Investigation on the Permafrost Degradation and Carbon Budget in Mongolian Grassland Ecosystems

Qinxue Wang[1*], Tomohiro Okadera[1], Tadanobu Nakayama[1], Tonghua Wu[2],
Ochirbat Batkhishig[3], and Masataka Watanabe[4]

[1]National Institute for Environmental Studies, Tsukuba, Ibaraki, Japan
[2]Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu, China
[3]Institute of Geography and Geoecology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia
[4]Research and Development Initiative, Chuo University, Tokyo, Japan
*Corresponding author: wangqx@nies.go.jp

Abstract. Driven by global warming, permafrost degradation has significant implications for the global climate system, especially in its potential to alter the carbon budget and biodiversity of terrestrial ecosystems. This study seeks to clarify the nexus between permafrost degradation and carbon budget dynamics in Mongolian grassland ecosystems. Permafrost degradation was assessed using three primary indicators: mean annual ground temperature ($MAGT$)), active layer thickness (ALT), and depth of zero annual amplitude ($DZAA$), which were derived from eight boreholes between 2009 and 2020. To deeply analyze carbon fluxes in both permafrost and non-permafrost areas, we considered indicators such as Gross Primary Production (GPP), Ecosystem Respiration ($Reco$), and Net Ecosystem Exchange (NEE), taken from two monitoring sites from 2016 to 2019. The results indicate that global warming leads to ground warming and changes in soil water content, both of which contribute to permafrost degradation in these ecosystems. Additionally, areas with permafrost mainly function as carbon sinks, while regions without permafrost serve as carbon sources. These dynamics imply that permafrost degradation affects soil water content, which in turn impacts the carbon balance, creating a feedback loop with climate change. This study emphasizes the urgent need for comprehensive climate change mitigation and adaptation strategies to counteract the potential impacts of permafrost degradation on soil moisture and carbon dynamics in grassland ecosystems.

Keywords: Permafrost degradation, Carbon dynamics, Ground warming, Grassland ecosystems, Climate change impacts.

1 Introduction

The effects of global warming remain at the forefront of environmental research, particularly its impact on permafrost degradation. This degradation is more than just a

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Notably, it has the potential to reshape the carbon budget and influence biodiversity within terrestrial ecosystems [1, 2]. The Mongolian grasslands, a significant part of the expansive Eurasian steppe ecosystem, sit at the heart of this complex environmental interplay. These grasslands are not only biodiverse but also encompass vast permafrost regions, covering approximately 60% of Mongolia's land area [3, 4]. The carbon stored within this permafrost is a key piece of the global carbon puzzle, and its stability is of paramount importance to climate scientists [5].

The intensifying effects of global warming threaten this permafrost, bringing with them the concerning possibility of releasing significant amounts of carbon dioxide and methane into the atmosphere [6]. Such releases could amplify global warming, creating a self-perpetuating cycle. This heightens the urgency of understanding permafrost degradation and its interconnectedness with the carbon cycle. Significantly, research has shown unique dynamics in places like the Mongolian grasslands: areas with permafrost largely act as carbon sinks, whereas regions without permafrost tend to be carbon sources [5, 7].

Building on our earlier research, this study aims to elucidate the relationship between permafrost degradation and carbon budget dynamics in Mongolian grassland ecosystems. One aspect of our research assessed permafrost degradation using three primary indicators: mean annual ground temperature (*MAGT*), active layer thickness (*ALT*), and depth of zero annual amplitude (*DZAA*), collected from eight boreholes between 2009 and 2020 [8]. Another facet examined carbon fluxes in both permafrost and non-permafrost areas, leveraging key indicators such as Gross Primary Production (*GPP*), Ecosystem Respiration (*Reco*), and Net Ecosystem Exchange (*NEE*), gathered from two sites between 2016 and 2019 [9].

2 Methodology

2.1 Indicators for Detecting Permafrost Degradation:

To detect the permafrost's reaction to climate change across various terrestrial ecosystems, we established a permafrost monitoring network in 2007. This network includes eight boreholes for monitoring ground temperatures within forest, meadow, steppe, moderately dry steppe, and wetland ecosystems, and three automatic weather stations (AWS) to track climatic factors like wind speed (*Ws*), air temperature (*Ta*), relative humidity (*RH*), precipitation (*P*), solar radiation (*Rs*), net radiation (*Rn*), soil heat flux (*SHF*), soil temperature (*Ts*), and soil water content (*SWC*) in forest, meadow, and steppe ecosystems in north-central Mongolia. Major indicators including the mean annual ground temperature (*MAGT*), active layer thickness (*ALT*), and depth of zero annual amplitude (*DZAA*) are essential parameters when studying permafrost dynamics and the effects of climate change in cold regions. The equations commonly used to calculate them:

MAGT is the average temperature of the ground over a year at a particular depth, typically taken at the depth where seasonal temperature fluctuations are negligible (e.g., at the base of the active layer for permafrost regions). A simplified equation to estimate *MAGT* is:

$$\boldsymbol{MAGT = \frac{1}{T}\int_0^T T_g(t)\,dt} \qquad (1)$$

Where:

- $\boldsymbol{T}$ is the period of one year,
- $\boldsymbol{T_g(t)}$ is the ground temperature as a function of time.

ALT refers to the layer of ground above permafrost that thaws during the summer and refreezes during the winter. The thickness of this layer can vary due to several factors, including air temperature, snow cover, and soil properties. A simplified equation to estimate *ALT* based on the Stefan solution is:

$$\boldsymbol{ALT = \sqrt{\frac{2K(T_s - T_f)}{\rho L}\,t}} \qquad (2)$$

Where:

- $\boldsymbol{K}$ is the thermal conductivity of the soil,
- $\boldsymbol{T_s}$ is the mean summer surface temperature,
- $\boldsymbol{T_f}$ is the freezing temperature of the soil (typically taken as 0°C for unfrozen water),
- $\boldsymbol{\rho}$ is the density of ice,
- $\boldsymbol{L}$ is the latent heat of fusion for ice,
- $\boldsymbol{t}$ is the time (duration of thaw season).

DZAA is the depth at which seasonal temperature fluctuations are negligible and represents a transition between the active layer and the permafrost. A typical equation used to estimate *DZAA* is based on the theory of periodic heat conduction:

$$\boldsymbol{DZAA = \sqrt{\frac{\alpha T}{\pi}}} \qquad (3)$$

Where:

$\boldsymbol{\alpha}$ is the soil's thermal diffusivity,
$\boldsymbol{T}$ is the period of one year.

2.2 Indicators for Monitoring Carbon Fluxes:

Despite numerous studies indicating that global warming triggers permafrost thawing, understanding of the mechanisms linking permafrost thawing and ecosystem carbon budgets remains limited. To compare the impacts of freeze-thaw cycles on the grassland ecosystem carbon budget between a permafrost area and a non-permafrost area, we set up two carbon dioxide flux towers in 2015 to monitor net ecosystem exchange (*NEE*) by using eddy covariance systems at the Nalaikh site and Hustai site. Here, the ecosystem respiration (*Reco*) from 2016 to 2019 was calculated using the Lloyd–Taylor model as shown in equation (4):

$$Reco = R_{ref}\exp\left[E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T_a-T_0}\right)\right] \tag{4}$$

Where, T_0 is kept constant at −46.0 °C, T_{ref} is 15.0 °C, R_{ref} is the rate of $Reco$ at T_{ref}, and E_0 is the activation energy. Additionally, E_0 quantifies the temperature sensitivity of $Reco$, and was calculated using 15 days of continuous night data [10]. Then, the gross primary production (GPP) was calculated using equation (5):

$$GPP = Reco - NEE \tag{5}$$

3 Result

3.1 Ground Warming and Permafrost Degradation:

Using key indicators like *MAGT*, *ALT*, and *DZAA*, we sought to identify signs of permafrost degradation. Areas with less ice-rich permafrost experienced a modest rise in *MAGT*, whereas areas with ice-rich permafrost, specifically Pingos and wetlands, witnessed a pronounced increase as shown in (see Fig. 1.) On the other hand, the *ALT* growth rates differed among ecosystems; notably, steppe ecosystems displayed the most marked rise, showing a yearly increase between 23.0-28.9 cm over the recent decade [8], depicted in (see Fig. 1.) This trend underscores the accelerating degradation of permafrost in these areas.

ALT exhibited varying correlations with climatic parameters across ecosystems. For instance, in meadow ecosystems, ALT was linked with precipitation, whereas in forest ecosystems, it correlated with soil water content. Conversely, steppe ecosystems manifested a pronounced relationship between *ALT*, *MAGT*, and pivotal climatic variables such as air temperature, relative humidity, soil heat flux, and soil water content. (see Fig. 2) distinctly shows that as ground temperatures rose, soil water content (*SWC*) increased. A consistent inverse correlation between *DZAA* and air temperature was evident across all examined ecosystems.

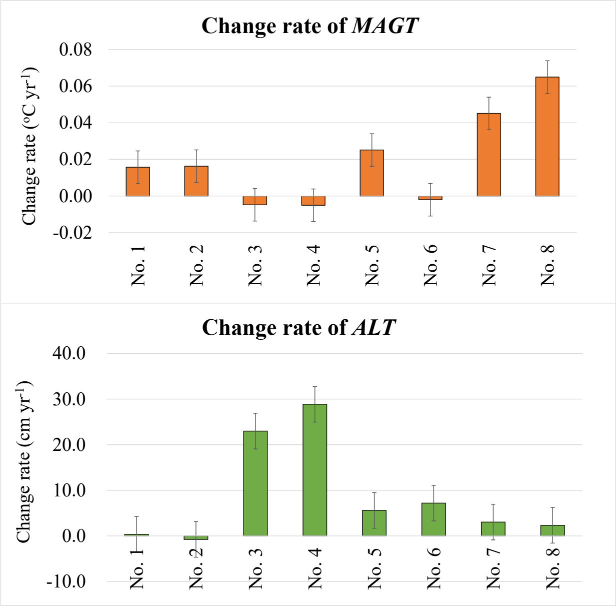

Fig. 1. Annual Change Rates of MAGT and ALT from 2009 to 2020 in North-central Mongolia (Locations: 1. Davaat_steppe, 2. Davaat_forest, 3. Argalant, 4. Nalaikh, 5. Olon Dovt, 6. Baganuur, 7. Honhor, 8. Bust Lake)

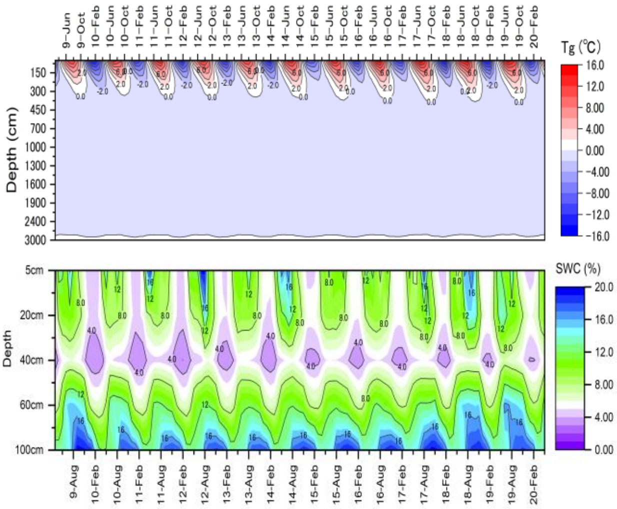

Fig. 2. Trends in Ground Temperature (0-30m) and Soil Water Content (0-1m) from 2009 to 2020 at Nalaikh, emphasizing the SWC increase with ground warming.

In essence, this study confirms signs of permafrost degradation in varied terrestrial ecosystems of Mongolia, each responding distinctly to climate change. The rapid degradation of steppe ecosystems is especially noteworthy and offers a pivotal understanding of the ecological consequences of climate change in permafrost regions.

3.2 Analysis of Carbon Fluxes and Contributing Factors:

Our investigation ascertained that regions with permafrost predominantly function as carbon sinks, absorbing more carbon than they release. Conversely, areas devoid of permafrost predominantly act as carbon sources, emitting more carbon than they sequester. This inference is based on the measurements of *GPP*, and *Reco* represented in (see Fig. 3).

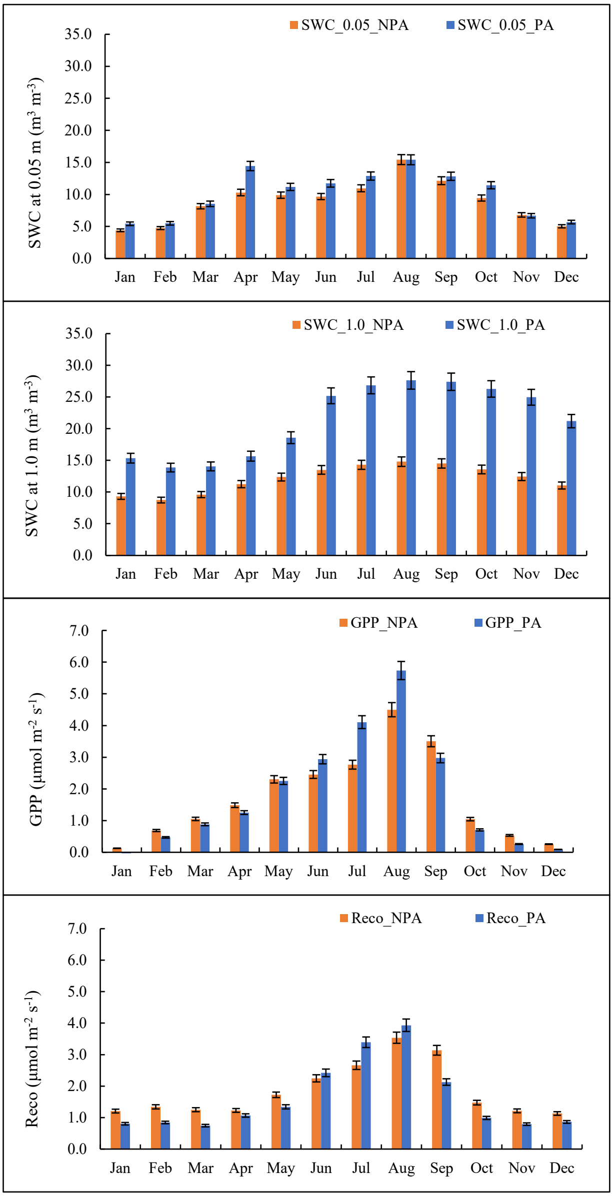

Fig. 3. Monthly Averages of Soil Water Content (0.05m and 1.0m), Gross Primary Production, and Ecosystem Respiration from 2016 to 2019 in Permafrost (Nalaikh) and Non-Permafrost (Hustai) Regions

Remarkably, the permafrost region consistently exhibited a higher NEP during both thawing and thawed stages, suggesting enhanced carbon sequestration compared to the non-permafrost area. Soil water content emerged as a pivotal determinant affecting carbon dynamics. The interplay between *SWC*, *Reco*, and *GPP* exhibited distinct variations through the freeze-thaw cycle. Both *Reco* and *GPP* surged with the rise in surface *SWC*. Still, an intriguing S-shaped growth pattern was evident in the permafrost region, attributable to its gradual soil thawing rate and consequent incremental soil surface water content during spring thaw. As thawing progressed, water seeped deeper into the soil. Concurrently, as surface *SWC* diminished and temperatures rose, a minor increase in ecosystem respiration was observed.

These findings posit that climate change, inducing permafrost degradation, could hasten soil thawing and modify soil water content, profoundly influencing the carbon budget of these ecosystems. Yet, more research is warranted to elucidate the specific interrelations between thawing permafrost and ecosystem carbon budgets.

4 Discussion

4.1 Implications of Permafrost Degradation:

This research underscores the role of permafrost degradation in global warming. As permafrost thaws, it releases carbon, further exacerbating climate change. The study reveals concerning rates of permafrost degradation, marked by increases in *ALT* and *GT*. The relationship between *GT* and primary climatic factors differs among ecosystems, influenced by their topography, hydrology, climatic conditions, and vegetation cover.

In meadow and forest ecosystems, *GT* in active layers displays only slight correlations with air temperature (Ta). In contrast, steppe ecosystems exhibit a strong correlation between *GT* and *Ta* across all layers. Additionally, *SWC* is correlated with *GT* at various depths in meadow, forest, and steppe ecosystems.

The study investigates the changes in *ALT* and *MAGT* across diverse ecosystems. Mountainous regions show the least increase in *ALT*, while moderate increases are observed in ice-rich permafrost areas, like Pingos and wetlands. Flat regions with ice-poor permafrost, where drier soil conditions enhance heat transfer, witness the most pronounced increase in *ALT*.

When examining *MAGT*, ecosystems respond differently. Ice-poor permafrost in forest and meadow ecosystems warms at a comparatively slower pace, whereas ice-rich permafrost in steppe ecosystems and wetlands warms more rapidly. These results are consistent with findings from other global permafrost regions.

In summary, this research highlights the crucial impact of permafrost degradation on global warming. A deep understanding of these dynamics is vital to accurately gauge the ramifications of permafrost thawing on our changing climate.

4.2 Carbon Dynamics and Soil Water Content:

This research delves into the repercussions of permafrost thaw on carbon dynamics within grassland ecosystems. It meticulously examines the interplay between permafrost, freeze-thaw cycles, soil water content, and carbon budgets. Observations suggest that ground warming significantly exacerbates permafrost degradation, resulting in an expanded active layer thickness and a reduction in ground ice content. To pinpoint the extent of permafrost degradation, we focused on key indicators: *MAGT*, *ALT*, and *DZAA*.

Our findings reveal that permafrost degradation profoundly influences the freeze-thaw cycle and, consequently, the carbon budget. Elevated *SWC*, stemming from permafrost degradation, hastens soil heat flow, narrowing the temperature gradient between the surface and the deeper soil strata. Consequently, the onset of the thawing season is earlier, and its duration extends. We discerned disparities in *Ts* and *SWC* between permafrost and non-permafrost regions: permafrost zones exhibit reduced Ts and augmented *SWC* in their deeper soil layers.

When scrutinizing the carbon budget, it's evident that grassland ecosystems within permafrost regions predominantly act as carbon sinks. In contrast, regions devoid of permafrost tend to be carbon sources. Permafrost presence stabilizes lower soil temperatures and augments soil moisture levels, promoting increased carbon sequestration. Conversely, the continuous degradation of permafrost in regions without it leads to reduced soil moisture and a lag in the commencement of plant photosynthesis. This manifests in a counterclockwise hysteresis pattern between *Ts*, *Reco*, and *GPP*.

To conclude, the thawing of permafrost notably sways soil water content, influencing carbon dynamics and altering the carbon characteristics of grassland ecosystems, either as sinks or sources. This investigation accentuates the necessity for continued research, especially to validate the premise that permafrost degradation might curtail net carbon sequestration and escalate greenhouse gas emissions, potentially intensifying global warming.

4.3 Feedback Mechanisms and Climate Change:

This research spotlights the critical feedback loop precipitated by permafrost degradation and subsequent carbon release. It accentuates the imperative to fathom this mechanism for anticipating the ramifications of climate change. The study delves into primary climatic factors that influence permafrost degradation across varied ecosystems.

From 2009 to 2020, the study probed correlations between climatic variables—namely air temperature, relative humidity, precipitation, and soil water content—and pivotal indicators of permafrost degradation. The findings divulge that these relationships are nuanced and vary among different ecosystems. For instance, within meadow ecosystems, *ALT* modestly correlates with precipitation, yet *MAGT* demonstrates a pronounced affiliation with relative humidity. Forest ecosystems, on the other hand, reveal that *ALT* is strongly influenced by soil water content, but it bears minimal correlation to both air temperature and precipitation. Contrastingly, steppe ecosystems exhibited a robust association of both *ALT* and *MAGT* with key meteorological indicators. Notably, *DZAA* was discerned to inversely correlate with air temperature.

Such revelations underscore the diversified responses of terrestrial ecosystems to climate change. These insights are pivotal for refining and corroborating models that forecast permafrost degradation and its subsequent implications. A comprehensive grasp of the interrelations between climatic variables and permafrost dynamics is quintessential for a precise evaluation of climate change's bearing on permafrost territories.

In summation, the research unveils the intricate symbiosis between permafrost degradation, carbon fluxes, and climate change within grassland ecosystems. The investigation emphasizes the ramifications of permafrost degradation on global warming and spotlights the multifaceted nature of permafrost degradation responses across distinct ecosystems. Deciphering these processes and feedback loops is paramount for not only prognosticating but also adeptly mitigating the impacts of climate change on permafrost landscapes.

5 Conclusions

In this comprehensive exploration of the interplay between permafrost degradation and carbon budget dynamics within Mongolian grassland ecosystems, our research presented a clear connection anchored by an array of indicators. By utilizing data from eight boreholes spanning 2009 to 2020, we assessed permafrost degradation via three pivotal markers: mean annual ground temperature (*MAGT*), active layer thickness (*ALT*), and depth of zero annual amplitude (*DZAA*). Additionally, a nuanced examination of carbon fluxes in both permafrost and non-permafrost domains was undertaken, predicated on indicators like Gross Primary Production (*GPP*), Ecosystem Respiration (*Reco*), and Net Ecosystem Exchange (*NEE*) collected from dual monitoring sites between 2016 and 2019.

Our findings illuminate the stark reality: global warming precipitates not only ground warming but also modulates soil water content, both of which further the degradation of permafrost within these intricate ecosystems. Significantly, we discerned a clear dichotomy in carbon dynamics; areas suffused with permafrost predominantly operate as carbon sequesters, whereas their non-permafrost counterparts emerge as carbon emitters. Such dynamics underscore a pivotal revelation: the degradation of permafrost invariably alters soil moisture levels, which subsequently recalibrates the carbon equilibrium, forging a potent feedback loop with overarching climate change.

In synthesizing these insights, our study not only amplifies our understanding of the profound repercussions of permafrost degradation on grassland ecosystems but also signals an exigent call to arms. The intricate dance between soil moisture and carbon dynamics, set against the backdrop of permafrost degradation, necessitates proactive, holistic climate change mitigation and adaptation strategies. As we navigate the challenges of a warming world, it's imperative to devise robust countermeasures to mitigate the cascading impacts of permafrost degradation, safeguarding the delicate balance of our grassland ecosystems and, by extension, our global climate framework.

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