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Research Status, Problems and Direction of Soil Organic Carbon in Zoige Peat Wetland

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ABSTRACT

Peatlands, as a special type of wetland, occupy only 3% of the Earth's surface, but bear about one-third of the world's soil carbon storage and play an important role in the global carbon cycle. The Zoige Wetland is located on the eastern edge of the Qinghai-Tibet Plateau, and its peat reserves are up to 1.9 billion tons, accounting for more than 40% of the country's peat resources, which is an important support for China to achieve the "double carbon" goal. This paper reviews the research status and storage estimation of soil organic carbon in Zoige Wetland. The statistical results show that there is a large difference in the estimation of carbon storage in the peatland of Zoige (0.43-1.42 Pg). The reasons are mainly related to marked differences in values reported for soil densities, organic carbon levels, and accumulation rates. There are still great uncertainties in the estimation of wetland carbon stocks, and future studies should focus on reducing soil carbon sink uncertainties, climate change, the impact of permafrost melting on carbon sink functions, the impact of degraded ecosystem restoration and sink enhancement pathways, and other greenhouse gas functions. In order to accurately reveal the current situation and future trend of carbon sink in peat wetlands, a model-multi-source observation data fusion system was constructed to complement the observation shortcomings in key areas, and provide reference and support for the construction of carbon neutral ecological civilization.

Keywords: Zoige peat wetland; Soil organic carbon; Organic carbon storage; Climate change; Greenhouse gases

1. Introduction

Soil is one of the most abundant carbon reservoirs on Earth, and 90% of its carbon reserves are stored in the form of soil organic carbon [1]. Soil organic carbon (SOC) refers to all carbon-containing organic

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substances in soils in various forms, including all kinds of animal and plant residues, microbial bodies and various organic substances decomposed and synthesized in soil. Soil organic carbon is the largest active carbon pool in terrestrial ecosystems, with a reserve of about 1500 Pg, about twice that of atmospheric carbon pool and three times that of vegetation carbon pool. Moreover, the SOC cycle is highly sensitive to climate change due to the huge capacity of the SOC carbon pool, which is directly related to atmospheric carbon pool [2-4]. Small changes in soil carbon pool can cause significant changes in atmospheric CO_2 concentration [5].

Soil carbon pool in wetland ecosystems is an important contributor to "carbon neutral" and "carbon sequestration end". As a special type of wetland, the peatland soil organic carbon storage is significantly higher than other types of soil [6]. Peatland covers only 3% of the Earth's surface, but bears about one-third of the global soil carbon storage. Peatland has long played a "climate cooling" role and played a crucial role in regulating the global climate. Located on the eastern edge of the Qinghai-Tibet Plateau, the Zoige Wetland stores up to 1.9 billion tons of peat, accounting for more than 40% of the country's peat resources, making it the largest plateau peat swamp wetland in the world [7]. Therefore, it is necessary to further improve the research and exploration of carbon storage and soil physicochemical properties in the peatland of Zoige wetland, so as to provide basic support for the accurate estimation of organic carbon storage of Zoige wetland and scientific guidance for the protection and ecological restoration of Zoige wetland (peatland). Therefore, the research status and development direction of soil organic carbon in the Zoige peat wetland ecosystem affect both the local ecological environment, but also seriously affect and the realization of China's "double carbon" goal.

In recent years, domestic researchers have carried out relevant studies on the carbon cycle of Zoige wetland. This paper summarizes the research status, main problems and future development prospects of soil organic carbon in Zoige wetland, in order to provide a scientific basis for the research on feasible carbon sequestration policies of wetland ecosystems and serve the realization of the national "dual carbon" strategy. Therefore, the accurate interpretation of the vertical distribution of soil organic carbon and its control mechanism in the Zoige Alpine swamp is not only helpful to better predict the impact of global change on the soil organic carbon pool, but also helpful to estimate the deeper soil organic carbon pool and provide parameters for the global carbon cycle model.

2. Research status of soil organic carbon in Zoige wetland

2.1 Research direction

China's research in the direction of wetland carbon is relatively late, generally divided into two stages, the initial stage and the in-depth multivariate stage, with 2007 as the boundary. In the initial stage, the theory and research method of wetland soil organic carbon triggered discussions among domestic scholars and gradually carried out exploration and research. Tian Yingbing first studied the distribution and flow characteristics of organic carbon in the alpine swamp ecosystem of Zoige in 2003, and believed that plant residues were the main source of soil organic carbon [8]. The theory and method of wetland soil organic carbon research have been widely concerned and applied, and the corresponding evaluation model has been gradually applied to this research field. Gao Junqin studied the spatial distribution characteristics of surface soil organic carbon in Zoige Alpine marsh, and the results showed that in 0-30 cm soil layer, the organic carbon content of Zoige Alpine marsh showed a trend of gradual decline from the surface layer down, and the soil organic carbon density was higher than that of other ecosystem types [9-11]. Li Li et al. showed through field monitoring experiments that soil organic carbon content in 0-50 cm soil layer in the alpine peat wetland of Zoige was exponentially correlated with groundwater level, and with the decrease of groundwater level, soil organic carbon content gradually decreased [12]. Ma Qiongfang estimated the soil organic carbon density in 2 m deep soil layer of Zoige Alpine wetland based on field monitoring experiment data, and its value was between 77-276 kg/m^2, and made correlation analysis on natural factors (such as altitude, climate, etc.) affecting soil organic carbon in Zoige Alpine wetland [13]. Chen et al. estimated the organic carbon reserves of peatland in the alpine region of Zoige through field sampling and indoor analysis, and the results showed that the organic carbon reserves of peatland in the alpine region of Zoige were 0.48 Pg [14]. Zhou Wenchang et al. studied vegetation carbon storage, soil carbon storage and ecosystem carbon storage in peatland under three water level states in Zoige by using the soil profile method and vegetation harvesting method [15]. Liu Lijuan et al. reassessed the carbon storage of peatland on the Zoige Plateau based on the area change and carbon accumulation rate of peatland on the Zoige Plateau every thousand years, and used the peat decomposition model and carbon flux reconstruction model to discuss the dynamics of carbon flux in the peatland on the Zoige Plateau over the past 15,000 years [16]. Dong Lijun et al. used the method of spatial series instead of time series to study the changes of soil organic carbon content at different degradation stages of alpine meadow in Zoige Wetland and the causes [17]. Wang Wenbo et al. collected soil samples of different vegetation types (wetland vegetation and grassland) at different depths to analyze the distribution characteristics of soil organic carbon [18].

These studies mainly focus on the surface soil, and there is a lack of regional scale carbon storage estimation, and the vertical distribution of soil organic carbon in this region is rarely reported. The deep soil may also store a large amount of organic carbon. In addition, the influence of different water environments, different landforms and climate factors on soil carbon sequestration in wetlands is still poorly understood.

2.2 Estimation method

The estimation of soil organic carbon storage in wetlands is mainly based on the extrapolation method based on observation data and the ecological model simulation method. The extrapolation method is based on the measured soil organic carbon density data and area multiplication to obtain the estimated amount. In most of China, the extrapolation method is used to estimate wetland soil carbon storage, but the estimated results differ by as much as four times [19-21], as shown in **Table 1**. The ecological model simulation law is used to estimate the change of organic carbon storage driven by climate, soil, grazing management and other factors. The extrapolation method does not integrate the organic carbon turnover process in the estimation of organic carbon storage changes, so it is difficult to obtain the dynamic "evolution" law of organic carbon, and cannot predict the "future" carbon storage potential. The ecological model simulation law integrates the organic carbon turnover mechanism, and is mostly used to predict the "future" carbon storage changes under different hypothetical scenarios.

The statistical results show that there are big dif-

Table 1. Size of soil organic carbon storage in Zoige wetland by different estimation methods.

	Estimation method	Soil organic carbon storage in Zoige wetland	Reference
Extrapolation method	Estimation of ground carbon accumulation rate combined with area	0.477 Pg	Chen et al., 2014 [14]
		1.42 Pg	Wang et al., 2014 [22]
	Estimation of peat reserves by provinces and cities	0.71 Pg (710 Tg)	Wang Ming, 2012 [23]
	Years of data combined with peat volume method were used to estimate	0.63 Pg	Liu et al., 2012 [24]
Model simulation method	EPIC model	0.514 Pg (514 Tg)	Ma Kun et al., 2016 [25]
	HPM model	0.435 Pg	Liu Xinwei et al., 2016 [26]
	Peat decomposition model	1.4 Pg	Liu Lijuan et al., 2018 [16]

ferences in the estimation of carbon storage in Zoige Peatland, which is mainly due to the uncertainties of soil bulk density, peat depth, peatland area, soil carbon content and peatland carbon accumulation rate [16]. As a result, the estimation of organic carbon storage in peatlands in the same area is quite different, and the data are not comparable. Therefore, to accurately estimate global and regional organic carbon reserves, more detailed remote sensing and measured profile data should be collected to understand the physical and chemical properties of peatland area, peat thickness, bulk density, organic matter content and their spatial variability, plot the distribution map of organic carbon reserves in peatland, and provide the uncertainty range of the estimated data. On this basis, the organic carbon storage and greenhouse gas emission inventory of peatland were prepared using unified technical standards.

It is found that the extrapolation method has the advantages of being direct, clear and simple, but it requires a large amount of data support (small or lack of data will have a great impact on the estimation results), and is limited by a large time scale, and cannot be estimated for a long period of history or future situations. The model estimation method, which includes the influence of climate, soil and other environmental factors on soil carbon storage, is the best method to simulate the change of wetland soil carbon storage in the past or future under the background of climate change. At present, most of the models use climate change or wetland degradation and other environmental factors to study the impact of ecosystem carbon storage changes.

3. Main problems

3.1 Effects of climate change on soil organic carbon in Zoige Wetland

In the context of global warming, extreme climate has become more frequent and stronger. The frequent occurrence of extreme climate will directly lead to the low survival rate of vegetation and the degradation of grassland (wetland) and other long-term and difficult to repair conditions, which will greatly affect the carbon sink function of wetlands. In addition to human activities, Kingsford (2011) pointed out that climate change may also pose a threat to wetlands. Guo Jie and Li Guoping (2007) used the data of meteorological stations to study and point out that the climate of the Zoige Wetland showed a warming and drying feature of increasing temperature and decreasing precipitation at the end of the 20th century [27], and the soil moisture on the Qinghai-Tibet Plateau decreased during this period [28]. However, since the 21st century, the temperature in the wetland area of the Qinghai-Tibet Plateau has increased, which has led to the increase of evapotranspiration on the underlying surface and the corresponding increase in precipitation, resulting in changes in wetland animal and plant elements [29] and a slow increase in soil moisture [28].

Current research focuses more on the impact of drought on the Zoige wetland ecosystem, and the understanding of the sensitivity, resilience and vulnerability of the Zoige wetland carbon sink function in response to extreme climate is almost blank, which cannot provide a basis for scientific response to climate change. Therefore, it is urgent to reveal the resistance and resilience of carbon source sink function of peatland in Zoige Wetland to different climate change events, especially compound extreme climate change, and its mechanism, and to evaluate climate change and its impact on the carbon sink function of wetland ecosystem under different emission scenarios in historical period and future.

3.2 Effects of human activities on soil organic carbon in Zoige Wetland

Wetland drying (trench drainage)

The Zoige area contains the largest alpine swamp in the world [30,31]. To cope with the pressures associated with population growth, parts of Zoige's wetlands have been converted to pasture by artificial drainage over the past few decades. Trenching and drainage not only changed the original hydrological conditions of the Zoige wetland, but also led to a rapid reduction of the wetland area [32].

Wetland drying, soil hydrological environment is destroyed, and wetland soil organic carbon content changes. Existing studies on the change of soil organic carbon content after trenching and drainage in wetlands generally agree that trenching and drainage will lead to the reduction of soil organic carbon content in wetlands [15,33,34]. Previous studies believe that the acceleration of soil microbial respiration after drainage will enhance the decomposition rate of soil organic matter, resulting in the reduction of soil organic carbon content. However, other research reports have drawn opposite conclusions. For example, Huo et al. found that soil organic carbon density showed an increasing trend after trenching and drainage [35]. According to Bai et al., the surface organic matter content of Zoige wetland increased from 40.8 g/kg to 63.8 g/kg when the surface water level decreased from 30 to 0 cm [36].

Overgrazing

Grazing is one of the main controlling factors of soil organic carbon storage in non-cultivated grassland [37]. In a higher intensity grazing environment, the main reason for the higher organic carbon content in soil is the increase of carbon input through the improvement of primary productivity [38]. Grazing changes the amount of material returned to the soil [39]. A large amount of nitrogen and other nutrients from livestock manure are returned to the soil as manure. At the same time, the availability of other nutrients in the soil is indirectly improved, and the activity of soil microorganisms is promoted. Other researchers have come to the same conclusion. Chen Huai et al. believed that light or moderate grazing reduced the above-ground biomass of grassland through feeding, but increased the underground biomass of grassland to a certain extent, and imported nitrogen-rich manure into grassland, which helped maintain soil carbon and nitrogen storage of grassland [40]. Secondly, grazing directly reduces vegetation coverage, exposes the surface, increases the ground temperature, accelerates the mineralization and decomposition rate of organic matter in the soil, and makes the content of alkali-hydrolytic nitrogen in the soil under grazing environment higher than that in the non-grazing area. Therefore, although overgrazing reduces the return of vegetation organic residues to a certain extent, the organic carbon content in soil shows an increasing trend [41].

According to the existing research analysis, there is still no clear relationship theory between grazing and soil organic carbon content. Some researchers believe that grassland ecosystem is quite flexible to grazing, and grazing has no effect on soil organic carbon content [42]. Some studies also conclude that artificial grazing reduces soil organic carbon content [43]. The inconsistent results indicate that there is a complex relationship between grazing and soil organic carbon content, and the response of soil organic carbon content to grazing is affected by many factors.

Peat resource exploitation

Peat is an important organic mineral resource, which is widely used in industry, agriculture, medicine, environmental protection and other fields. The continuous growth of market demand stimulates the phenomenon of unlicensed mining, indiscriminate mining and so on. However, peat wetlands can be carbon "sink" or "source", which plays an important role in global climate change. Under natural conditions, peat can accumulate 0.22-1.31 mm per year. The rate of human destruction of peatland is far greater than the rate of peat development, and the protection of peat wetlands is urgent [44].

4. Discussions on the next research direction

4.1 Reduce the uncertainty of soil organic carbon storage estimation

Although a large number of observational studies on soil carbon pools and their dynamic changes have been carried out, on the whole, the estimation technology of soil carbon stocks in Zoige Wetland has not reached the mature stage, and the estimation results are highly uncertain.

It is worth noting that the spatial difference of soil organic carbon is the result of the co-action of multiple factors such as climate, vegetation and soil properties on a 100-year or longer time scale, which generally leads to the temporal sensitivity of soil organic carbon to climate factors than the spatial sensitivity. To accurately assess the dynamic changes of the plateau soil carbon pool in the historical period, it is necessary to clarify the different organic carbon sources of the soil carbon pool, and build a soil carbon model-satellite remote sensing and ground inventory fusion system based on microbial dynamic processes.

4.2 Effects of permafrost melting on soil organic carbon storage in wetlands

In recent years, the phenomenon of permafrost melting in alpine wetland has shown a significant increase trend. For example, in the eastern part of the Qinghai-Tibet Plateau, the thermal karst phenomenon has increased by 40 times in the past 50 years, and the frequent thawing of permafrost will exacerbate soil carbon loss. Under the climate warming environment, the status quo of permafrost melting will become the new normal. To determine whether permafrost melting will cause a large amount of CO_2 gas to be released into the atmosphere, it is necessary to simulate the spatio-temporal pattern under different emission scenarios and different types of permafrost melting, and reveal the main ways and mechanisms of soil carbon loss during permafrost melting.

At present, the vast majority of studies still lack the exploration of the carbon cycle process of thawing permafrost. Some studies have shown that soil organic carbon stored in permafrost faces a higher risk of emission, but the estimation of carbon emissions from melting deep permafrost is still unclear.

4.3 Impact of wetland carbon sink in degraded ecosystem restoration

The wetland (grassland) ecosystem is seriously degraded, and the restoration of degraded grassland will significantly enhance the carbon sink of alpine wetland. However, the current status of wetland (grassland) degradation is still uncertain. Accelerating the restoration of degraded wetlands (grasslands) can help achieve the national 2060 carbon neutrality strategy target. By comparing the soil organic carbon content of degraded and non-degraded wetland (grassland), the study showed that under the premise of natural restoration without human interference, the soil carbon pool of degraded grassland on the plateau would take 281 years on average to recover to the non-degraded state [45]. According to the study on the scale of sample plots, the implementation of different ecological restoration measures on degraded grassland, such as fencing, no-tillage reseeding technology, artificial planting and topsoil transplantation, will accelerate the recovery time of soil carbon pool and is expected to double the carbon sink before 2060. It is urgent to reveal the increasing potential of different ecological restoration measures and the recovery time of soil carbon pool, evaluate the increasing potential of existing wetland (grassland) ecological projects, and optimize the current and layout of future major ecological projects of plateau wetlands.

4.4 Functional effects of other greenhouse gases in the Zoige Wetland

In addition to CO_2, methane and nitrous oxide are also important greenhouse gases. Carbon exists not only in the form of CO_2 but also in the form of methane, so the study on the carbon source and sink function of methane and other greenhouse gases is helpful to fully reveal the function and mechanism of wetland carbon source and sink. The IPCC (Intergovernmental Panel on Climate Change) Sixth Assessment Report singled out methane emissions reductions as one of the most effective ways to slow global warming in the coming decades. Inland water bodies and animal husbandry are important sources of methane emissions, and plateau lakes, swamps and peatlands account for 57% and 30% of the country's total area, respectively. Therefore, an accurate assessment of plateau methane source and sink functions is of great significance [46].

5. Conclusions

This paper analyzed and summarized the research results of different techniques and methods of soil organic carbon utilization in Zoige wetland. Studies on ecosystem carbon storage in peatland mainly focused on soil organic carbon storage, because soil organic carbon storage in peatland accounted for a large proportion. The large variation of soil organic carbon storage in the peatland is due to the lack of data, and further information acquisition of soil data in the peatland of the Zoige Plateau needs to be increased.

The continuous warming and humidification of the future climate and the restoration of degraded ecosystems are expected to help the plateau terrestrial ecosystem double its carbon sink by 2060, which will make a great contribution to China's carbon neutrality. However, due to the structural shortcomings of current observations and models, the risk of carbon emissions from the melting of deep permafrost has not been scientifically assessed. In addition, Zoige is rich in lakes, rivers, marshes and other resources. As an important carrier of methane and other greenhouse gas emission sources, how these water ecosystems will affect the carbon source and sink function of wetlands is the focus and focus of future research.

Therefore, in order to accurately estimate the status of carbon sink in peat wetlands and predict the potential of future increase in carbon sink, it is urgent to establish a unified standard observation system for carbon sink in peat wetlands, make up for the missing observational data in key areas, and improve the simulation and reduction ability of biogeochemical models in peat wetlands for key carbon cycle processes in the field. Continue to deepen the mechanism of dynamic change of carbon source and sink function in peat wetlands under the influence of different factors. We should strengthen the research on carbon in deep frozen soil, greenhouse gas fluxes in ecosystems with different degrees of degradation, carbon source and sink processes in water bodies, including greenhouse gas fluxes at the water-atmosphere interface, and organic carbon burial. At the same time, attention should be paid to the strong carbon sequestration ability of peat wetlands, and systematic and complete protection of wetland ecosystems such as water, plants and microorganisms should be implemented to promote the peat wetlands to maintain a high level of soil carbon sequestration function.

Author Contributions

Ma Chanhua contributed significantly to analysis and manuscript preparation;performed the data analyses and wrote the manuscript.

Xu Zhengqiang contributed to the conception of the study;helped perform the analysis with constructive discussions.

Conflict of Interest

The authors declared that they have no conflicts of interest to this work. No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication.

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References

[1] Amundson, R., 2001. The carbon budget in soils. Annual Review of Earth and Planetary Sciences. 29(1), 535-562.

[2] Carvalhais, N., Forkel, M., Khomik, M., et al., 2014. Global covariation of carbon turnover times with climate in terrestrial ecosystems. Nature. 514(7521), 213-217.

[3] Friedlingstein, P., O'sullivan, M., Jones, M.W., et al., 2020. Global carbon budget 2020. Earth System Science Data Discussions. 12(4), 3269-3340.

[4] Hicks Pries, C.E., Castanha, C., Porras, R.C., et

al., 2017. The whole-soil carbon flux in response to warming. Science. 355(6332), 1420-1423.

[5] Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma. 123(1-2), 1-22.

[6] Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature. 440(7081), 165-173.

[7] Jiang, W., Lv, J., Wang, C., et al., 2017. Marsh wetland degradation risk assessment and change analysis: A case study in the Zoige Plateau, China. Ecological Indicators. 82, 316-326.

[8] Tian, Y.B., Xiong, M.B., Xiong, X.Sh., et al., 2003. Ruo er gai gao yuan shi di tu rang-zhi wu xi tong you ji tan de fen bu yu liu dong (Chinese) [Distribution and flow of organic carbon in soil-plant system of Zoige Plateau wetland]. Chinese Journal of Plant Ecology. (4), 60-65.

[9] Gao, J.Q., Lei, G.Ch., Li, L., et al., 2010. Ruo er gai gao yuan san zhong shi di tu rang you ji tan fen bu te zheng (Chinese) [Distribution characteristics of soil organic carbon in three kinds of wetlands in the Zoige Plateau]. Wetland Science. 8(4), 327-330.

[10] Gao, J.Q., Ouyang, H., Bai, J.H., 2006. Ruo er gai gao han shi di tu rang huo xing you ji tan chui zhi fen bu te zheng (Chinese) [Vertical distribution of soil active organic carbon in Zoige Alpine wetland]. Journal of Soil and Water Conservation. 20(86), 76-79.

[11] Gao, J.Q., Ouyang, H., Zhang, F., et al., 2007. Ruo er gai gao han shi di biao ceng tu rang you ji tan kong jian fen bu te zheng (Chinese) [Spatial distribution of surface soil organic carbon in Zoige Alpine wetland]. Ecological Environment. 16(6), 1723-1727.

[12] Li, L., Gao, J.Q., Lei, G.Ch., et al., 2011. Ruo er gai bu tong di xia shut wei ni tan shi di tu rang you ji tan he quan dan fen bu gui lü (Chinese) [Distribution of soil organic carbon and total nitrogen in peat wetlands with different groundwater levels in Zoige, China]. Chinese Journal of Ecology. 30(11), 2449-2455.

[13] Ma Q.F., 2013. Ruo er gai gao han zhao ze sheng tai xi tong tan chu liang yan jiu (Chinese) [Research on carbon storage of alpine swamp ecosystem in Zoige] [Ph.D. thesis]. Chinese Academy of Forestry.

[14] Chen, H., Yang, G., Peng, C., et al., 2014. The carbon stock of alpine peatlands on the Qinghai–Tibetan Plateau during the Holocene and their future fate. Quaternary Science Reviews. 95, 151-158.

[15] Zhou, W.Ch., Solangduerji, Cui, L.J., et al., 2016. Pai shut dui ruo er gai gao yuan ni tan di tu rang you ji tan chu liang de ying xiang (Chinese) [Effects of drainage on soil organic carbon storage in peatland of Zoige Plateau]. Acta Ecologica Sinica. 36(8), 2123-2132.

[16] Liu, L.J., Liu, X.W., Ju, P.J., et al., 2018. 15000 Nian yi lai ruo er gai gao yuan ni tan di fa yu ji qi tan dong tai (Chinese) [Development and carbon dynamics of peatland in Zoige Plateau during 15000 years]. Acta Ecologica Sinica. 38(18), 6493-6501.

[17] Dong, L.J., 2017. Ruo er gai shi di tui hua guo cheng zhong tu rang tan dan lin han liang ji sheng tai hua xue ji liang bi bian hua te zheng yan jiu (Chinese) [Changes in soil carbon, nitrogen, phosphorus content and ecological stoichiometric ratio during the degradation of Zoige wetland] [Master's thesis]. Lanzhou University.

[18] Wang, W.B., Bai, B., Zhang, P.Q., et al., 2021. Bei jing ruo er gai shi di tu rang you ji tan han liang he mi du de fen bu te zheng (Chinese) [Distribution characteristics of soil organic carbon content and density in Zoige wetland]. Chinese Journal of Ecology. 40(11), 3523-3530.

[19] Zheng, Y., Niu, Z., Gong, P., et al., 2013. Preliminary estimation of the organic carbon pool in China's wetlands. Chinese Science Bulletin. 58, 662-670.

[20] Niu, Zh.G., Gong, P., Cheng, X., et al., 2009. Zhong guo shi di chu bu yao gan zhi tu ji xiang guan di li te zheng fen xi (Chinese) [Preliminary remote sensing mapping of wetlands in China and analysis of related geographical features]. Science in China: Series D. (2), 16.

[21] Zhang, X.H., Li, D.Y., Pan, G.X., et al., 2008. Zhong guo shi di tu rang tan ku bao hu yu qi hou bian hua wen ti (Chinese) [Conservation of wetland soil carbon pool and climate change in China]. Advances in Climate Change Research. 4, 202-208.

[22] Wang, X., Cammeraat, E.L., Cerli, C., et al., 2014. Soil aggregation and the stabilization of organic carbon as affected by erosion and deposition. Soil Biology and Biochemistry. 72, 55-65.

[23] Wang, M., Liu, Z.G., Ma, X.H., et al., 2012. Zhong guo ni tan di you ji tan chu liang fen qu (Chinese) [Organic carbon storage zoning in peatlands in China]. Wetland Science. 10(2), 157-163.

[24] Liu, W., Chen, S., Qin, X., et al., 2012. Storage, patterns,and control of soil organic carbon and nitrogen in the northeastern margin of the Qinghai-Tibetan Plateau. Environmental Research Letters. 7(3), 035-041.

[25] Ma, K., 2016. Ruo er gai gao han shi di tu rang you ji tan chu liang shi kong bian hua yan jiu (Chinese) [Study on spatiotemporal changes of soil organic carbon storage in the alpine wetland of Ruoergai] [Ph.D. thesis]. Beijing: Beijing Forestry University.

[26] Liu, X.W., Wu, J.H., Zhu, D., et al., 2016. San jiang ping yuan ni tan de guo qu 10 ka ni tan chu liang yu tan chu liang de mo xing gu suan (Chinese) [Model estimation of past 10 ka of peat reserves and carbon reserves in peatland, Sanjiang Plain]. Chinese Journal of Applied & Environmental Biology. 22(4), 586-591.

[27] Guo, J., Li, G.P., 2007. Ruo er gai qi hou bian hua ji qi dui shi di tui hua de ying xiang (Chinese) [Climate change and its impact on wetland degradation in Zoige]. Plateau Meteorology. 2, 422-428.

[28] Chen, S.Ch., 2019. Qing zang gao yuan tu rang shi du de shi kong fen bu te zheng (Chinese) [Spatial and temporal distribution of soil moisture in the Tibetan Plateau]. Scientia Naturalis Sinica. 7(4).

[29] Liu, Zh.W., Li, Sh.G., Wei, W., et al., 2019. Jin san shi nian qing zang gao yuan shi di bian hua ji qi qu dong li yan jiu jin zhan (Chinese) [Research progress of wetland change and its driving forces in the Tibetan Plateau in the past 30 years]. Chinese Journal of Ecology.

[30] Guo, X.L, Du, W., Wang, X., et al., 2013. Degradation and styucture change of humic acids corresponding to water decline in Zoige peatland, Qinnghai-Tibet Plateau. Science of the Total Environment. 445, 231-236.

[31] Xiang, S., Guo, R.Q., Wu, N., et al., 2009. Current status and future prospects of Zoige Marsh in eastern Qinghai-Tibet Plateau. Ecological Engineering. 35, 553-562.

[32] Cui, Y., Zhang, X.X., Zhang, X., et al., 2020. ruo er gai xian shi di wen tai zhuan huan de shut wen di mao sheng tai yu zhi (Chinese) [Hydrological and geomorphologic ecological threshold of steady-state transformation of wetland in Zoige County, Sichuan Province]. Acta Ecologica Sinica. 40(23), 8794-8804.
DOI: http://dx.doi.org/10.5846/stxb202001030023

[33] Luan, J., Cui, L., Xiang, C., et al., 2014. Different grazing removal exclosures effects on soil C stocks among alpine ecosystems in east Qinghai—Tibet Plateau. Ecological Engineering. 64, 262-268.

[34] Li, K., Yang, Y.X., Yang, Y., et al., 2012. Ji yu zhi bei shu liang fen lei de pai shui shu gan ying xiang xia ruo er gai gao yuan zhao ze tui hua te zheng (Chinese) [Characteristics of swamp degradation in Zoige Plateau under the influence of drainage and dewatering based on vegetation quantity classification]. Chinese Journal of Applied Ecology. 23(7), 1781-1789.

[35] Huo, L., Chen, Z., Zou, Y., et al., 2013. Effect of Zoige alpine wetland degradation on the density and fractions of soil organic carbon. Ecological Engineering. 51, 287-295.

[36] Bai, J.H., Gao, J.Q., Ouyang, H., 2006. Vertical distribution characteristics of soil labile organic carbon in Ruoergai Wetland. Journal of Soil and Water Conservation. 20(1), 76-86.

[37] McSherry, M.E., Ritchie, M.E., 2013. Effects of grazing on grassland soil carbon: a global review. Global Change Biology. 19(5), 1347-1357.

[38] Maillard, É., Angers, D.A., 2014. Animal manure application and soil organic carbon stocks: A meta-analysis. Global Change Biology. 20(2), 666-679.

[39] Wu, G.L., Liu, Z.H., Zhang, L., et al., 2010. Long-term fencing improved soil properties and soil organic carbon storage in an alpine swamp meadow of western China. Plant and Soil. 332, 331-337.

[40] Wang, Y.F., Lv, W.W., Xue, K., 2022. Grassland changes and adaptive management on the Qinghai-Tibetan Plateau. Nature Reviews Earth & environment. 3, 668-683.

[41] Lai, J.D., Tian, K., Zhao, Y.H., et al., 2013. Jin mu dui gao yuan shi di na pa hai tui hua cao dian tu rang li hua xing zhi de ying xiang (Chinese) [Effects of grazing ban on soil physicochemical properties of degraded meadow in Napa Sea Plateau wetland]. Western Forestry Science. 42(2), 43-48.

[42] Wang, Y.F., Chen, Z.Zh., Tieszen, L.T., 1998. Ren lei huo dong dui xi lin guo le di qu zhu yao cao yuan tu rang you ji tan fen bu de ying xiang (Chinese) [Effects of human activities on soil organic carbon distribution in major grasslands in Xilin Gol Region, China]. Chinese Journal of Plant Ecology. 22(6), 545-551.

[43] He, G.Y., Sun, H.Zh., Shi, X.M., et al., 2015. Qing zang gao yuan gao han shi di bu tong ji jie tu rang li hua xing zhi dui fang mu mo shi de xiang ying (Chinese) [Response of soil physicochemical properties to grazing patterns in alpine wetland of Qinghai-Tibet Plateau in different seasons]. Journal of Agrochemistry. 24(4), 12-20.

[44] Liu, L.J., Liu, X.W., Ju, P.J., et al., 2018. 15000 nian yi lai ruo er gai gao yuan ni tan di fa yu ji qi tan dong tai (Chinese) [Peatland development and carbon dynamics histories of zoige peatlands for 15000 years]. Acta Ecologica Sinica. 38(18), 1-9.

[45] Yu, Z., Li, Q.,Wang, P., et al., 2022. Changes of organic carbon density in desert steppe ecosystem driven by degradation and restoration. Journal of Desert Research. 42(2), 215-222.
DOI: 10.7522/j.issn.1000-694X.2022.00015

[46] Wang, T., Piao, Sh.L., 2023. Qing cang gao yuan lu di sheng tai xi tong tan hui gu suan: jin zhan, tiao zhan yu zhan wang (Chinese) [Estimate of terrestrial carbon balance over the Tibetan Plateau: Progresses, challenges and perspectives]. Quaternary Sciences. 43(2), 313-323.