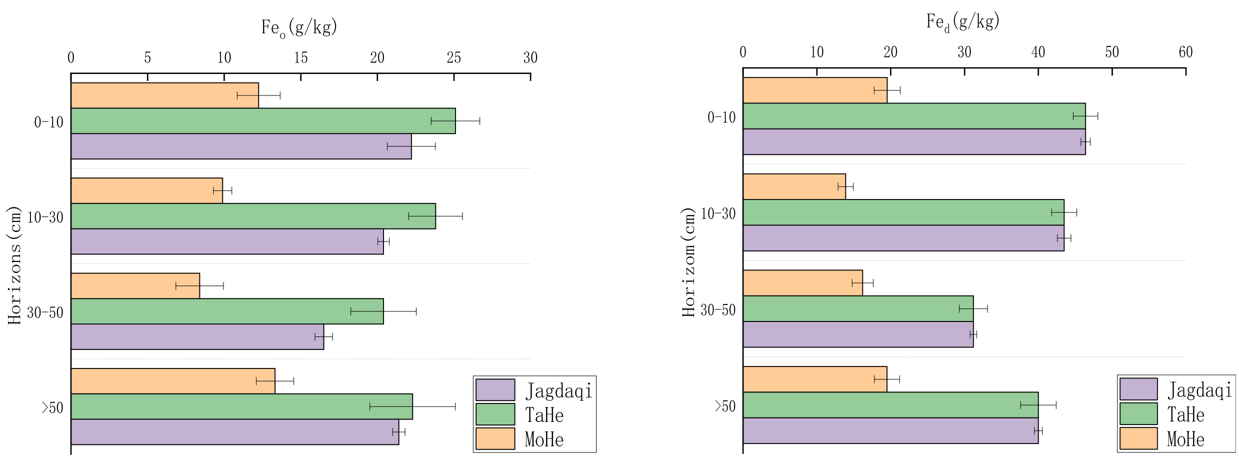

Fig. 3. The concentration of Fe_o and the Fe_d in the three types of the permafrost.

horizons, while both the last two layers were significantly different compared to the topsoil.

Through correlation analysis, our results showed that soil organic carbon was extremely significantly correlated with Fe_o, Fe_d, and Fe_p, and Fe-CO was also significantly correlated with Fe_o, Fe_d, but was not significantly correlated with Fe_p. In the large continuous permafrost regions, Fe_o, Fe_d, and Fe_p were relatively low, but compared to Fe_o and Fe_d, the content of Fe_d was higher. In the island-shaped permafrost area, the content of Fe_o was much higher than that of Fe_d, while the change in the island permafrost area was the opposite, as shown in Fig. 3.

At the three sites, the Fe_o, Fe_d, and Fe_p contents generally exhibited decreasing trends along the vertical horizon (0–50 cm). And in the whole, the Fe_o, Fe_d, and Fe_p contents in the soil layers of continuous permafrost were less than the other areas. One-way analysis of variance showed that Fe_d and Fe_o significantly differed between the permafrost types and between soil horizons. However, the results of a multivariate analysis of variance showed that permafrost types and soil layers only significantly affected the Fe_d and did not significantly impact the Fe_o content, as shown in Fig. 4.

3.2. Variations of soil organic carbon with edatope

The total carbon and Fe-CO concentrations significantly increased from continuous permafrost to islands of permafrost and decreased with depth, however, pH did not significantly vary with the type of permafrost or depth. Therefore, soil pH was not a significant driver of the carbon accumulation in the different permafrost types.

Both the concentration of soil clay and silt decreased with depth. The total carbon and Fe-CO concentrations were negatively correlated with soil clay content, while there was a significant positive correlation with silt content in each of the soil depths among the three permafrost types. The correlation between carbon and sand content was not significant for each permafrost type.

Both total carbon and Fe-CO concentrations significantly increased with the two different forms of Fe (Fe_o and Fe_d) in the soil of the three permafrost types. While soil clay was negatively correlated with free or noncrystalline Fe. As can be seen in Figs. 5 and 6, the concentration of total carbon gradually increased, while the soil clay content decreased as the concentration of free or noncrystalline Fe increased.

3.3. Relationships between biotic factors and SOC

By clustering the sequences of the three permafrost types, 8224 OTUs were found in the continuous permafrost areas, 12,088 OTUs in the island-shaped areas, and 10,732 OTUs in the island permafrost areas. Among them, 81 were unique to the large continuous permafrost region, 96 were unique to the island-shaped

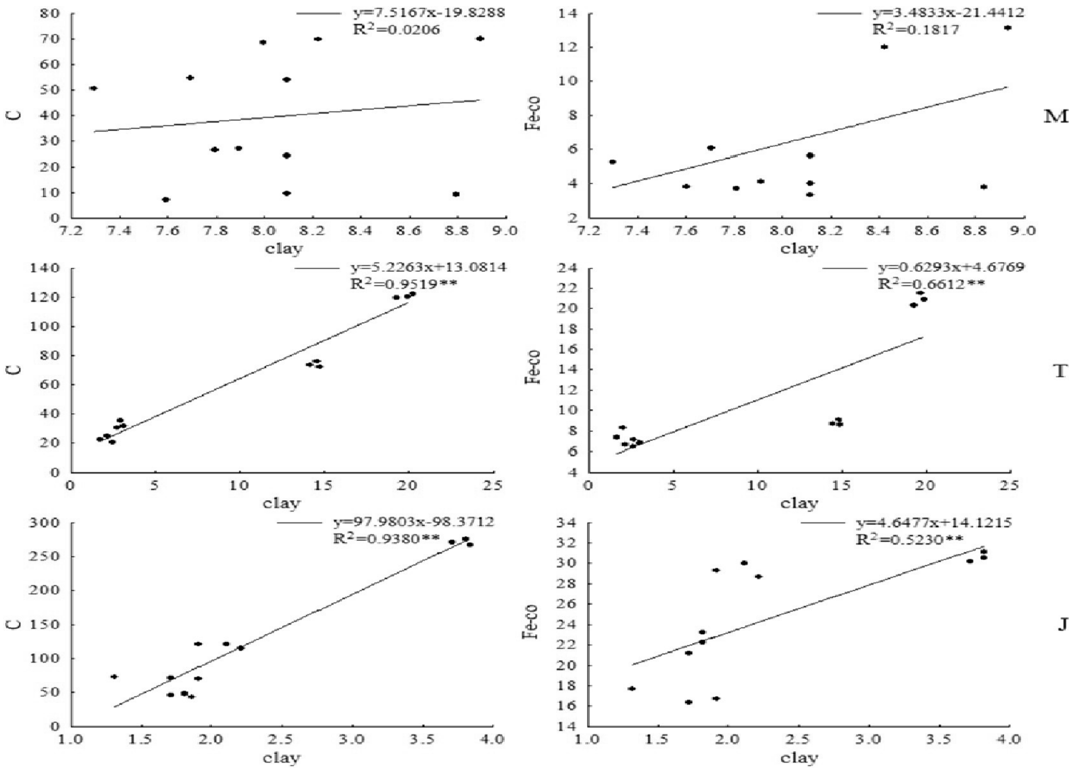

Fig. 4. Correlation between clay content (%) and C (toc) or Fe-CO concentration in the three types of the permafrost (M—Continuous permafrost, T-Island thaw zone permafrost, J-Island permafrost).

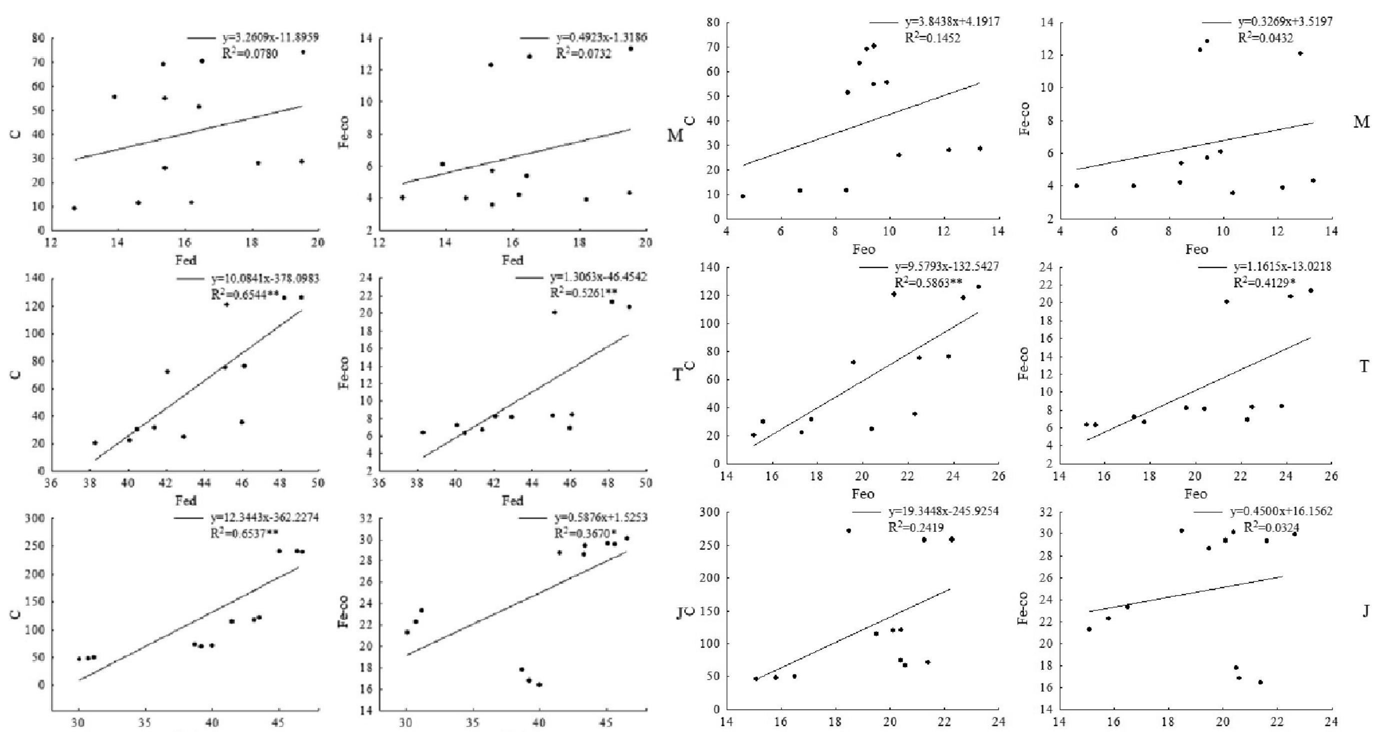

Fig. 5. Relationship between the C (TOC) or Fe-CO concentrations and two types of Fe oxides (Fe_d and Fe_o) in the three types of permafrost (M—Continuous permafrost, T-Island thaw zone permafrost, J-Island permafrost).

permafrost region, and 84 were unique to the island permafrost region. In order to study the abundance and diversity of bacterial communities in the different types of permafrost, a diversity analysis was carried out (Table 2). The results of the Ace index and Chao1 index showed that the abundance of soil bacterial communities increased with the degradation of the frozen soil. The results

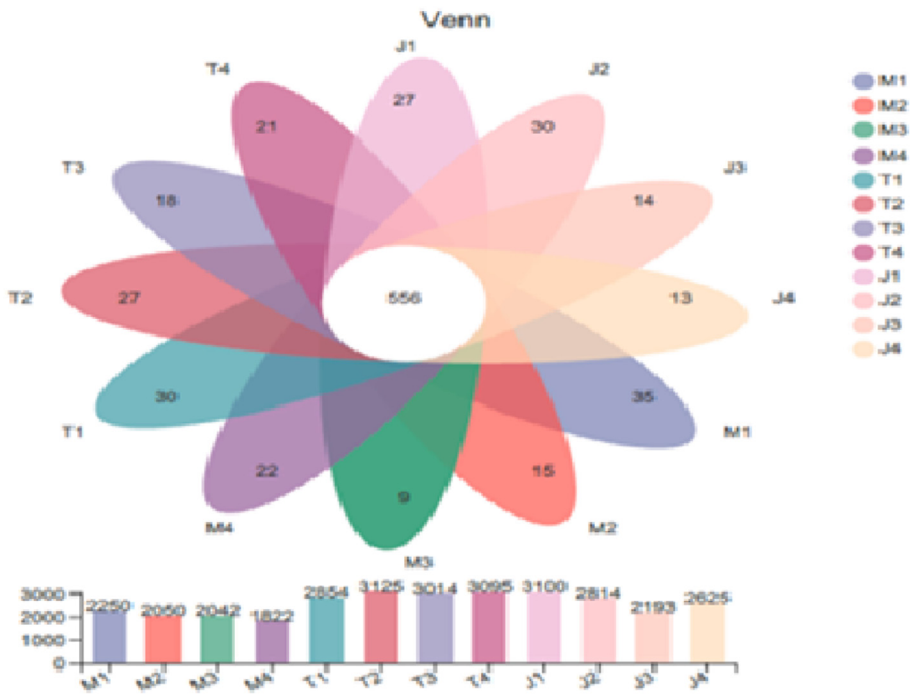

Fig. 6. OTUs Veen diagrams of bacteria in each soil layer of three types of frozen soil.

Table 2
The effect of bacteria on the microbial α diversity index in different types of permafrost.

Sample	Sobs	shannon	simpson	ace	chao	Coverage
M1	1446.667 ± 161.203	5.391 ± 0.179	0.012 ± 0.002	1879.436 ± 199.952	1889.716 ± 257.840	0.999 ± 0.001
M2	1389.333 ± 143.810	5.058 ± 0.099	0.019 ± 0.003	1795.272 ± 156.534	1807.555 ± 173.465	0.998 ± 0.001
M3	1369.667 ± 125.437	5.030 ± 0.089	0.020 ± 0.003	1781.007 ± 210.734	1798.984 ± 200.540	0.999 ± 0.001
M4	1217.667 ± 143.950	5.037 ± 0.096	0.017 ± 0.001	1602.644 ± 169.089	1595.412 ± 161.378	0.999 ± 0.001
T1	1832.000 ± 213.197	5.941 ± 0.209	0.006 ± 0.001	2400.192 ± 315.315	2410.984 ± 269.889	0.989 ± 0.003
T2	1917.000 ± 268.631	5.892 ± 0.293	0.007 ± 0.002	2525.930 ± 325.476	2553.496 ± 341.046	0.998 ± 0.003
T3	1752.000 ± 152.073	5.789 ± 0.091	0.007 ± 0.001	2481.714 ± 244.526	2404.996 ± 137.741	0.999 ± 0.001
T4	1813.000 ± 181.005	5.651 ± 0.251	0.010 ± 0.003	2428.346 ± 230.139	2441.176 ± 239.208	0.999 ± 0.002
J1	1954.667 ± 113.443	5.976 ± 0.059	0.006 ± 0.0003	2842.976 ± 262.215	2689.936 ± 121.201	0.989 ± 0.003
J2	1889.000 ± 52.374	5.819 ± 0.002	0.008 ± 0.0003	2606.565 ± 153.535	2595.095 ± 168.900	0.999 ± 0.001
J3	1485.333 ± 53.154	5.599 ± 0.079	0.009 ± 0.0007	1976.677 ± 79.909	2006.636 ± 114.484	0.999 ± 0.001
J4	1425.667 ± 129.373	5.537 ± 0.202	0.010 ± 0.003	1867.794 ± 113.050	1869.124 ± 124.694	0.999 ± 0.001

of the Shannon index were similar to those of the Ace and Chao1 indexes, while the Simpson index showed an inverse trend.

4. Discussion

4.1. The differences in soil physical and chemical properties

The unique wet, low temperature, and anaerobic peatlands of northern high latitudes (Baird et al., 2008) have accumulated 1400–1800 Pg of carbon (Hugelius et al., 2014; Schuur et al., 2015; Tarnocai et al., 2009) and 40–60 Pg of nitrogen (Harden et al., 2012; Jonasson et al., 1999; Weintraub and Schimel, 2003) since the Holocene. Since the 1980s, the temperature of the Arctic permafrost has generally risen as high as 3 °C (IPCC, 2013), which has significantly degraded the permafrost (Brown and Haggerty, 2013), deepened the active layer of the permafrost, and changed the availability of soil nutrients (Anisimov et al., 2007). For the alpine northern latitudes, the degradation of permafrost under climate warming and the special nature of the peatland soil has resulted in an increase in depth of the active layer in the Greater Khingan Mountains permafrost region. The deepening of the active layer makes more organic matter accessible to decomposition, which leads to changes in soil habitats (Weiss et al., 2016). Furthermore, changes in temperature, humidity, acidity, and other abiotic conditions affect the REDOX process and the main minerals in the soil are strongly decomposed, with a large number of basic cations being leached, in addition to an increasing clay content (Houlton et al., 2018; Jiang et al., 2018). As our results showed, the content of soil clay was closely related to Fe oxide content among the three permafrost types, with the lowest Fe oxide content occurring in the continuous permafrost type. This difference among the three permafrost types may be related to the degradation of the permafrost. The degradation of permafrost can affect soil carbon in many ways, such as by altering soil moisture, temperature, and acid deposition (Zhang et al., 2019). The unique nature of peatland soil inhibits the energy exchange of the active layer and weakens the intensity and speed of permafrost degradation. In continuous permafrost regions, the permafrost is widely distributed, which is conducive to the growth of peatland. As all three permafrost types grew under the same vegetation, the observed physical differences in peatland may have contributed to the observed changes in soil properties among the three permafrost types. The significant impact of the soil structure is consistent with a decrease in soil-clay content. By contrast, the soil habitat of continuous frozen regions has been protected from degeneration, and thus, has better structure and soil properties compared to the other two types of permafrost.

Degradation of permafrost can also have an influence on soil ion balance, with iron oxides disappearing and Fe forming complexes with carboxyl groups (Riedel et al., 2013). After such a reaction, degradation of SOC is prevented, which results in a stable Fe-CO complex (Salvadó et al., 2015). After the frozen soil is thawed, the humid soil environment reduces the decomposition of organic matter, and the respiration rate is correspondingly weakened. High-nutrient organic matter is easier to decompose, and the rate of consumption is faster. Our result shows that there was a significant difference in soil carbon content among the three types of permafrost peatland, which is consistent with the above studies. Changes in the organic carbon within the three permafrost types also affect the nitrogen cycle and other soil properties. Under the conditions of a suitable temperature with sufficient water, leaching would likely lead to a large amount of carbon and nitrogen loss (Yan et al., 2015), and then solubility changes experienced by redox-active metals would result in oxides co-precipitating (Eusterhues et al., 2005). Previous studies of peatlands also found that dissolved and solid-phase organics can function as regenerable electrons and impact organic terminal electron acceptors (Agethen et al., 2018; Klupfel et al., 2014; Olefeldt et al., 2017). Finally, the composition of the microflora significantly differed between the three types of permafrost peatlands, with wps-2 gradually decreasing and Caldisericota gradually increasing in the peatlands from continuous permafrost areas to areas with island permafrost (Fig. 6). The microbiological reduction of the iron process, as well as sulfate reduction and denitrification, play an important role in the organic matter transformation (Fedorov et al., 2018; Abramov, 2019). The structure of the soil microbial community and a variety of soil ecological processes controlled by microorganisms, change the structure and function of forest ecosystems in permafrost regions. This difference in the microbial composition can also influence the turnover of organic carbon through associated environmental factors.

4.2. Mechanisms of SOC stabilization by soil clay or Fe oxides

4.2.1. The role of soil clay in stabilizing SOC

The distribution of organic carbon in peatlands shows obvious carbon storage layers and sedimentary layers, so the organic carbon content in the upper part is higher and decreases with depth (Zhang et al., 2014). Our studies support the result that there is a decrease in organic carbon concentration along a vertical profile within the soil. Previous studies have found that clay can physically and chemically adsorb and react with organic matter, which slows down the degradation rate of organic matter (Christensen and Blackburn, 1982; Hernes et al., 1996; Henrichs, 1993; Wang et al., 1993). This is consistent with our result, which shows a significant negative correlation between the soil clay content and the concentration of organic carbon.

Soil silt is also an important factor to protect the stability of organic matter (Hassink et al., 1993; Six et al., 2002), as shown by the proportion of Fe-CO increasing significantly with silt. The adsorption mechanism of soil silt also plays an effective role in the adsorption process (Teng and King, 1981). Clay and silt are important mechanisms for stabilizing the soil carbon pool, and soils with different particle sizes have different protection mechanisms for organic carbon (Chung et al., 2007; Six et al., 2004), which our results are consistent with. From continuous permafrost to island-shaped permafrost, the soil environment changes, and organic carbon increases with an increase in silt. The results further prove that sludge also has a stabilizing effect on organic carbon, but the adsorption effect of clay has a stronger effect on stabilizing organic carbon.

The organic carbon content of the three types of permafrost peatlands was significantly positively correlated with iron oxides, indicating that iron oxides play an important role in stabilizing organic carbon in the peatlands. The results of our studies are consistent with previous research in acidic soil (Eusterhues et al., 2005; Kaiser and Guggenberger, 2000; Wiseman and Puttmann, 2005). The correlation of Fe-CO with Fe_o and Fe_d was significant, but not significant with Fe_p. Such a difference may result from Fe_p not participating in the redox reaction. Due to the protection of soil structure conditions, iron-bound carbon is not easily used by decomposers (Emerson and Widmer, 1977), therefore, the Fe-OM compound is considered to have a significant impact on long-term carbon storage in many environments (Asano and Wagai, 2014; Coward et al., 2018; Kleber et al., 2005; Riedel et al., 2013; Totsche et al., 2018).

4.2.2. The role of Fe oxides in stabilizing SOC

The moist soil and sufficient nutrients of peatlands are beneficial to the adsorption capacity of organic matter to iron oxide (Wagai and Mayer, 2007). The mono-layer of SOM is stabilized through the cross-linking of Fe and hydrogen bonds in the soil (Emerson and Widmer, 1977). Several studies about Fe-OM have demonstrated that it is resistant to microbial or chemical reduction (Coward et al., 2018; Eusterhues et al., 2014; Henneberry et al., 2012) so that organic carbon compounded with iron oxides is not easy to oxidize and degrade (Kaiser and Guggenberger, 2003; Zimmerman et al., 2004). In our research, the correlation of Fe-CO with Fe_o and Fe_d was significant, which is consistent with the above research. Thus, the conversion of iron oxides is particularly important as a stabilization mechanism of organic carbon.

The peatland soils in the study area are all acidic and have a high content of metal ions. The effectiveness of iron oxides is the limiting factor for the stability of organic matter and seems to have a greater impact on organic carbon than clay minerals (Wiseman, 2015). However, in our research, there is not only a significant correlation between organic carbon or Fe-CO and iron oxides but also a linear relationship, which indicates that the chemical stabilization of iron oxides has not yet been fully saturated. Therefore, more organic carbon can be stabilized by iron oxides from peatlands in permafrost regions through strong adsorption of organic matter.

4.3. Contribution of biological factors to soil organic carbon

It is known that the reduction of iron by microorganisms through an anaerobic process creates favorable conditions, and the hypoxic conditions are conducive to driving iron-reducing bacteria to reduce iron minerals. The increase in the thickness and temperature of the sub-zero permafrost active layer leads to changes in this habitat (Abramov et al., 2019; Fedorov et al., 2019; Fedorov and Konstantinov, 2008), threatening the stability of the microbial community. Our research found that some bacteria stably exist in permafrost peatlands, while others decrease or disappear as the temperature rises and the active layer deepens, which impacts the stability of organic carbon.

Microorganisms are sensitive to temperature, and the thawing of frozen soil activates microorganisms to also change the soil habitat. The results of previous studies (Li et al., 2017; Zhang et al., 2018) have shown that different types of permafrost regions have different microbial diversities due to different hydrothermal processes. Our research also found that some bacteria gradually disappear from the continuous permafrost area to the island-shaped permafrost area, and the decrease in microbial activity may be one of the reasons for the increase in organic carbon. The study of Baumann et al. (2009) shows that soils with high carbon and nitrogen content have higher microbial abundance, and suitable soil pH is conducive to the metabolism and reproduction of microorganisms (Wang et al., 2011). Therefore, the unique environmental adaptability of soil microorganisms plays a significant role in the soil carbon cycle in permafrost peatland.

Soil acidification changes biological activity, affects soil respiration, and thus affects the accumulation of organic carbon (Chen et al., 2015; Johnson et al., 2018). Thus, the thawing of frozen soil, deepening of the active layer, weakening of acidity, and changes in bacterial activity are all important factors affecting the accumulation of organic carbon from continuous permafrost to island-shaped permafrost regions. In the permafrost peatland, the degradation of permafrost, the decrease of soil clay, and the activity of microorganisms that promote iron reduction and participate in iron reduction seriously affect the stability of organic carbon.

5. Conclusions

Taking the three typical types of soils in Da xing'an ling permafrost peatlands as the research objects, the effects of physical and chemical properties on the structure and stability of organic carbon in the soil are discussed. TOC has a significant negative correlation with soil clay particles and a significant positive correlation with iron oxides. Soil clay particles are reduced, and the oxidation–reduction reaction of iron oxides is not conducive to the stability of organic carbon in peatlands. The iron reduction process and its related microorganisms are important factors that change soil development. The results showed that keeping the soil habitat from being destroyed, maintaining the soil texture, reducing the loss of clay, and the reduction of iron oxides not only inhibits the reaction of microorganisms, but also positively impacts the accumulation of organic carbon in peatlands in permafrost regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

National Natural Science Foundation of China (NSFC) (No. 41971151), Dr. Innovation Fund (HSDBSCX2020-02).

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