Effects of nitrogen deposition on the carbon budget and water stress in Central Asia under climate change (Postprint)

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Tg C and slightly decreased water stress in Central Asia. Findings of this study will expand both our understanding and predictive capacity of C characteristics under future increases in N deposition, and also serve as a valuable reference for decision-making regarding water resources management and climate change mitigation in arid and semi-arid areas globally.

Full Text

Preamble

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Effects of Nitrogen Deposition on the Carbon Budget and Water Stress in Central Asia Under Climate Change

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Abstract: Atmospheric deposition of nitrogen (N) plays a significant role in shaping the structure and functioning of various terrestrial ecosystems worldwide. However, the magnitude of N deposition on grassland ecosystems in Central Asia remains highly uncertain. In this study, a multi-data approach was adopted to analyze the distribution and amplitude of N deposition effects in Central Asia from 1979 to 2014 using a process-based denitrification-decomposition (DNDC) model. Results showed that total vegetation carbon (C) in Central Asia was 0.35 ($±0.09)PgC/aandtheaveragedwaterstressindex(WSI)was0.20(±0.02)forthewholearea.IncreasingNdeposi
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Keywords: carbon dynamics; climate change; grassland ecosystems; nitrogen deposition; water stress index

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1 Introduction

The grasslands of Central Asia play a critical role in the global carbon (C) cycle (Li et al., 2015a; Zhu et al., 2022). A variety of factors—including temperature, precipitation, carbon dioxide (CO_2) concentration, and land use change—affect the C cycle in the terrestrial biosphere, among which nitrogen (N) deposition is a key constraint on C dynamics (Lamarque et al., 2005; Liu et al., 2022). In recent decades, atmospheric N deposition has rapidly increased in global terrestrial ecosystems due to significant emissions of reactive N resulting from anthropogenic activities such as the production and utilization of N fertilizers and the combustion of fossil fuels (Li et al., 2013; Decina et al., 2020; Li et al., 2021). The potential impact of increased atmospheric N deposition on grassland C sequestration is significant, particularly in N-limited Central Asian ecosystems (Jarsjö et al., 2017; Zang et al., 2022). However, the impact of N deposition on the C cycle in this region remains uncertain.

The amount of accessible N in the soil controls both C and water cycles in terrestrial ecosystems. Primary productivity in arid and semi-arid areas is restricted by the availability of water and, to a lesser degree, by the supply of N (Serafini et al., 2019). The IPCC (Intergovernmental Panel on Climate Change) report predicts that global surface average temperature will increase by around 1.1 °C to 6.4 °C by the end of this century (Mateus et al., 2022). It is estimated that drought stress would be intensified with global warming (Kim et al., 2023). The interactive effects of N deposition will be influenced by water scarcity, as water plays a crucial role in both soil microbial activity and plant photosynthetic capacity. However, the coupling effects of N deposition and climate change on water stress remain unclear. Few studies have investigated the impacts of elevated N levels on plants' responses to water stress, and the findings have been contradictory. Specifically, some studies have reported that N deposition alleviated the detrimental effects of water stress on plants, while others observed an opposite trend (Zhou et al., 2011; Friedrich et al., 2012; Liu et al., 2016).

Different approaches have been proposed to assess the impact of atmospheric N deposition on C dynamics in forest lands, including model simulation, N fertilizer experiments, empirical correlation between C uptake and N deposition, and stoichiometric scaling methodology (van der Graaf et al., 2021; Karlsson et al., 2022; McDonough and Watmough, 2023; Walker et al., 2023). However, accurately assessing the response of grassland C sequestration to atmospheric N deposition on a large scale remains a significant challenge due to the intricate processes involved in external N uptake and allocation within natural ecosystems (Templer et al., 2012). Based on the biogeochemical cycling of C and N, Li et al. (1992) developed a process-oriented denitrification-decomposition (DNDC) model, which describes C dynamics and greenhouse gas emissions. The model is capable of predicting vegetation growth and productivity, soil C and N dynamics, C sequestration, as well as soil-borne trace gas emissions across diverse ecosystems.

Therefore, this study investigated the effects of N deposition in driving changes in C and water status in the grasslands of Central Asia. The aims of this study are: (1) to ascertain the specific impact of N deposition on C and water dynamics in diverse grasslands in Central Asia; and (2) to evaluate the combined effects of climate change and N deposition on C and water status at regional scales.

2.1 Study Area

The grasslands of Central Asia are located between 30°–50°N and 40°–105°E (Fig. 1 [Figure 1: see original paper]), and belong to a typical temperate continental climate. The significant variation in altitude within the area (–173–7347 m a.s.l.) results in distinct vertical zonation of vegetation, with grassland types ranging from desert grassland (DG) and temperate grassland (TG) to forest meadow (FM) (Han et al., 2014). The annual mean temperature in this area is recorded at 3.80 °C, while the mean annual precipitation is 1949.0 mm, with June to September contributing approximately 60.6% of the annual total precipitation. The mountainous areas in southeastern Central Asia are much wetter with an average of 500.0 mm/a (Ta et al., 2018). The mean temperature is 15.00 °C in low-latitude areas and below 0.00 °C in high-latitude areas (Mitchell and Jones, 2005). Datasets revealed a significant regional increase in surface air temperature ranging from 0.36 °C to 0.42 °C over the past 33 years (Hu et al., 2014).

2.2 DNDC Model and Data Collection

The DNDC model was originally developed for the estimation of C sequestration and N_2O emissions in agricultural ecosystems. Through long-term application (Li et al., 1992), researchers have used this model to simulate biogeochemical C cycles for almost all terrestrial ecosystems (i.e., farmlands, forest lands, wetlands, and grasslands) (Smakgahn et al., 2009; Li et al., 2012; Katayanagi et al., 2013; Guest et al., 2017; Wu et al., 2018). The model comprises six interconnected sub-models encompassing soil and climate processes, vegetation growth dynamics, decomposition mechanisms, as well as nitrification, denitrification, and fermentation processes. It is primarily driven by four fundamental ecological factors: climate conditions, soil properties, vegetation characteristics, and management practices (Li et al., 1992).

Detailed information on soil parameters—including clay fraction, textural class, drainage rate, bulk density, organic C content, pH value, and cation exchange capacity—was extracted from the Harmonized World Soil Database (https://gaez.fao.org/pages/hwsd) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009). Elevation data were derived from WorldClim (http://www.worldclim.org/download) (Hijmans et al., 2005). The spatial data were subsequently smoothed to a resolution of 40 km × 40 km. N deposition data were derived from a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the Model Inter-Comparison Study for Asia (MICS-Asia) (Li et al., 2017).

Three different long-term gridded atmospheric reanalysis datasets were used: ECMWF Re-Analysis-Interim (ERA-Interim), Modern-Era Retrospective analysis for Research and Applications (MERRA), and Climate Forecast System Reanalysis (CFSR). ERA-Interim is a global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts with a spatial resolution of about 80 km (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-interim). The dataset covers the period from 1 January 1979 and is continuously updated in near-real time, with a detailed description provided in Dee et al. (2011). MERRA was generated utilizing the Goddard Earth Observing System Data Assimilation System v.5.0 (GEOS-5), comprising the GEOS-5 atmospheric model and the Grid-point Statistical Interpolation (GSI) analysis system (Rienecker et al., 2011). The MERRA dataset is available from 1979 onwards with a resolution of 0.50° × 0.65° (https://disc.gsfc.nasa.gov/information/mission-project?title=MERRA-2). The CFSR is designed and executed as a globally comprehensive, high-resolution coupled atmosphere-ocean-land surface-sea ice system, aiming to provide the most accurate estimation of the state of these interconnected domains during the study period (https://rda.ucar.edu/datasets/ds093.0/). The CFSR global atmosphere data exhibit a spatial resolution of approximately 38 km and have been available since 1979 (Saha et al., 2014).

These datasets exhibit variations in terms of spatial and temporal resolution, available time period, and methodology employed for their derivation. To facilitate direct comparison among simulations, we standardized the datasets to a uniform spatial (40 km × 40 km) and temporal scale (daily resolution). The period of 1979-2014 was adopted as the common interval for air temperature, precipitation, and shortwave radiation serving as shared climate variables across all datasets.

2.3 Model Validation and Simulation Design

After parameterizing the DNDC model for arid grasslands, a total of 48 net primary productivity (NPP) and 6 vegetation C observations were used for model validation. Due to limited validation data availability in Central Asia, we collected data from grasslands exhibiting similar conditions to our study ecosystem from other literature sources (Anwar et al., 2006; Zhao et al., 2006, 2007; Zhang et al., 2008; Fan et al., 2009; Toderich et al., 2009; Yan, 2009; Yang et al., 2010; Zhang et al., 2012). We used R^2 to verify the accuracy of the DNDC model, which reflects the consistency between simulated and observed values.

For this study, the effects of N deposition, climate change, and grazing on C and water dynamics were evaluated through three distinct simulations. We designed two groups of management practice scenarios for this purpose: with and without N deposition. Prior to conducting various simulations, we utilized the mean values of temperature, precipitation, and N deposition rates spanning from 1979 to 2014 in conjunction with other model initial datasets for model spin-up until C and N pools achieved equilibrium.

2.4 Water Stress Index (WSI)

Leaf temperature data were utilized to calculate the WSI for both the controlled environment and field components of this study. To determine WSI, we employed the empirical method proposed by Gardner et al. (1992), consisting of the following equation: where dT is the difference between leaf temperature and ambient air temperature (°C); and the subscripts m, LL, and UL represent measured, lower limit, and upper limit temperature differences, respectively.

3.1 Validation

We conducted a comparative analysis between site simulations and observations to assess the accuracy of NPP and vegetation C estimates, which serve as indicators of ecosystem C dynamics. The R^2 values between observed and simulated NPP and vegetation C were 0.83 and 0.99, respectively (Fig. 2 [Figure 2: see original paper]). The agreement between observed and simulated values was generally satisfactory, indicating that the model is suitable for simulating the spatial and temporal variations of C dynamics in Central Asia.

Fig. 2 Validation of simulated and observed net primary productivity (NPP; a) and vegetation carbon (C; b). Shaded gray area represents the 95% confidence interval. Dashed line represents the 1:1 goodness-of-fit line.

3.2 Trends in Simulated Vegetation C and WSI

Figure 3 [Figure 3: see original paper] shows the spatial distribution of simulated annual average vegetation C during the period 1979-2014. Total vegetation C in Central Asia was 0.35 (\$±0.09)$PgC/aforthewholearea.Thehighestvegetationproductivitywasdistributedin F$
Fig. 4a), while WSI showed no upward or downward trend.

Fig. 3 Spatial distribution of vegetation C and water stress index (WSI) of grasslands in Central Asia during the period 1979-2014 under nitrogen (N) deposition simulated by Climate Forecast System Reanalysis (CFSR) (a and d), Medium-Range Weather Forecasts (ECMWF) Re-Analysis-Interim (ERA-Interim) (b and e), and Modern-Era Retrospective analysis for Research and Applications (MERRA) (c and f). The abbreviations are the same in the following figures.

Fig. 4 Trends of vegetation C (a) and WSI (c) and their values (c and d) of different types of grassland in Central Asia during the period 1979-2014 under N deposition simulated by CFSR, ERA-Interim, and MERRA. DG, desert grassland; TG, temperate grassland; FM, forest meadow. Shaded gray area in Figure 4a and c represents the 95% confidence interval and dashed line represents the fitting line. Bars are standard errors. The abbreviations are the same in the following figures.

3.3 N Effects on C Dynamics and WSI

Figures 5 and 6 show N influence on vegetation C difference and WSI variation during the period 1979-2014. During the past 36 years, increasing N deposition led to an increase in vegetation C of 65.56 (\$±83.03)$TgCattheregionalscale.Assimulatedinourexperiments, the$
Tg C in TG during the period 1979-2014. During the past 36 years, N deposition slightly decreased WSI in Central Asia. In addition, N deposition-induced decline in WSI was more apparent in TG than in other grasslands. N deposition had almost no effect on WSI in the enriched DG (Figs. 5d-f and 6b).

Fig. 5 Spatial distributions of vegetation C difference and WSI variation under N deposition simulated by CFSR (a and d), ERA-Interim (b and e), and MERRA (c and f).

Fig. 6 Vegetation C difference (a) and WSI variation (b) of different types of grassland in Central Asia during the period 1979-2014 under N deposition simulated by CFSR, ERA-Interim, and MERRA. Bars are standard errors.

3.4 Climate Change Effects on C Dynamics and WSI

We compared the effects of changing climate (without N deposition effect) on modeled C dynamics and WSI (Fig. 7 [Figure 7: see original paper]) during the period 1979-2014. All results simulated by three reanalysis datasets showed a significant increasing trend in vegetation C, ranging from 2.10 ($±0.41)$gC/(m^{\{2\}\cdot a)forCFSRto5.04(\pm0.36)gC/(m}$\{2\}$ · a) for ERA (Fig. 7a). Thus, our simulations suggested that climate change was the major driver for increased terrestrial productivity compared with N deposition. Meanwhile, no significant trend in WSI for the same period was detected.

The three types of grassland in this study showed the same trends but different extents in C and water dynamics over the last three decades. All grassland types showed an increasing trend in vegetation C (Fig. 7c); however, FM showed a more significant increasing value of 5.31 ($±0.25)$gC/(m^{\{2\}\cdot a)(R}\{2\}= 0.49), whilevalueswere2.94(\pm0.49)gC/(m^{\{2\}\cdot a)(R}\{2\}= 0.92)forTGand1.54(\pm0.02)gC/(m^{\{2\}\cdot a)(R}$\{2\}$=0.57) for DG, respectively. No significant trend in WSI for the same period was detected.

Fig. 7 Effects of climate on vegetation C (a and c) and WSI (b and d) of grasslands in Central Asia during the period 1979-2014 simulated by CFSR, ERA-Interim, and MERRA. Shaded area represents the 95% confidence interval and dashed line represents the fitting line.

4.1 N Effect on C Dynamics

Atmospheric N deposition can significantly influence the C and N cycles of terrestrial ecosystems, thereby impacting their structure and functioning. In recent years, numerous experimental studies have been conducted globally to simulate N deposition effects in various ecosystems (Stevens et al., 2011; Kinugasa et al., 2012; Zhang et al., 2023). Previous research has highlighted the crucial role of N as a limiting factor for grassland growth (Li et al., 2015b; Stevens et al., 2015). However, it is worth noting that in arid and semi-arid areas where vegetation growth is primarily constrained by precipitation, the contribution of N has often been overlooked. Lu et al. (2016) illustrated in their research that increased N deposition raised NPP by 9.60 g C/(m^2 · a) on average, accounting for around 92.20 Tg C/a of the national total. In Europe, the average NPP under N deposition was 5.00-75.00 g C/g N (de Vries et al., 2009). In China, the average NPP under N deposition in grasslands was 25.00 g C/g N in the early 21st century (Lu et al., 2012). Our study indicated that N deposition led to an increase of 65.56 ($±$83.03) Tg C in the grasslands of Central Asia. The substantial increase in vegetation C can be attributed to enhanced photosynthesis resulting from the rise in plant N with N addition (Kinugasa et al., 2012). Zhu et al. (2021) also observed that N input in arid and semi-arid grasslands could stimulate root growth for improved nutrient and water uptake. Considering the prevalence of widespread N limitation in Central Asian grasslands as indicated by experimental and monitoring studies, our modeled C sequestration under N deposition further supported the hypothesis of N limitation in this area, although with moderate magnitude diminishing over time.

In terms of N deposition-induced C sequestration, our simulations and other field investigations (Wang et al., 2021) suggest that grasslands serve as a stronger C sink. While there are limited indications of N saturation in our simulations, determining the threshold for N saturation is crucial across different types of grassland ecosystems.

4.2 C-Water Dynamics in Different Types of Grassland

The results showed different trends in C and water dynamics under N deposition over the past 36 years. Different climate zones and soil characteristics associated with each grassland type affect their trends. Our study indicated that different grassland types responded variably to N deposition. In detail, N deposition had positive effects on DG productivity, which was consistent with the findings of Li (2021). DG was modeled to exhibit a higher degree of N limitation on vegetation C compared with other grassland types, which is consistent with empirical observations and modeling results. Kinugasa et al. (2012) imply that increased N deposition can enhance grassland recovery after a drought even in arid areas like the Mongolian Steppe. This greater productivity might be attributed to plants enhancing photorespiration under drought conditions, which stimulates malate production in chloroplasts and generates reductants for nitrate assimilation, making them particularly adept at utilizing soil nitrate as a source of N (Eisenhut et al., 2019).

Notably, the effects of N dynamics were negative in TG; it was uncertain whether this was due to compensation by other process settings in the model or because the system had reached N saturation. The negative effects of N deposition on species richness in temperate grasslands in China have been widely observed (Fang et al., 2012), as well as decreased belowground biomass with N addition. One probable explanation is that N addition increased plant growth, which will increase the rate of water loss from plants and result in drier conditions, causing drought in the long term.

4.3 WSI Under N Deposition

Water and N are two primary limiting factors across many ecosystems (Kamran et al., 2022). It has been suggested that applying N should only be done in areas with sufficient plant-available water since its uptake depends on soil and plant water status (Tilling et al., 2007). In numerous studies, researchers have demonstrated that adequate N nutrition can enhance plant drought resistance and effectively improve water relations when growing under dry soil conditions (Dang et al., 2006; Adamtey et al., 2010). Lin et al. (2012) found no significant effect of N fertilization on crop WSI under different soil drought treatments, which aligns with our findings. In the fields of agriculture and forestry, WSI is extensively utilized for irrigation scheduling and N fertilization (Emekli et al., 2007); yet, our findings suggested that the calculation of N and water should be different, depending on different ecosystems.

4.4 Uncertainty

In this study, we used three sets of climate data to partially correct the uncertainty of parameters; however, due to time constraints on the data, our analysis is limited to the situation prior to 2015. Simulations driven by different climate datasets yielded different NPP results, and when compared with field observations, the simulation ability of different meteorological datasets varied in different areas (Smakgahn et al., 2009; Gaillard et al., 2018). The model structure represents another significant source of uncertainty. We have not considered grasslands reclaimed for farmlands and other land use and land cover (LULC) changes, which have been estimated to result in substantial C emissions (Chang et al., 2022; Feng et al., 2023), especially in TG where the anthropogenic influence was more obvious. Interactions among the N cycle, deposition, and anthropogenic effects have primarily shown a net loss of C from ecosystems, potentially offsetting the effects of N deposition alone. In addition, LULC changes can modify the properties of N deposition by altering ground surface features and reactive N emissions (Lu et al., 2016). Furthermore, this model also lacks other essential elements like phosphorus.

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5 Conclusions

This study analyzed the effects of N deposition on C and water dynamics in the grasslands of Central Asia. Results showed that total vegetation C in Central Asia was 0.35 (\$±0.09)$PgC/afortheholearea.IncreasingNdepositionledtoanincreaseinvegetationCof$65.56 Tg C and slightly decreased WSI in Central Asia. Our findings have significant implications for how N deposition affects the C balance in arid and semi-arid areas. Moreover, there were differences in water and nutrient conditions among different grassland types, which resulted in inconsistent responses of productivity to N deposition. N deposition had positive effects on desert grasslands, while it had negative effects on temperate grasslands. In addition, the interactions of nutrient and C cycles and the extent to which N is limited are key to understanding water use efficiency and making reliable predictions under future climate change. Models should further be rigorously tested with relevant parameters, particularly in the integration of fluxes and pools of C and N, as well as phosphorus.

Conflict of 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.

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Author Contributions

Conceptualization: HAN Qifei, LI Chaofan; Methodology: HAN Qifei; Formal analysis: HAN Qifei, XU Wei; Writing—original draft preparation: HAN Qifei, XU Wei; Writing—review and editing: HAN Qifei; Funding acquisition: HAN Qifei, LI Chaofan. All authors approved the manuscript.

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Note: Figure translations are in progress. See original paper for figures.