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Recent CO_2 and water vapor fluxes at Udleg forest research station, northern Mongolia baseline data for climate–ecosystem studies

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ABSTRACT
This study investigated seasonal and interannual patterns of net ecosystem exchange (NEE) and evapotranspiration (ET) obtained at a larch-dominated forest in northern Mongolia between 2010–2012 and 2022–2024. Seasonal and interannual variability in both fluxes has been observed; years with earlier leaf-out and higher early-season leaf area index (LAI) resulted in higher CO_2 uptake, while wetter summers promoted higher ET. Bayesian regression analysis revealed a shift in the relative influence of environmental drivers in the two periods. The soil water effect is remarkable in summer ET variation in previous relatively drier years. In contrast, surface soil temperature and solar radiation have become more influential than soil water in recent years. LAI emerged as a significant driver of NEE only in the latter period, suggesting improved photosynthetic responsiveness under favorable water conditions. These results indicate the sensitivity of larch ecosystems to decadal scale climate variability and suggest the importance of phenological dynamics and soil–plant–atmosphere interactions. Although these changes were likely within the natural variability range, they indicate the need for sustained monitoring. Long-term, interdisciplinary studies will be essential to understand the ecosystem's water–carbon coupling in the forest–steppe transition zone.

KEYWORDS

CO_2 and water vapor fluxes, EDDY covariance, Larch forest, Precipitation, Soil water

1. INTRODUCTION

Forest and water interactions are fundamental to driving the Earth's carbon and hydrological cycles [1]. Boreal forests are key in carbon sequestration and water regulation on their cycles on regional to continental scales [2]. In northern Mongolia, larch-dominated forests extend under a semi-arid climate at the southern limit of the boreal forest and permafrost distribution, forming an ecological transitional zone sensitive to climate change [3], [4]. Recent studies have shown that *Larix sibirica*, the dominant species in this region, has a larger carbon uptake potential than L. cajanderi in more humid northern areas such as Siberia [5], [6]. However, it is vulnerable to drought and heat stress [6]. These findings emphasize the importance of understanding vegetation–climate interactions at the dry-cold margin of the boreal zone.

Based on this ecologically and climatologically unique environment, previous research has examined forest–climate relationships across multiple scales in Mongolia. Dendroclimatic analyses indicate that tree growth responds strongly to early summer precipitation [7], [8], while stand-level studies show the effect of soil water availability on trees' water and nutrient use [9]. Geospatial approaches have presented spatial dependency of forest response to climate [10], and impacts of permafrost degradation, wildfire, and land-use change on forest dynamics have been investigated [11], [12]. These findings reveal that short-term and long-term hydroclimatic variability characterizes Mongolian forests.

Among these studies, long-term observations of ecosystem-scale carbon and water dynamics in Mongolian boreal forests remain limited [13], [14]. The Udleg forest research station in northern Mongolia provides an opportunity to investigate forest response to seasonal to decadal-scale climate variability. Previous project conducted measurements from 2010 to 2012 and achieved foundational insights into carbon and water fluxes in larch-dominant forest [14]. Following this work, we present recent (2022–ongoing) flux observations and explore potential changes in CO_2 and water flux, and climate sensitivity over the past decade.

This study utilizes forest flux observation to examine: (1) interannual variation in CO_2 and water fluxes with precipitation variation, (2) seasonal sequence in flux and their relation to phenological events, and (3) changes in sensitivity of summertime fluxes to the environment between the two study periods. Based on these findings, we aim to clarify how larch forests in the Mongolian forest–steppe transition zone respond to changing climate conditions.

2. METHODS

2.1. Study site

The study was conducted at the Udleg forest research station of the National University of Mongolia (48°16′24″N, 106°51′03″E, 1338 m above sea level) in the transition zone between the boreal forest and steppe ecosystems in northern Mongolia. The site is dominated by larch (*Larix sibirica*) mixed with birch (*Betula Platyphylla*) and partly evergreen trees [14]. Mean annual precipitation ranges from 230 to 340 mm (2010, 2011, 2012, 2023, 2024), with approximately 80% occurring during the growing season (June–August) [14]. Beneath the forest cover, permafrost with an active layer of ca.2–3 m is present [15].

2.2. Ground observation data

To quantify vertical fluxes of carbon dioxide (net ecosystem exchange, NEE) and water vapor (evapotranspiration, ET) between the forest and atmosphere, eddy covariance measurement [16] has been continued since August 2022. An integrated open-path gas analyzer and 3-D sonic anemometer (IRGASON, Campbell Scientific) was installed at 25 m above ground. Flux data were processed using standard procedures, including double rotation of coordinate axes, density correction, spike removal, and friction velocity filtering, implemented with EddyPro software (LI-COR). Gap-filling and partitioning of NEE into gross primary production (GPP) and ecosystem respiration followed the standard protocol described in [17]. The same procedures were also applied to the earlier dataset (2010–2012) to ensure consistency in flux comparisons across years.

Meteorological variables, including air temperature, relative humidity, wind speed, and radiation components, were monitored using an automated system above the canopy and at ground level. Soil temperature and volumetric water content were measured at multiple depths. The transmissivity of shortwave radiation through the canopy layer and its reflectance at the ground were used to determine the canopy and ground conditions. Time-lapse imagery of the canopy layer and forest floor was also used to check key phenological stages, including snowmelt, the onset of leaf expansion, and leaf fall.

2.3. Remote sensing data

To complement temporal-divided flux tower observations, we utilized Moderate Resolution Imaging Spectroradiometer (MODIS) satellite products such as MOD17A2H.061 for gross primary production (GPP), MOD16A2GF.061 for evapotranspiration (ET), and MCD15A3H.061 for leaf area index (LAI), all with 500 m spatial and 8-day/4-day temporal resolution. Filtering low-quality observations using quality control flags, grid cells covering and surrounding the Udleg site were sampled and aggregated to the 1000 m grid based on better agreement in interannual variability with tower data. These satellite-derived variables supported the interpretation of tower flux variability and phenological transitions. All datasets were retrieved and analyzed on the Google Earth Engine platform [18].

2.4. Statistical analysis

To detect changes in the climate sensitivity of ecosystem fluxes over time, we applied a Bayesian hierarchical regression model using the Python module PyMC [19]. The model estimated separate regression coefficients (intercepts and slopes) for two observational periods (2010–2012 and 2022–2024), allowing us to compare flux–climate relationships between the early and recent periods. Specifically, period-specific intercepts and slopes were estimated from shared normal distributions, permitting partial pooling across the two periods. The posterior distributions of the slope parameters (standardized regression coefficients) with 95% highest density intervals (HDIs) were used to evaluate whether the influence of daily environmental variables including soil water content at 10 cm depth (θ), surface soil temperature (T_s), air temperature (T_a), solar radiation (S), and LAI on NEE and ET differed between the two periods.

3. RESULTS AND DISCUSSION

3.1. Interannual variations in nee and et

Interannual variability in NEE (negative value indicates net CO_2 uptake) and ET at the Udleg site was strongly associated with differences in annual precipitation and vegetation condition presented as LAI (Figure 1). In 2024, the wettest year during the observation period, the highest annual CO_2 uptake (NEE = −373 gC m^{-2}) and the highest ET (369 mm) were observed. In contrast, in drier years such as 2010, the NEE and ET were reduced to −321 gC m^{-2} and 272 mm, respectively. Correlation to precipitation suggests that annual water availability is a primary control on carbon assimilation and water use in this semi-arid larch forest, consistent with prior dendroclimatology studies in the region [4, 8]. However, since NEE is the sum of GPP and ecosystem respiration, the effect of precipitation is not linear. Wet conditions after rainfall can enhance both components, especially under sudden wetting from dry soil [20].

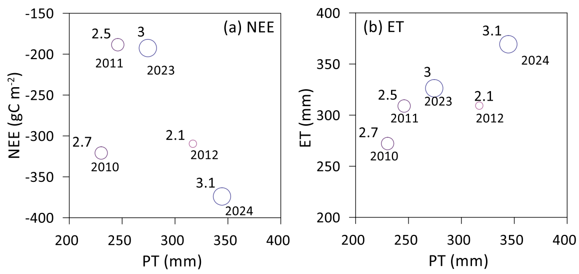

Figure 1. Annual NEE (a) and ET (b) with precipitation PT at Udleg site. The plot size indicates the June-August averaged LAI, and its values are given with the year

These annual GPP and ET at the Udleg site are compared to the long-term satellite-based products (Figure 2). Although the MODIS GPP tended to be underestimated, it captured the interannual variation of observed fluxes, particularly the recent increases. Conversely, MODIS ET consistently exceeded tower observations. This discrepancy likely reflects insufficient representation of deciduous forest function [21] or spatial resolution mismatches. However, developing appropriate methods for this region using satellite and ground-based observations is expected to fill the gaps in understanding climate-driven ecosystem flux variability.

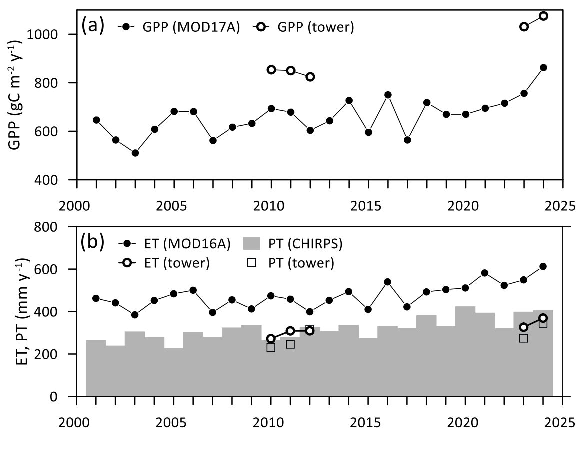

Figure 2. Interannual variations of tower- and satellite-based annual GPP (a) and ET with annual precipitation PT (b) in 2000–2024 at Udleg site

3.2. Seasonal patterns in nee and et

Seasonal variations in NEE and ET revealed that the dynamics of the growing season contributed substantially to interannual variability in carbon and water fluxes (Figure 3). In 2024, although the snow disappearance time was similar to that in 2023, the early thawing of the upper soil layer and canopy layer leaf-out resulted in an earlier onset of CO_2 uptake and an increase in ET than in the other years.

Furthermore, higher LAI values in May 2024 corresponded with earlier initiation of CO_2 uptake. In contrast, the seasonal decline of NEE in late summer did not show significant interannual variation, suggesting that spring phenology plays a more critical role than autumn senescence in shaping the annual carbon uptake period (Table 1). These results expect the utility of satellite-derived vegetation indices for detecting the relationship between plant phenology and carbon and water dynamics in boreal larch forests.

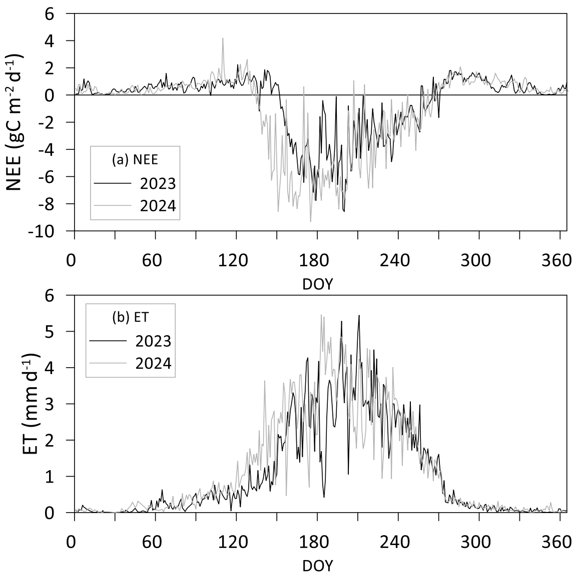

Figure 3. Seasonal variation of daily NEE (a) and ET (b) in 2023 and 2024 at Udleg site

Table 1. Dates of seasonal events and growing season vegetation index

	2010	2011	2012	2022	2023	2024
Ground observation of event dates (month/day)						
Snow disappear	NA	NA	NA	NA	4/11	4/9
Surface soil thaw	NA	4/12	4/16	NA	4/28	4/9
Canopy leaf-out	NA	NA	5/14	NA	5/25	5/7
Start of CO_2 uptake	6/4	5/31	5/20	NA	6/1	5/14
Start of leaf falling	NA	10/8	9/28	9/27	10/2	9/25
End of CO_2 uptake	9/21	9/16	9/24	9/9	9/30	9/22
CO_2 uptake period (days)	110	109	128	NA	122	133
Satellite-based leaf area index (LAI)*						
LAI (May)	0.6	0.5	0.7	0.7	0.5	1.5
LAI (June-Aug.)	2.5	2.4	2.2	2.4	2.9	3.0
LAI (Sep.)	0.8	0.8	0.9	0.8	1.1	1.0

* *LAI is* the average of a 4-day composite dataset (MCD15A3H.061)

3.3. Shifting environmental controls on growing season nee and et

The sensitivity of the daily NEE and ET to environmental drivers during the growing season for the 2010-2012 and 2022-2024 periods is evaluated using a Bayesian hierarchical regression model. The posterior distributions of slope parameters (standardized regression coefficient) β indicated notable changes in climatic controls between these periods (Figure 4).

In the earlier period (2010–2012), ET was positively influenced by soil water (θ) with $\beta = 1.0$. In contrast, θ had no significant influence on NEE during this period. This suggests that while water availability modulated evaporative fluxes, it did not impose a unidirectional constraint on photosynthesis (its HDIs crossed zero). Such a pattern may reflect the relatively high summer precipitation at the Udleg site compared to the other forest areas in Mongolia, where water limitation more strongly suppresses photosynthetic activity [13], [22]. Otherwise, different species composition (the other species mix at Udleg forest) can affect the response to soil water conditions. These conditions likely allowed the forest ecosystem to maintain stable carbon uptake even in moderate drought, while transpiration was still sensitive to soil water supply.

In recent years (2022–2024), the influence of soil water on ET weakened, while surface soil temperature (T_s) emerged as a more dominant control on both ET and NEE. In particular, the effect of T_s on NEE became significantly positive (β = 0.61), suggesting increased carbon losses via respiration during warmer periods. These changes imply a shift in the dominant environmental constraint on fluxes, from soil moisture availability in the early 2010s to thermal conditions in recent years. A possible explanation is that, in recent summers, soil water remained sufficiently high throughout the growing season, thereby reducing water limitation and amplifying the relative role of T_s and solar radiation (S).

The LAI emerged recently as a remarkable predictor of NEE (β = −0.82), indicating enhanced photosynthetic capacity following the higher canopy density. The expansion of leaf density as a significant control variable suggests that in recent years, seasonal vegetation conditions substantially influenced carbon dynamics more effectively than before.

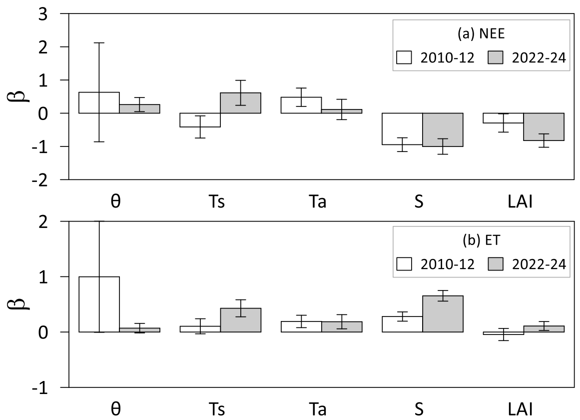

Figure 4. Posterior means and 95% highest density intervals (HDIs) of standardized regression coefficients β for daily NEE (a) and ET (b) during the growing season (June–August) in 2010–2012 and 2022–2024. Environmental variables tested include soil water content at 10 cm depth (θ), surface soil temperature (T_s), air temperature (T_a), solar radiation (S), and leaf area index (LAI)

4. CONCLUSIONS

This study presented interannual and seasonal variability in carbon and water fluxes in a semi-arid larch forest of northern Mongolia. We identified different climatic sensitivity of NEE and ET by comparing eddy covariance data from 2010–2012 and 2022–2024. The results revealed that annual ecosystem CO_2 and water balances were strongly regulated by precipitation. Bayesian regression analysis for intraseasonal NEE and ET variation showed a temporal shift in the dominant controls on fluxes: earlier years were more influenced by soil moisture. In contrast, recent years exhibited larger sensitivity to solar radiation and surface soil temperature, possibly reflecting altered growing season hydrological conditions.

These findings suggest a transition from water- to thermally-constrained flux dynamics over the past decade, potentially linked to increasingly stable summer soil moisture conditions. While our results can reflect natural variability within the regional climate [23], [24], they indicate the high responsibility of larch forest ecosystems to decadal-scale hydrothermal variation. Given the ecological and hydrological importance of forest–water interactions in this region, continuous flux measurements combined with vegetation and hydrological monitoring will be essential for understanding forest resilience and carbon–water interaction under changing climate.

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REFERENCES

[1] D. F. Levia, Forest Hydrology and Biogeochemistry. *Dordrecht: Springer*, 2011, Available: doi: 10.1007/978-94-007-1363-5

[2] S. Gauthier et al., "Boreal forest health and global change," *Science*, vol. 349, pp. 819–822, 2015, Available: doi:10.1126/science.aaa9092.

[3] P. D. Gunin et al., Vegetation Dynamics of Mongolia. *Dordrecht: Kluwer Academic Publishers,* 1999. Available: doi: 10.1126/science.aaa9092

[4] C. Dulamsuren et al., "Recent drought stress leads to growth reductions in Larix sibirica in the western Khentey, Mongolia," *Global Change Biol*., vol. 16, pp. 3024–3035, 2010, Available: doi: 10.1111/j.1365-2486.2009.02147.x.

[5] J. Liu et al., "Quantifying an overlooked deciduous-needleleaf carbon sink at the southern margin of the central-Siberian permafrost zone," *J. Geophys. Res. Biogeosci*., vol. 128, e2022JG006845, 2023, Available: doi: 10.1029/2022JG006845.

[6] M. P. Rao et al., "Approaching a thermal tipping point in the Eurasian boreal forest at its southern margin," *Commun. Earth Environ*., vol. 4, no. 247, 2023, Available: doi: 10.1038/s43247-023-00910-6.

[7] L. De Grandpré et al., "Seasonal shift in the climate responses of Pinus sibirica, P. sylvestris, and Larix sibirica trees from semi-arid, north-central Mongolia," *Can. J. For. Res.,* vol. 41, no. 6, pp. 1242–1255, 2011, Available: doi: 10.1139/x11-051.

[8] A. Gradel et al., "Climate-growth relationships and pointer year analysis of a Larix sibirica chronology from the Mongolian mountain forest steppe compared to white birch," *For. Ecosyst*., vol. 4, no. 22, 2017, Available: doi: 10.1186/s40663-017-0110-2.

[9] S.-G. Li et al., "Seasonal variation in oxygen isotope composition of waters for a montane larch forest in Mongolia," *Trees*, vol. 20, pp. 122–130, 2006, Available: doi:10.1007/s00468-005-0019-1.

[10] M. Klinge et al., "Climate effects on vegetation vitality at the treeline of boreal forests of Mongolia," *Biogeosciences*, vol. 15, pp. 1319–1333, 2018, Available: doi: 10.5194/bg-15-1319-2018.

[11] D. Juřička et al., "Large-scale permafrost degradation as a primary factor in Larix sibirica forest dieback in the Khentii massif, northern Mongolia," *J. For. Res*., vol. 31, pp. 197–208, 2020, Available: doi:10.1007/s11676-018-0866-4.

[12] K. Sakamoto et al., "Effects of large-scale forest fire followed by illegal logging on the regeneration of boreal forests in Mongolia," *Landscape Ecol. Eng*., vol. 17, pp. 267–279, 2021, Available: doi: 10.1007/s11355-021-00457-8.

[13] S.-G. Li et al., "Year-round measurements of net ecosystem CO_2 flux over a montane larch forest in Mongolia," *J. Geophys. Res*., vol. 110, D09303, 2005, Available: doi: 10.1029/2004JD005453.

[14] S. Miyazaki et al., "Interannual and seasonal variations in energy and carbon exchanges over the larch forests on the permafrost in northeastern Mongolia," *Polar Sci*., vol. 8, no. 2, pp. 166–182, 2014, Available: doi: 10.1016/j.polar.2013.12.004.

[15] M. Ishikawa et al., "Thermal states, responsiveness and degradation of marginal permafrost in Mongolia," *Permafrost and Periglac Process*, vol. 29, pp. 271–282, 2018, Available: doi:10.1002/ppp.1990.

[16] M. Aubinet et al., Eddy Covariance A Practical Guide to Measurement and Data Analysis. *Dordrecht: Springer*, 2012, Available: doi: 10.1007/978-94-007-2351-1

[17] T. Wutzler et al., "Basic and extensible post-processing of eddy covariance flux data with REddyProc," *Biogeosciences*, vol. 15, pp. 5015–5030, 2018, Available: doi: 10.5194/bg-15-5015-2018.

[18] N. Gorelick et al., "Google Earth Engine: Planetary-scale geospatial analysis for everyone," *Remote Sensing of Environ*., vol. 202, pp. 18–27, 2017, Available: doi: 10.1016/j.rse.2017.06.031.

[19] A. Patil et al., "PyMC: Bayesian Stochastic Modelling in Python," *J. Stat. Software*, vol. 34, pp. 1–81, 2010, Available: doi: 10.18637/jss.v035.i04.

[20] D. Gushchina et al., "Temperature and precipitation extremes in temperate and boreal forests," *Climate*, vol. 11, 206, 2023, Available: doi: 10.3390/cli11100206.

[21] J. Liu et al., "Precipitation extremes influence patterns and partitioning of evapotranspiration and transpiration in a deciduous boreal larch forest," *Agric. For. Meteorol*., vol. 287, 107936, 2020, Available: doi: 10.1016/j.agrformet.2020.107936.

[22] C. Dulamsuren et al., "Water relations and photosynthetic performance in Larix sibirica growing in the forest-steppe ecotone of northern Mongolia," *Tree Physiol*., vol. 29, no. 1, pp. 99–110, 2009, Available: doi: 10.1093/treephys/tpn008.

[23] N. Davi et al., "Is eastern Mongolia drying? A long-term perspective of a multidecadal trend," *Water Resource Res*., vol. 49, no. 1, pp.151–158, 2013, Available: doi: 10.1029/2012WR011834.

[24] T. Hiyama et al., "Recent interdecadal changes in the interannual variability of precipitation and

atmospheric circulation over northern Eurasia," *Environ. Res. Lett.*, vol. 11, 065001, 2016, Available: doi: 10.1088/1748-9326/11/6/065001.