

Drought will constrain ongoing increase in net ecosystem productivity under future climate warming over alpine grasslands on the Qinghai-Tibetan Plateau, China

Chan Zuo^{a,b}, Junbang Wang^{a,*}, Xiujuan Zhang^b, Hui Ye^c, Shaoqiang Wang^a, Alan E. Watson^d, Yingnian Li^e, Xinquan Zhao^{e,f}

^a National Ecosystem Science Data Center, Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

^b College of Horticulture and Gardening, Yangtze University, Jingzhou 434023, China

^c School of Tourism and Geography, Jiujiang University, Jiujiang 332005, China

^d USDA Forest Service, Rocky Mountain Research Station, Missoula, MT 59801, USA

^e Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining 810008, China

^f State Key Laboratory of Plateau Ecology and Agriculture, Qinghai University, Xining 810016, China

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ABSTRACT

The alpine grasslands of the Qinghai-Tibetan Plateau play an important role in multiple ecosystem functions, all of which are key in regulating regional climate influences and providing pristine headwaters for millions of people downstream from this basin. Alpine grasslands act as a carbon sink, storing carbon dioxide and keeping heat-trapping greenhouse gases out of the atmosphere, but it is not clear how this will change in a warming climate in the future. In this paper, the net ecosystem productivity (NEP) of alpine grasslands in Qinghai province, on the Qinghai-Tibetan Plateau, was predicted for the period from 2010 to 2099. Trends and stability were analyzed under two climate scenarios, Representative Concentration Pathway 4.5 (RCP4.5) and 8.5 (RCP8.5) representing the lower and higher emission scenarios for greenhouse gases. The results suggest that grasslands will continue to contribute as a carbon sink, with a positive NEP through this century. Almost the same magnitude (38 Tg C a^{-1} , $1 \text{ Tg} = 10^{12} \text{ g}$) of contribution was projected under both scenarios. Grasslands are projected to be the major contributor to NEP in Qinghai province, with more than 89% of NEP in the future. The carbon sink function will increase over more than 69% of the grasslands and peak around 2069 (RCP4.5) or 2066 (RCP8.5). Then the carbon sink function will begin to decrease and it will decrease more quickly and become more variable under the RCP8.5 than the RCP4.5. The impacts of temperature and precipitation changes were analyzed and NEP was found to be more sensitive to temperature than precipitation change. The trend of increasing contribution to NEP is driven by a warming climate, while the stability of NEP is mainly influenced by the precipitation, which results in an upward trend before the peak and a decline due to stresses from limits in available water in a continued warming climate.

1. Introduction

Net Ecosystem Productivity (NEP) is the difference between net primary productivity (NPP) and soil heterotrophic respiration (R_H), representing the net photosynthetic carbon entering ecosystems from the atmosphere (Tang et al., 2021; Yu, 2014). NEP plays a critical role in the global carbon cycle as an important and intuitive indicator of the carbon source or sink function of ecosystems (Cao and Woodward,

1998a; Cao and Woodward, 1998b; Lin et al., 2017; Menefee et al., 2020; Rodda et al., 2021; Song et al., 2020). Two completely different biological processes, vegetation photosynthesis and soil respiration, respond differently to global climate change, which will lead to significantly different phasing and regional variations in NEP (Chu et al., 2019; Guo et al., 2021; Keenan and Williams, 2018; Song, 2019; Wang et al., 2018a). It is widely acknowledged that the productivity of terrestrial ecosystems will change significantly in response to a changing

* Corresponding author at: A11, Datun Road, Chaoyang District, Beijing 100101, China.

E-mail address: jbwang@igsrr.ac.cn (J. Wang).

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climate (Bispo et al., 2017; Ellsworth et al., 2017; Hadden and Grelle, 2016), although many uncertainties about its changes in spatiotemporal patterns and response mechanisms remain (Sasai, 2016; Yu, 2020).

The Qinghai-Tibetan Plateau (QTP), within the Qinghai Province of northwest China, is an important region with its many ecosystem service functions. One important function is regulation, acting as a carbon sink by absorbing atmospheric carbon to mitigate the effects of a changing climate (Han et al., 2022; Liu et al., 2022). A great deal of research has been conducted to understand the carbon process of grasslands due to the particular vulnerability and sensitivity of alpine ecosystems to climate change (Ganjurjav et al., 2018; Leng et al., 2020; Tharammal et al., 2019; Xue et al., 2015; Yang et al., 2022). The carbon sink contribution of the QTP has been estimated by different studies based on different models (Chen et al., 2022; Wu et al., 2022; Zhuang et al., 2010). Accurately modelling and predicting the spatial and temporal dynamics of carbon in alpine ecosystems is challenging owing to the high heterogeneity of carbon fluxes in spatial and temporal scales as well as substantial uncertainty for carbon cycling in climate predictions for the future.

Previous studies have shown that vegetation productivity will increase with global warming in the future (Gang et al., 2015; Huang et al., 2021; Sakalli et al., 2017; Sun and Mu, 2018; Zhu et al., 2018). However, some studies suggest that net terrestrial carbon uptake will decline in the 21st century due to accelerating decomposition of soil organic matter due to water scarcity, extreme climatic events, and land use change, among other changes (Ciais et al., 2005; Schimel et al., 2015; Seidl et al., 2017; Yu and Piao, 2014). In recent years, many studies have been conducted on carbon exchange and its environmental control factors under climate change scenarios of the Representative Concentration Pathway (RCP) to stabilize radiative forcing at 2.6, 4.5, 6.0 and 8.5 W m⁻² by 2100, which are abbreviated as RCP2.6, RCP4.5, RCP6.0 and RCP8.5, respectively. Wei et al. (2021a) concluded that the NEP would increase to 178.1 and 317.9 Tg C a⁻¹ under RCP2.6 and RCP8.5 until the 2090 s in QTP. Jin et al. (2015) found that NEP will continually increase from the near neutral state to around 40 Tg C a⁻¹ under all RCPs except RCP8.5, for the period 1979–2100. Wang et al. (2020) found that QTP will change from a carbon sink to a carbon source under continuous climate warming conditions by the end of the 21st century. Carbon dynamics of alpine ecosystems and its spatial distribution remains uncertain, as well as influence of climate change in the extended future (Shang et al., 2016). The stability of carbon sink mechanisms in terrestrial ecosystems have become an important issue to be explored in the field of carbon cycling (Piao et al., 2019a), while relevant studies are currently insufficient and mostly focused at large scales (Marcos et al., 2023; Wang et al., 2023a). Therefore, quantifying and projecting the trend and stability of NEP over alpine grassland ecosystems for the future is crucial for decisions on environmental protection and restoration, which will contribute to fully utilizing the advantages of ecological resources on the QTP and achieving the target of carbon neutrality in China.

Many methods have been developed and applied to explore NEP and its changes. The methods include ecosystem process models (Piao et al., 2022; Yan et al., 2015), field-based biomass inventory approach (Pan et al., 2011), atmospheric inversion methods (Peylin, 2013; Wang et al., 2021a), and up-scaling of flux observation data based on machine learning (Jung et al., 2017; Yao et al., 2018). But few methods can be used to project changes in the future. As the only approach to project future change of NEP, ecosystem process models were well developed and improved continually. As one of the ecosystem process models, Carbon Exchanges in the Vegetation-Soil-Atmosphere system model (CEVSA), was developed to simulate the carbon cycle, constrained by hydrology and energy processes of global terrestrial ecosystems (Cao and Woodward, 1998a; Cao and Woodward, 1998b). The model has been improved in terms of simulation of the uptake rate for nitrogen (N) and its effects on the photosynthesis and its allocation, and soil carbon decomposition (Gu, 2006; Gu et al., 2017a; Gu et al., 2010). The model

was validated and calibrated by a large number of observations during its development (Gu, 2007; Zhang et al., 2022), by which the uncertainty of the simulation results were greatly reduced. The new version, CEVSA-RS used in this study, was further improved from its early version to simulate both actual carbon exchange by remote sensing-based leaf area index (LAI) data and potential carbon exchange by simulated LAI driven by climate data (Wang et al., 2021b). Though the method on the climate-based LAI was applied to estimate NEP in this study, the CEVSA-RS showed its potential to explore and quantify Gross Primary Productivity (GPP) changes and factors of influence, such as climate change and human activity (Wang et al., 2021b; Yang, 2019). The model was validated and evaluated by flux observations and the modeled GPP can explain the 58%–94% of seasonal variations in observed GPP. The modeled GPP showed better consistency, however, with a remote sensing-based GPP product (MYD17A2H) of MODIS (Wang et al., 2021b). The new version was found to be more accurate in estimating carbon exchange and has been applied to quantify the future spatiotemporal change of carbon uptake quantified by net primary productivity (NPP) for Chinese terrestrial ecosystems in a previous study (Chen et al., 2023).

The CEVSA-RS model, therefore, was applied to predict NEP under future climate scenarios from 2010 to 2099 for the alpine areas of the QTP in Qinghai province, in this study. The RCP4.5 and RCP8.5, as two contrasting scenarios representing, respectively, the medium carbon emissions scenario with insignificant shift in social, economic and technological trends from historical patterns, and the higher carbon emissions scenario with a very high level of greenhouse gas emission in the future, were considered in NEP predictions. The primary objectives of this study are to (1) predict the annual mean NEP and analyze the magnitude, trend, and stability of the carbon sink function under future climate change projections, and (2) explore the impact of climate on the carbon sink function of alpine ecosystems. The overall purpose is to provide a foundation for formulation of relevant policies to enhance the carbon sequestration capacity of these ecosystems, in a way that will contribute to the strategic goal of attaining carbon neutrality by 2060, as advocated by the Chinese government (Yang et al., 2022; Yu et al., 2022b).

2. Materials and methods

2.1. Study area

The hinterland of the QTP, Qinghai province, is expected to be a fragile and sensitive region to climate change. Its geographical location is between 89°25′–103°04′E longitude and 31°40′–39°19′N latitude (Fig. 1). As the headwaters of the Yangtze, Yellow and Lancang Rivers, the region is an essential biodiversity conservation area and ecological security barrier in China (Liu and Zeng, 2021). The topography is characterized as high elevation in the western, northern and southern regions and lower elevations in the east and middle regions, with the average elevation across all regions above 3000 m. The annual cumulative precipitation is 387 mm a⁻¹ in the study region, ranging spatially from 40 mm a⁻¹ in its northwest to 880 mm a⁻¹ in its southeast region. The annual mean temperature is −1.3 °C a⁻¹, varying from −15 °C a⁻¹ in the northwest region of Qinghai province to 9 °C a⁻¹ in its southeastern region. The vegetation can be classified broadly as evergreen coniferous forests, deciduous broad-leaved forests, alpine shrub, alpine meadows, alpine grasslands, alpine deserts, and temperate grasslands. Grasslands (including alpine and temperate) is the major land cover, extending across more than 91% of all vegetated land in the study region.

2.2. The CEVSA-RS model

In this study, the CEVSA-RS model (Fig. 2) was applied to simulate NEP using a recently improved form of its earlier version (Cao and Woodward, 1998a; Cao and Woodward, 1998b; Wang et al., 2021b). In

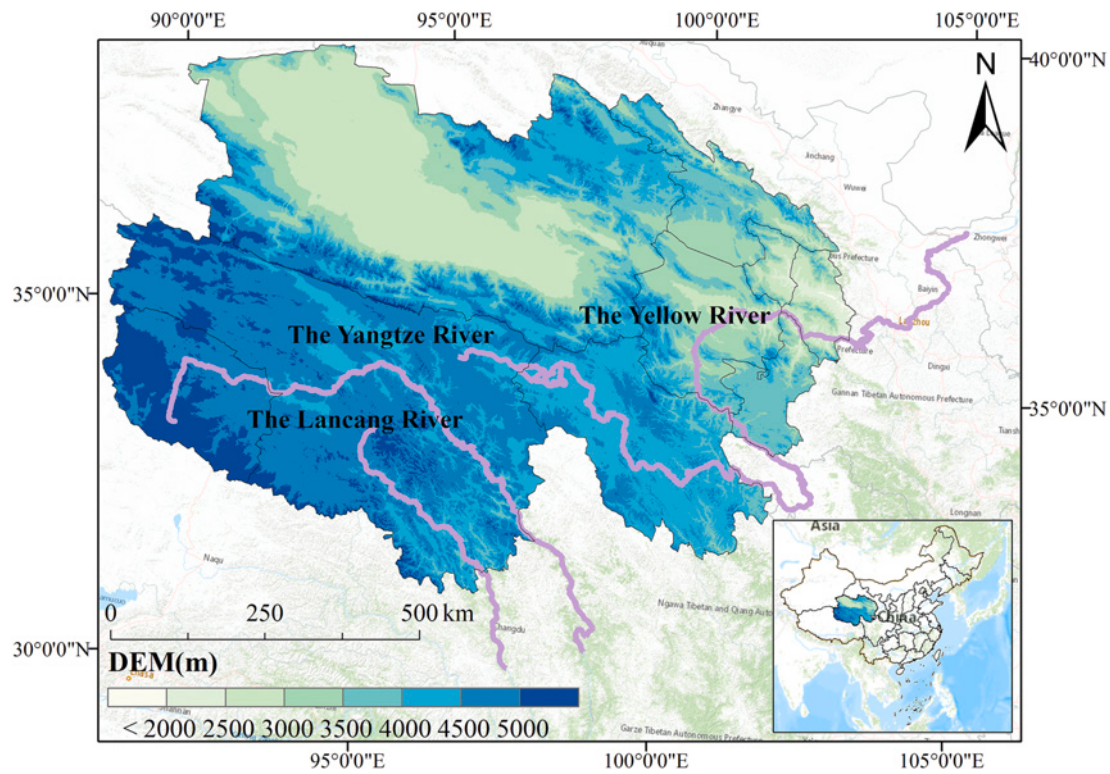


Fig. 1. The geographic location of Qinghai province.

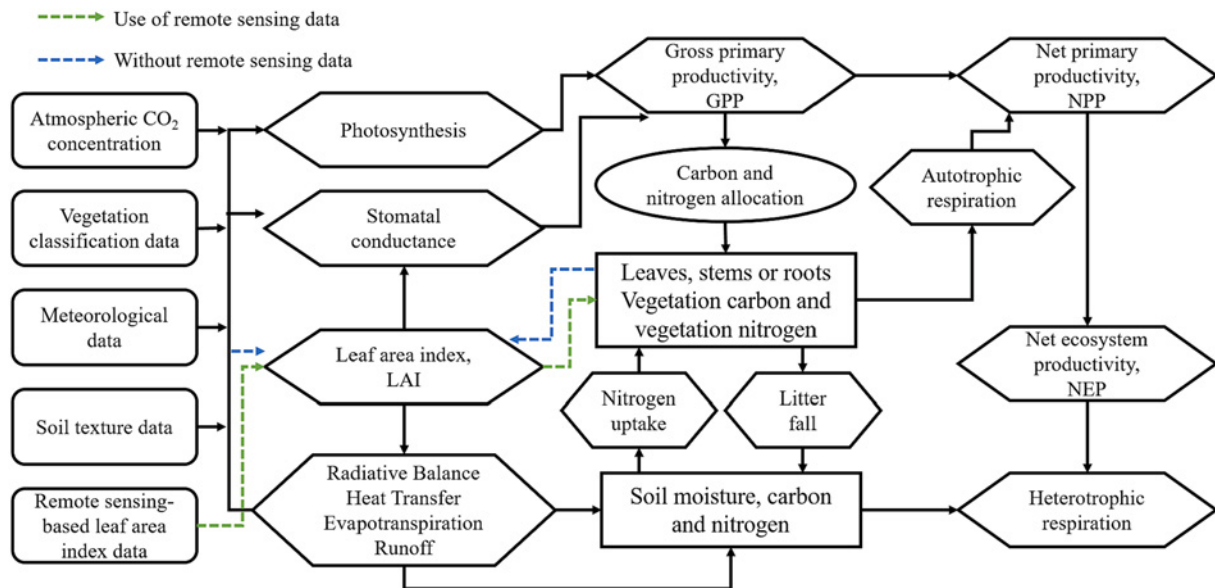


Fig. 2. The basic framework structure of the CEVSA-RS model.

its early version, photosynthesis, stomatal conductance, respiration, N uptake and evapotranspiration are taken into account to determine NPP and Leaf Area Index (Cao and Woodward, 1998b; Cao et al., 2002). It was further improved on the estimations of the nitrogen uptake rate and its effects on photosynthesis, autotrophic respiration, carbon allocation, and soil organic carbon decomposition (Gu, 2006; Gu et al., 2016; Gu et al., 2017a; Gu et al., 2010). The new CEVSA-RS model, Fig. 2, can simulate both actual carbon exchange by remote sensing-based leaf area index (LAI) data and potential carbon exchange by simulated LAI driven by climate data (Wang et al., 2021b).

The LAI was simulated using climate data and the absorbed carbon

was allocated to leaf and specific leaf area (Cao and Woodward, 1998b). Specifically, the absorbed carbon by photosynthesis is allocated among vegetative organs and could be expressed as the annual amount of NPP (g C m^{-2}) allocated to leaves (C_L), stems (C_S) and roots (C_R) as

$$\text{NPP} = C_L + C_S + C_R \quad (1)$$

where C_L is calculated as follows:

$$C_L = \frac{\text{LAI}}{S} \quad (2)$$

where LAI is leaf area index ($\text{m}^2 \text{m}^{-2}$), and S is the specific leaf area ($\text{m}^2 \text{g}^{-1}$). For grasses, the carbon allocation between leaves, stems, and roots was estimated with a fractional parameter, where alpine grasses accounted for 10%, 20%, and 70% for leaves, stems, and roots, respectively (Cao and Woodward, 1998a; Cao and Woodward, 1998b).

In this version of the CEVSA-RS model, remote sensing-based LAI was applied to replace the simulated LAI in order to quantify the spatial heterogeneity within the same vegetation type and capture actual vegetation growth status (Wang et al., 2021b). The model has been validated and evaluated with flux observations in grasslands, as well as forest and cropland ecosystems, explaining between 58% and 94% of the seasonal variation in GPP observations, while performance demonstrates better consistency with the remote sensing product of MODIS (MYD17A2H) (Wang et al., 2021b; Yang, 2019). In this study, the model simulated LAI used to project NEP is driven by climate scenarios data from 2010 to 2099.

2.3. Data source and processing

In this study, the CEVSA-RS model applied climate scenario data as model inputs and vegetation classification data as model auxiliary data to predict the future NEP of alpine grasslands of the QTP in Qinghai Province. Based on climate scenario data, the annual scale data of the aridity index and vapor pressure deficit under different climate scenarios were calculated, which were used to analyze the NEP of alpine grasslands in this area of Qinghai Province in response to climate change.

2.3.1. Climate scenario data

The climate scenario data used in this study are derived from future climate projections of China, based on the latest regional climate model (RegCM4.6) from 2007 to 2099, published by the National Qinghai-Tibetan Plateau Scientific Data Centre (Pan and Zhang, 2019). Pan et al. (2020) confirmed that RegCM4.6 not only simulates the temperature, precipitation, and climate extremes in Northwest China well, but also provides finer climate information in complex terrain compared to the Met Office Hadley Centre Earth System (HadGEM2-ES) global climate model.

The climate scenario data include four different representative concentration pathways for the emission of greenhouse gases based on variations in radiative forcing (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). Among these, the RCP2.6 scenario, referring to the peak of radiative forcing by 2100, is the strictest carbon emission scenario and an ideal climate scenario in the future (Chen and Lin, 2010; Lu et al., 2022). Additionally, considering the relatively high levels of aerosol emissions in China (Wang et al., 2018b), the level of radiative forcing published in the Coupled Model Intercomparison Project Phase 5 (CMIP5) have rarely been as low as the RCP 2.6 scenarios (He and Tong, 2022; Lu et al., 2022). Therefore, the RCP 2.6 scenario which has relatively low possibility of occurrence, was not considered in this study. The RCP4.5 and RCP6.0, known as the balanced development model of greenhouse gas emissions and the economy, without social-economic development significantly shifting from historical patterns, are priority development models (Chen et al., 2023; Chu et al., 2017), but the RCP 6.0 scenario is mostly used for benchmarking scenarios without climate policy (IPCC, 2014). On the contrary, the RCP8.5 scenario is the highest impact scenario in which human activities result in temperature gas concentrations without the implementation of effective climate change mitigation measures (Zhang et al., 2019). It is the worst possible climate state that human beings may face in the future, and can be used as a worst case scenario for climate change (Zhang et al., 2019). Therefore, this study only considered the RCP4.5 and RCP8.5 scenarios for simulation and analysis, aiming to reveal the changes and contribution to the response to climate change in the alpine grasslands of the QTP under the stable development scenario and the worst case scenario, respectively. The climate scenario data were processed from raw data with a spatial

resolution of 0.25° and temporal resolution of 3 h for model input with a spatial resolution of 0.1° and temporal resolution of 10 days. The data include precipitation (Fig. S1a), temperature (Fig. S1b), cloud cover fraction and air humidity.

2.3.2. Vegetation classification data

The vegetation classification data were derived from a fused database on the MODIS land cover product (MCD12Q1) and China Land Use/Cover Dataset (CLUDs), previously applied to estimate NPP over Chinese terrestrial ecosystems (Wang et al., 2017a). MCD12Q1 has the same vegetation classification scheme as the CEVSA-RS model but with lower data accuracy. Meanwhile, the CLUDs data are based on Landsat data with a spatial resolution of 30 m and a higher accuracy but a different classification scheme as the MODIS product (Liu et al., 2014). The fused data solved the two problems with the classification scheme and the accuracy of the two datasets used in this study.

2.3.3. Aridity index

The Aridity index (AI), based on temperature and precipitation was developed by deMartonne (1926) and is a relatively simple index (Meng et al., 2004). The Aridity index is suitable for research and application at a large-scale, with the advantages of simple calculation, easy understanding, and strong correspondence to water change with vegetation growth (Meng et al., 2004). The calculation formula is as follows (Sun et al., 2019; Sun et al., 2018).

$$AI_i = \frac{P_i}{T_i + 10} \quad (3)$$

where AI_i is the aridity index for year i , P_i is the annual total precipitation in year i (mm) and T_i is the annual mean air temperature in year i ($^\circ\text{C}$).

2.3.4. Vapor pressure deficit

Vapor Pressure Deficit (VPD) is the difference between the saturation vapor pressure and the actual vapor pressure, indicating the level of dryness of the air (Alduchov and Eskridge, 1996; Yuan et al., 2021). The saturation vapor pressure is a function of temperature and can be calculated directly from temperature by the empirical formula of Tetens (Wang, 2022a; Allen, 1998), while the actual vapor pressure is calculated from the relative humidity of the air. The formula is as follows (Liu et al., 2005).

$$VPD_i = 6.112 * e^{\left(\frac{17.67T_i}{T_i + 243.5}\right)} (1 - HUM_i) \quad (4)$$

where VPD_i is the saturation vapor pressure deficit (hPa) in year i , T_i is the annual mean temperature ($^\circ\text{C}$) in year i and HUM_i is the relative humidity of the air (%) in year i .

2.4. Analysis methods

2.4.1. Stability analysis

The stability is the inverse of the coefficient of variation. The stability of NEP for different scenarios in the future is quantified in this study. The stability is calculated with the following formula.

$$S = \frac{\mu}{\sigma} \quad (5)$$

where S is the stability of the series data, the σ and μ respectively are the standard deviation and the mean of time series data. If S is higher, it means that the distribution of the time series data is more centralized over time and the system has stable fluctuation. Conversely, if S is lower, the system is less stable (Chen et al., 2023).

2.4.2. Moving window analysis

Moving window analysis was used to explore stability changes in the

NEP time series under different climate scenarios in this study. Generally, the moving window is used specifically to study the non-stationary sequences data, reflecting maximally the characteristic information of the original data while reducing local variability (Gonzalez-Hidalgo et al., 2018; Song et al., 2022). Window sizes of 11 and 15 years were determined by test of varying window sizes, which will capture the changes of stability in NEP well.

2.4.3. Climate influence analysis

The random forest algorithm (RF) was applied to diagnose the climate variables' influence and contribution to NEP changes. The RF, proposed by Breiman in 2001, is a machine learning algorithm that integrates multiple decision trees through the idea of integration learning to be mainly applied in classification and regression (Breiman, 2001). It was assumed that the method can solve the problem of multi-collinearity in multivariate regression by considering interactions and non-linear relationships between predictors (Belgiu and Drăguț, 2016; Yin et al., 2021). The algorithm provides a feature selection tool to identify the importance of predictors with important variables having greater impact on prediction results of the model (Liu et al., 2021a), which is used to quantify the variables' contribution to the prediction. Here the annual mean temperature, annual cumulative precipitation, aridity index and vapor pressure deficit were applied as predictors to diagnose and explore the response of NEP to future climate change scenarios. A method to control variables was applied to explore the dominant climate variable driving carbon sinks; one variable was controlled without changes but others with changes in the random forest algorithm.

3. Result

3.1. The magnitude of NEP and its spatial distribution

The overall ecosystem of Qinghai Province will act as a carbon sink for a long time, according to the modeled NEP for the study region, during the period from 2010 to 2099 (Fig. 3). The annual regional NEP will be approximately $89 \text{ g C m}^{-2} \text{ a}^{-1}$ (38 Tg C a^{-1}) for the period 2010 to 2099 under two different climate change scenarios. The NEP calculations suggest higher carbon sink contributions over the east and south of Qinghai Province due to hydrothermal conditions, while western Qinghai Province is projected to have only half the NEP of the eastern and southern areas (Fig. 3 and Figure S2). The grasslands will contribute more than 89% of the carbon sink function capacity for the whole region, much more than the croplands or woodlands in the region and in each sub-region (Table S1).

3.2. Interannual trend of NEP

The annual mean NEP is projected to have an increasing trend under

both climate scenarios over most of the study region during the period from 2010 to 2099 (Fig. 4). The regional total NEP will increase at a rate of $1.4 \text{ Tg C } 10\text{a}^{-1}$ and $1.7 \text{ Tg C } 10\text{a}^{-1}$ under the RCP4.5 and RCP8.5 scenarios, respectively (Fig. 5). More than 69% of Qinghai Province, mainly in the southern region will have an increasing NEP. There will be significant decreases in NEP, mainly in the urbanized areas of eastern and western regions. However, the interannual NEP projections show a single-peak mode that initially increases but reaches a peak around 2069 (RCP4.5) or 2066 (RCP8.5) then a decline (Fig. 5).

The NEP will decrease more quickly for these grasslands and they will probably become a carbon source earlier under RCP8.5 than under the RCP4.5 scenario. The trend, from linear regression analysis, will be $4.6 \text{ Tg C } 10\text{a}^{-1}$ and $-1.54 \text{ Tg C } 10\text{a}^{-1}$ for the period before and after the peak under the RCP8.5, which will quickly increase by a rate of 1.4 times but more quickly decrease by a rate of 4.7 times than the corresponding rates under the RCP4.5 scenario (Fig. 5).

3.3. Interannual stability of NEP

The stability of NEP over the Qinghai alpine grassland ecosystem is shown in Fig. 6, with both scenarios showing a high stability of 479% and 443%, respectively. The stability is higher in the southeastern region of Qinghai Province, where vegetation as a carbon sink is stable and slowly increasing in function. The western and northern regions of Qinghai, which are more vulnerable to climatic conditions, and the urbanized development areas such as the river valleys in the east, show lower stability. The spatial distribution of NEP stability under both scenarios is relatively lower for the whole region during the 2010 s–2030 s, more stabilized during the 2040 s–2060 s, concentrated in the southeast, and then declines, especially in eastern and southeastern regions of Qinghai (Figure S3). The dynamics of carbon sink over alpine grassland ecosystems in Qinghai is generally stable in the future (Table S2), with the higher stability of carbon sink function under the RCP4.5 scenario.

The interannual trend of NEP stability was calculated for the moving windows of 11 and 15 years for 2010 to 2099 (Fig. 7). The trend in NEP stability shows significant non-linear changes under both scenarios ($p < 0.01$). The turning points for the trend of the NEP stability in the two windows size of 11 and 15 years respectively were 2058 ($R^2 = 0.33$) and 2059 ($R^2 = 0.43$) under the RCP4.5 scenario, while under the RCP8.5 scenario those are 2059 ($R^2 = 0.40$) and 2057 ($R^2 = 0.42$). The stability of NEP for alpine grasslands under both scenarios indicates steady fluctuations until the 2040 s, followed by a sudden increase, and then a relatively stable state until the late 2050 s. From the early 2060 s, the stability of NEP gradually declines under the RCP4.5 scenario, while the stability of NEP under the RCP8.5 scenario increases abruptly again, decreasing abruptly in the early 2070 s and remaining stable.

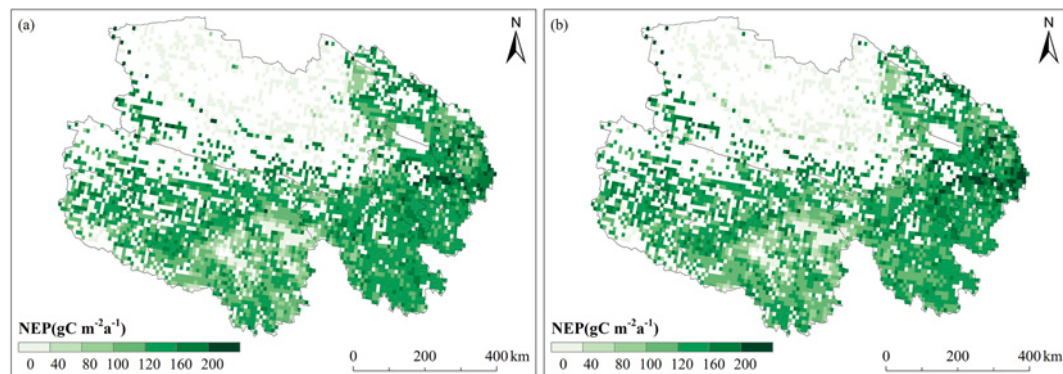


Fig. 3. Spatial distribution of multi-year average NEP in Qinghai Province under the medium (a RCP4.5) and higher (b RCP8.5) emissions scenarios from 2010 to 2099.

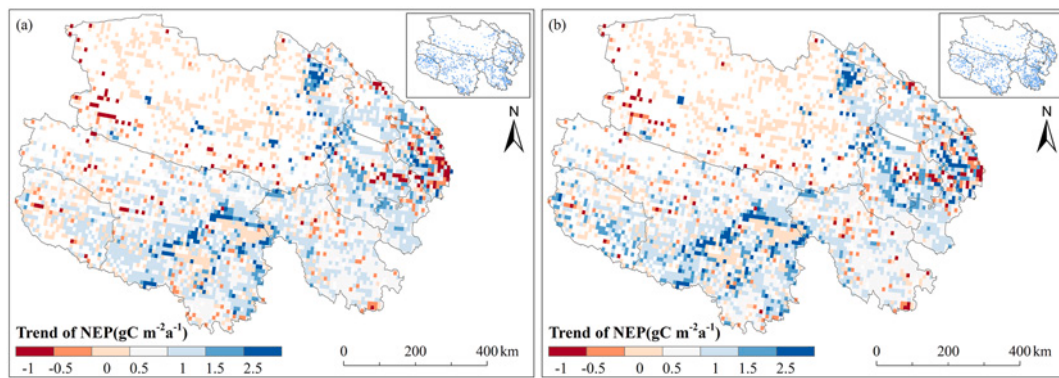


Fig. 4. Spatial distribution of interannual variability of multi-year mean NEP in Qinghai Province under the medium (a RCP4.5) and higher (b RCP8.5) emissions scenarios from 2010 to 2099 (where insets show areas with significant $P \leq 0.1$).

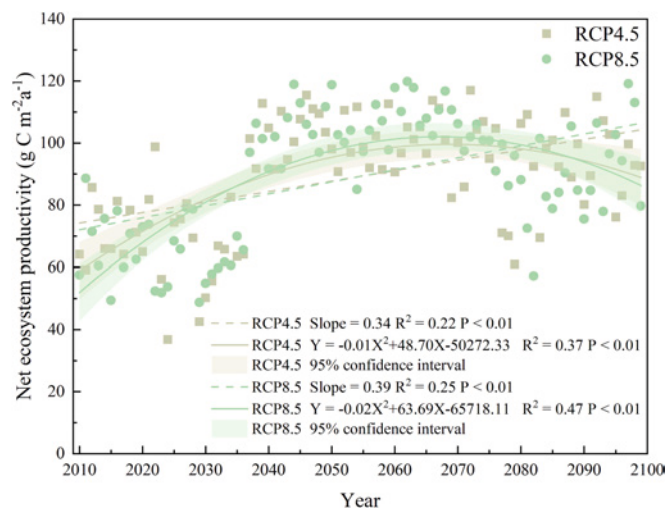


Fig. 5. Interannual and non-linear trend of multi-year average NEP in Qinghai Province under the medium (RCP4.5) and higher (RCP8.5) emissions scenarios from 2010 to 2099 (the squares and dots represent the annual averaged NEP under the RCP4.5 and RCP8.5 scenarios; the dashed and solid lines with brown are linear and nonlinear fits to the interannual variability of NEP under the RCP4.5 scenario, respectively, and the dashed and solid lines with green is the linear and nonlinear fit to the interannual variability of NEP under the RCP8.5 scenario). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. The climate impact on NEP

3.4.1. Climate change in the future

The climate is expected to become warmer and drier in the future over the study region (Table 1 and Fig. 8). The annual mean temperature will significantly increase and the rate of warming is expected to be 2.7 times higher under the RCP8.5 scenario than under the RCP4.5 scenario. Precipitation is expected to fluctuate insignificantly under both

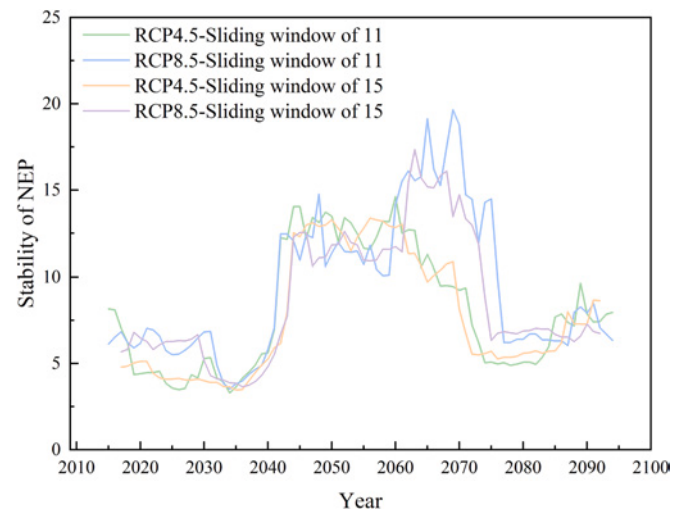


Fig. 7. Interannual trend of the stability on NEP by sliding windows in Qinghai Province under the medium (a RCP4.5) and higher (b RCP8.5) emissions scenarios.

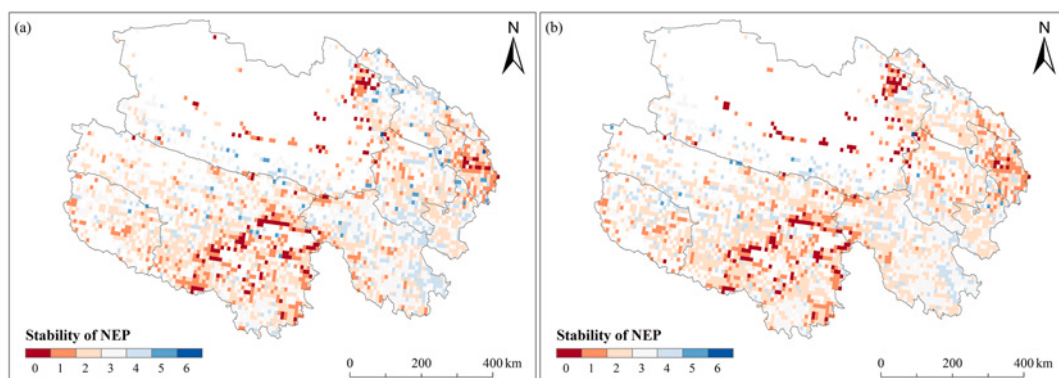


Fig. 6. Spatial distribution of the stability on NEP in Qinghai Province under the medium (a RCP4.5) and higher (b RCP8.5) emissions scenarios from 2010 to 2099.

Table 1

The statistics of climate change quantified by annual mean temperature, annual total precipitation, aridity index and vapor pressure deficit from 2010 to 2099 for Qinghai Province.

	Temperature (°C)		Precipitation (mm)		Aridity index		Vapor pressure deficit (hPa)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Mean	−3.08	−2.15	888.09	903.00	129.03	117.46	1.91	2.02
Standard deviation	0.56	1.25	48.77	62.05	12.06	16.93	0.07	0.15
Slope	0.02	0.05	0.27	1.05	−0.29	−0.54	0.002	0.005

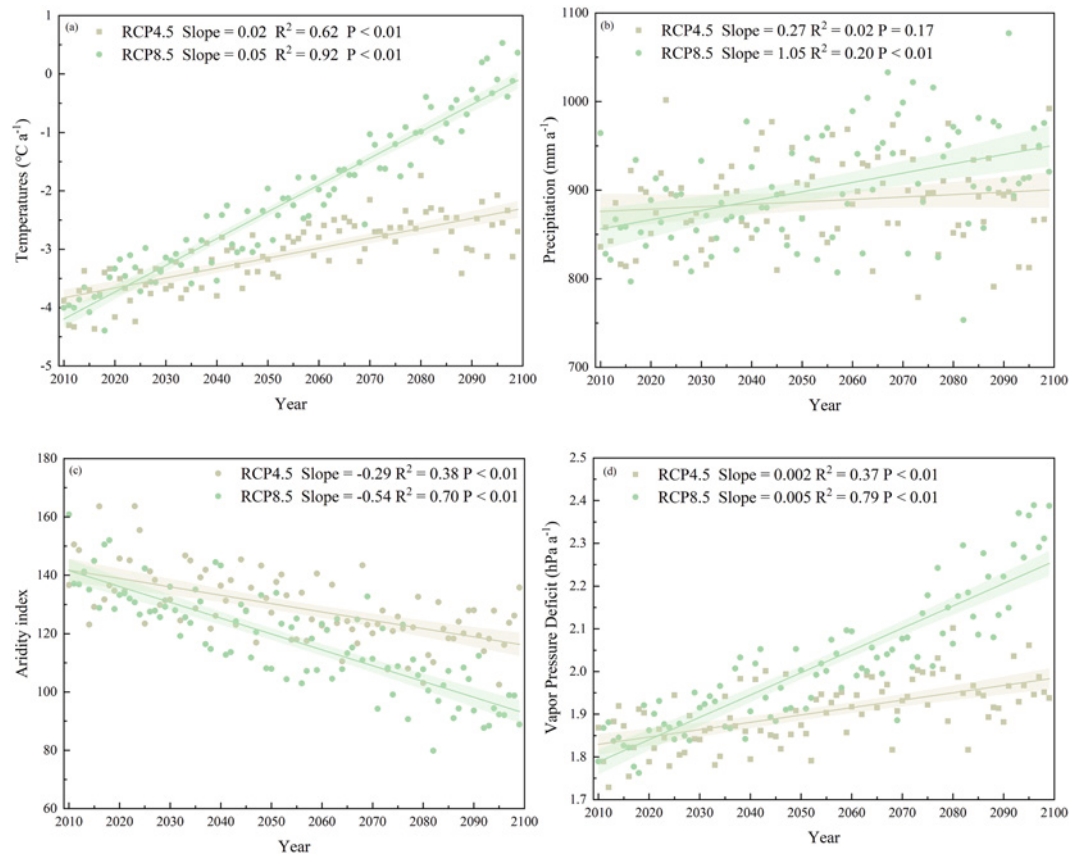


Fig. 8. Interannual trends in annual mean temperature (a), annual cumulative precipitation (b), annual mean aridity index (c), and annual mean vapor pressure deficit (d) in Qinghai Province under the medium (RCP4.5) and higher (RCP8.5) emissions scenarios from 2010 to 2099 (the brown colored squares and green colored dots respectively indicate the climate scenarios of the RCP4.5 and RCP8.5 for climate factors; the solid lines with brown and green are linear fits to the interannual variability of climate factors under the RCP4.5 and RCP8.5 scenario). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scenarios.

The aridity index (AI) and vapor pressure deficit (VPD) were applied to quantify the combined effect from temperature and precipitation changes in the future. The AI showed a significant decreasing trend under both scenarios. And under the RCP8.5 scenario, climate will more quickly dry by a decreasing rate of -0.54 a^{-1} compared to -0.29 a^{-1} under the RCP4.5 scenario, as indicated by a decreasing trend in the aridity index. Meanwhile, the VPD will increase significantly under both scenarios and the RCP8.5 scenario will produce a more quickly drying trend than that of RCP4.5. Therefore, the climate will be warmer and drier in Qinghai in the future and the RCP8.5 scenario will result in a faster drying climate than found for the RCP4.5 scenario.

3.4.2. Impacts of climate change on NEP

Warming and drying due to climate change can explain major variability in NEP over alpine grassland ecosystems in the future (Figure S4). The variability of NEP was more sensitive to temperature with

insignificant variability in precipitation (Figure S5a and Figure S6). The trend and stability of NEP were respectively attributed to the trend and stability of temperature and precipitation change through the method of variable controlling (Figure S7 and Table 2). The RF-based NEP estimations will have a trend of 0.27, 0.14 and 0.02 when both temperature and precipitation, only temperature, and only precipitation changes were input as predictors. Comparing to the trend (0.34) of CEVSA-RS-based NEP simulations, the contribution of both temperature and precipitation change will be 80.12% (RCP4.5) and 74.41% (RCP8.5), while the temperature itself will contribute 41.64% (RCP4.5) and 54.23% (RCP8.5) and is 6.3 and 5.2 times the precipitation's contribution.

The same method was used to derive the contributions of temperature and precipitation on the stability of NEP (Table 2). Both temperature and precipitation contribute 193% (RCP4.5) and 166% (RCP8.5) to the stability of NEP. Temperature itself contributes 396% (RCP4.5) and 270% (RCP8.5), while precipitation by itself contributes 715% (RCP4.5) and 823% (RCP8.5). The results mean temperature and precipitation

Table 2

Contribution of climate factors to the interannual variability of NEP in Qinghai Province from 2010 to 2009.

Scenario	Processing	Climate factors	Mean	Standard deviation	Slope	Stability of NEP	Contribution to trend (%)	Contribution to fluctuations(%)	Contribution to stability(%)
RCP4.5	The NEP simulated by CEVSA-RS		89.23	18.61	0.34	4.79			
	The NEP predicted by random forest		88.24	9.53	0.27	9.26	80.12%	51.78%	193%
	Control of precipitation	Temperature and precipitation	87.33	4.60	0.14	18.98	41.64%	25.24%	396%
	Control of temperature	Precipitation	89.82	2.62	0.02	34.28	6.62%	14.01%	715%
RCP8.5	The NEP simulated by CEVSA-RS		89.22	20.12	0.39	4.43			
	The NEP predicted by random forest		90.28	12.24	0.29	7.38	74.41%	60.12%	166%
	Control of precipitation	Temperature	89.52	7.47	0.21	11.98	54.23%	37.02%	270%
	Control of temperature	Precipitation	89.81	2.46	0.04	36.51	10.47%	12.14%	823%

changes will dominate the trend and stability of NEP in Qinghai over the rest of the century.

3.4.3. Nonlinear response of NEP to climate warming

The nonlinear responses of NEP to climate warming and an insignificant relationship with precipitation were found in Qinghai. Although NEP significantly correlates with the interannual variability in temperature (or AI, VPD), the relationship can be represented better by a quadratic equation (Fig. 9 and Fig. 10). Therefore, the threshold values, as shown in Table 3, can be determined from the quadratic equation

representing the relationship between NEP and these three climate variables. The threshold values mean that NEP increases with increasing temperature (or AI, VPD), but decreases with increasing temperature (or AI, VPD) when the temperature (or AI, VPD) exceeds threshold values. The threshold values are -1.98°C (RCP4.5) and -1.44°C (RCP8.5) for temperature in the study region, Qinghai Province. The threshold values vary and depend on region within Qinghai province, showing spatial heterogeneity (Figures S8 and S9). Its spatial distribution is consistent with that of annual mean temperature and the annual cumulative precipitation (Figure S1).

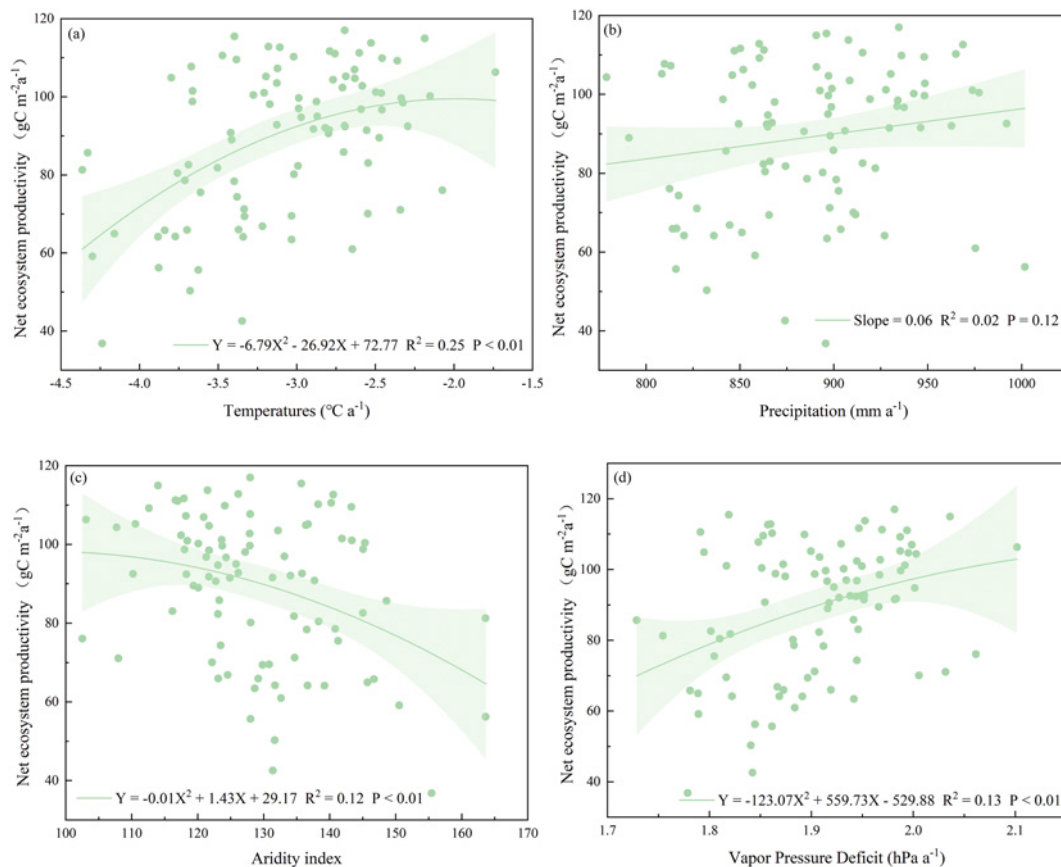


Fig. 9. Non-linear or linear correlation fit between annual mean temperature (a), annual cumulative precipitation (b), annual mean aridity index (c), annual mean vapor pressure deficit (d) and NEP in Qinghai Province under the medium emissions scenarios (RCP4.5) from 2010 to 2099 (the dots represent the annual mean of the NEP for Qinghai province under RCP4.5 scenarios).

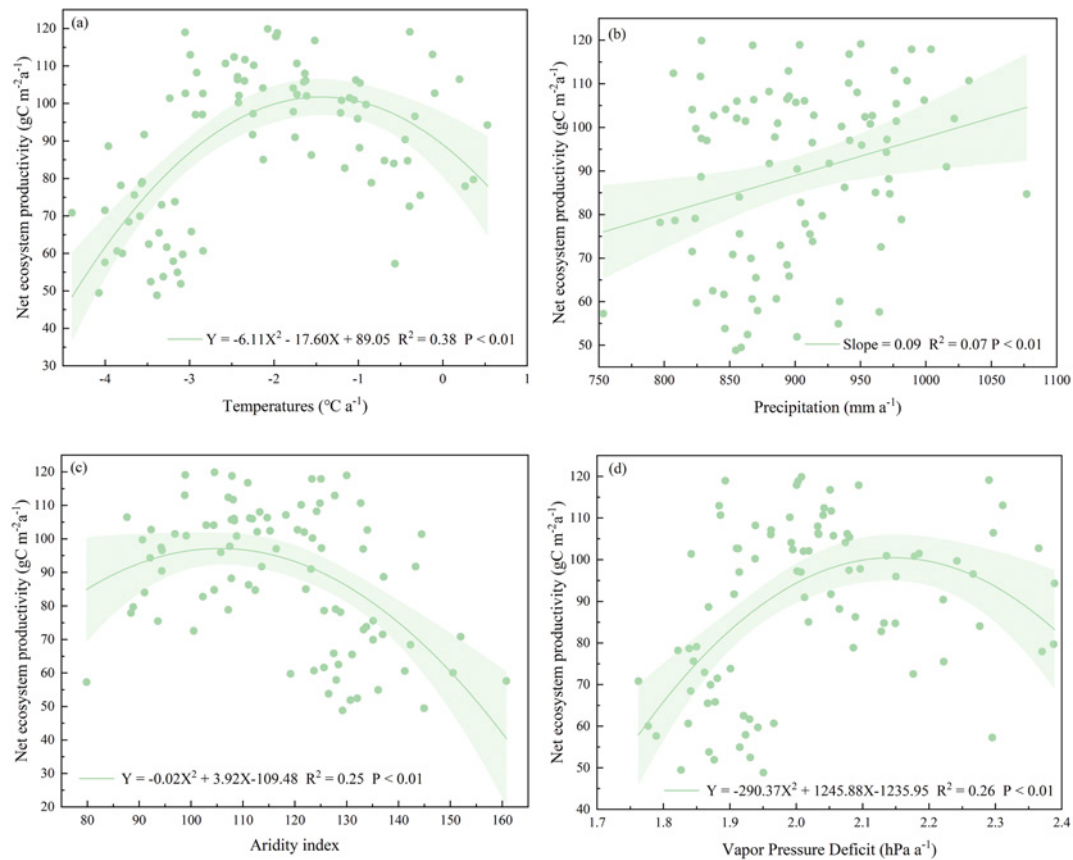


Fig. 10. Non-linear or linear correlation fit between annual mean temperature (a), annual cumulative precipitation (b), annual mean aridity index (c), annual mean vapor pressure deficit (d) and NEP in Qinghai Province under the higher emissions scenarios (RCP8.5) from 2010 to 2099 (the dots represent the annual mean of the NEP for Qinghai province under RCP8.5 scenarios).

Table 3

The threshold values of climate factors where NEP increases to the peak then declines along the gradient of climate variables for temperature, aridity index and vapor pressure deficit. The values in parentheses are 95% confidence intervals for the threshold values.

	Temperature (°C)		Aridity index		Vapor pressure deficit (hPa)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
The threshold value	-1.98(-2.07 ~ -1.90)	-1.44 (-1.53 ~ -1.35)	96.43 (93.84 ~ 99.03)	105.54 (103.90 ~ 107.18)	2.27 (2.25 ~ 2.29)	2.15 (2.13 ~ 2.16)
The peak value of NEP (g C m ⁻²)	99.46	101.72	98.26	97.14	106.56	100.48

4. Discussion

4.1. Uncertainty in NEP simulations

Understanding influences on NEP and resulting trends will be very meaningful for mitigating impacts and adapting to climate change influences in the future, especially with the background of national and global efforts to achieve net zero carbon emissions. Therefore, to predict NEP change and diagnose its response to climate change will provide a very important foundation for improving carbon sequestration capacity in fragile regions (Wang et al., 2022b; Yang et al., 2022). In this study, the region of focus will serve as an important carbon sink to the magnitude of 38 Tg C a⁻¹ (89 g C m⁻² a⁻¹) in future decades. It expected to account for 7.69%–26.67% of the total carbon sink over terrestrial ecosystems in China (Yang et al., 2022).

The NEP estimates in this study are consistent with those reported in most previous studies in terms of size. The NEP has been estimated at 16 Tg C a⁻¹ based on 40 site-year CO₂ flux data of healthy alpine grassland

ecosystems observed by eddy covariance techniques in Qinghai (Zhang et al., 2023). Previous estimates for Qinghai alpine grasslands were in the range of 16–25 Tg C a⁻¹ under RCP2.6, RCP4.5 and RCP8.5 scenarios in the future from 2006 to 2100 using the Century model (Li et al., 2020). The TEM model-based estimation was 35.8 Tg C a⁻¹ for the grasslands over the QTP (Leng et al., 2020). However, the QTP grasslands were predicted to become a carbon source only by some models (Leng et al., 2020; Tan et al., 2010).

Though these estimations are uncertain and varied in magnitude by method, the simulation in this study provides more precise estimates. Compared with other ecological process models, the physiological and ecological principles applied in this model and parameters incorporated into the computational equations involved in the simulation process were taken from a large number of field experimental observations (Gu, 2007; Zhang et al., 2022). Additionally, during the model development process, over 1600 sample plot survey data from the global and eddy flux observation data at different stations were applied for model validation and calibration, in which the carbon fluxes and carbon stocks

simulated by the model were more consistent with observed values (Cao and Woodward, 1998b; Gu et al., 2017b). Among them, the simulated value of NPP can explain 58% of the observed value, while the simulated value of soil respiration can explain 88% (Li et al., 2014), and the simulated soil carbon density was close to the observed values, better simulating the spatial variation of soil carbon density (55%) (Gu et al., 2014). In this version, the CEVSA-RS model can explain 58% to 94% of the seasonal variation in gross primary productivity of different ecosystems, while displaying performance more consistent with the remote sensing product (MYD17A2H) (Wang et al., 2021b). It suggests that the model can better simulate the magnitude, the dynamic characteristics of water carbon fluxes for different types of ecosystems, and their responses to climate change (Cao et al., 2003; Cao and Woodward, 1998b). Therefore, the results of this study with relatively high reliability and scientific validity, provide a trajectory on the trend and stability of NEP for this area under a range of future climate change scenarios.

The carbon cycle for terrestrial ecosystems is believed to be driven largely by climate along with environmental changes and human activities (Ganjurjav et al., 2018; Kato et al., 2006; Tharammal et al., 2019; Xue et al., 2015). Environmental changes could include atmospheric carbon dioxide concentration, nitrogen deposition, permafrost, and other events (Wang et al., 2017b; Wårlind et al., 2014; Wieder et al., 2015; Zimov et al., 2006). Human activities can involve grassland resource utilization by livestock grazing (Keenan and Williams, 2018; Sharma et al., 2022; Tharammal et al., 2019), land use change (Schurgers et al., 2018), and ecosystem restoration and protection measures (Fu et al., 2022; Li et al., 2021). The CEVSA model has been improved to simulate the effects of nitrogen deposition on the carbon cycle (Gu, 2006; Gu et al., 2016; Gu et al., 2017a; Gu et al., 2010). In this study, however, nitrogen and CO₂ were held constant and climate reflected interannual change to simulate the effects of climate change trends but with the lack of nitrogen deposition spatial data, as done in most carbon cycle models (Wårlind et al., 2014). However, more effort should be made in future studies to incorporate the dynamic effects from nitrogen, CO₂, land use change, and even ecosystem restoration and protection measures to reduce the simulation uncertainty in a changing environment.

4.2. Response of carbon sink to climate warming

The NEP is an important reflection of the carbon budget between carbon uptake by organic matter production through plant photosynthesis and carbon release by organic matter decomposition and ecosystem respiration, mainly including plant autotrophic and soil heterotrophic respiration. Warming temperatures promote organic matter production while also stimulating respiration in both vegetation biomass and soil organic matter, which are affected by soil water content and atmospheric humidity (Chen et al., 2016a; Chen et al., 2016b; Liang et al., 2013). Plants have higher photosynthetic rates within an optimum temperature range (Xu et al., 2009), i.e., there is a temperature threshold that affects vegetation carbon uptake. Ecosystem respiration was reported to increase with warming temperature and quantified with the temperature sensitivity (Q_{10} , the ratio of soil respiration rate for a 10 °C rise in temperature) of an average of 1.44 across the globe under a high emission trajectory (RCP 8.5) by the end of the century (Niu et al., 2021). And soil respiration rate has been found to increase with soil temperature up to a threshold value, above which the respiration rate decreases with further increases in temperature (Carey et al., 2016; Johnston et al., 2021). Therefore, the threshold of temperature and temperature-derived variables is available from this study (Figs. 9 and 10) and the effects of temperature variation on photosynthesis and ecosystem respiration can be understood (Zhang et al., 2021).

However, a precipitation threshold value was not found for NEP in this study, though it was reported that precipitation thresholds are between 750 and 950 mm for net carbon exchange in the contiguous United States (Liu et al., 2018). Increasing precipitation and

temperature were found to enhance carbon sinks, while lower temperatures and deficit precipitation may inhibit carbon sequestration (Chuai, 2018; Li et al., 2017), which could be related to the drought effect induced by increasing temperature. This could be examined more closely through the spatial pattern of the threshold points of the drought index found in this study (Figure S8 and S9). In the southern and northeastern regions of Qinghai Province, for instance, the capacity of carbon sequestration improves with increasing vegetation photosynthesis and warmer climate because there is also abundant precipitation. In contrast, the low cumulative annual precipitation and low soil moisture in the central and western parts of Qinghai have resulted in an intensification of the effects of the dry climate, which has stressed the photosynthesis of vegetation, increased the respiratory intensity of the ecosystem, and reduced the carbon sequestration capacity of grasslands, gradually moving them towards a carbon source (Wei et al., 2021b).

NEP responds differently to temperature and precipitation change, which could be explained by the asymmetrical response of ecosystem carbon uptake and release due to the combined effect of temperature and water conditions (Zhang et al., 2017). Temperature thresholds have higher values under the lowest precipitation conditions. With increasing precipitation, temperature thresholds increase from, taking an example with the RCP4.5-based NEP, -3.5 to -2.5 and 2.2 with water conditions of medium, high, and extreme higher precipitation (Figure S10). The results illustrate that warming temperatures mean more evapotranspiration and soil moisture deficits and stresses on vegetation growth (Chen et al., 2019). Therefore, warming can contribute to the carbon sequestration capacity of vegetation to some extent (Chen et al., 2012), while photosynthesis and ecosystem respiration can be affected and reduce carbon sequestration if thresholds are exceeded (Piao et al., 2019b; Shi et al., 2021).

Compared to AI, VPD was found to contribute more in determining the trend and stability of NEP changes in the future (Fig. S5b and Figure S6). Increasing VPD will enhance water stress on plant photosynthesis by reducing stomatal conductance and increasing water loss from the xylem (Ding et al., 2018; López et al., 2021; Konings et al., 2017), which in turn will result in higher evapotranspiration from terrestrial ecosystems (Dai, 2013; Grossiord et al., 2020; Huang et al., 2015), and severe drought, reducing photosynthetic rates. VPD, as an integrated effect of temperature and precipitation, would be a key predictor of the trend of carbon sink changes under a continuous warming scenario for the future.

The carbon cycle of terrestrial ecosystems involves multiple and complex processes, including carbon flux, such as GPP, NPP, NEP, and vegetation and soil organic carbon storage, which are driven by climatic conditions and change. The ecosystem carbon storage depends strongly on the carbon residence time in the ecosystem and on the carbon input from NPP (Luo et al., 2017). According to Chen et al. the NPP of alpine ecosystems in the QTP will increase rapidly in the early period and show a decreasing trend in the later period with climate warming. Ma et al. (Ma et al., 2022), also found that the trend of NPP in the QTP will gradually decrease from 2016 to 2050. Vegetation carbon storage of grassland more quickly transits to soil as indicated by root turnover time ranges, from 0.53 to 3.1 years on average across the global scale (Gill and Jackson, 2000; Wang et al., 2019), while it is faster (0.26–0.46 years) in the alpine ecosystems of the QTP (Dai et al., 2019; Li, 1998). Meanwhile, climate warming will accelerate the decomposition of soil organic carbon, with the rate of soil carbon release faster than the input from vegetation carbon, resulting in the loss of soil carbon stocks (Todd-Brown et al., 2013; Wang et al., 2023b). Therefore, in the future, the input for NPP is weakened with the continual warming climate, and the carbon input from plant production to soil would be decreased, which consequently reduces soil carbon storage, which could well explain the changes of NEP in alpine grassland ecosystems in the future in this study. However, more field experiments and long-term observation are essential to explore and verify those processes and mechanisms.

4.3. Implications and suggestions

According to the climate data used in this study, warming will continue on the Qinghai Province with insignificant changes in precipitation, which will likely lead to a warmer and drier climate, consistent with the results of previous studies (Han et al., 2019; Liu et al., 2009). Responding to climate change, the simulated NEP for alpine grasslands will reach peak carbon uptake in 2069 or 2066 and then will decline to become a carbon source in the future. Also, soil organic carbon in the permafrost of the QTP has been found to be a potential carbon source (Wang et al., 2020). A continuously warming climate could result in approximately 1.86 ± 0.49 Pg ($1 \text{ Pg} = 10^{15} \text{ g}$) or 3.80 ± 0.76 Pg of permafrost soil organic carbon thawing by 2100 under RCP4.5 and RCP8.5, respectively (Wang et al., 2020). Freezing and thawing have been found to prolong the growing season of alpine vegetation and accelerate decomposition of organic matter (Mao et al., 2015). This activity further supports our findings that alpine grasslands will likely be transformed from a carbon sink to a carbon source in the future.

To mitigate and adapt climate change, ecosystem restoration and protection measures should be implemented to enhance the ecosystem carbon storage capacity of grasslands in the QTP if we are going to achieve net zero carbon emissions targets (Bai and Cotrufo, 2022; Pan, 2021; Xu et al., 2022; Yang et al., 2022). Ecological restoration and protection measures can effectively improve the functions of carbon storage and carbon sequestration in grassland ecosystems (Yu et al., 2022a). These measures can be summarized in three aspects (Table 4):

i) Protection and restoration of natural grasslands, such as closed fencing of natural grasslands or establishing protected reserves to reduce the impact of livestock on grassland restoration. Zhao et al (2014) found that the potential for carbon sequestration in alpine grassland under fencing was approximately twice as much compared to the control treatment.

ii) Measures for increasing grassland productivity, for example, establishment of high-yield artificial grasslands to provide forage for livestock in some appropriate places. Han et al (2011) explored the effect of established artificial grassland on carbon sequestration in degraded alpine meadows on the QTP and showed an increase of 17 t hm^{-2} , demonstrating that the approach of 'preserving large areas of natural grasslands with small areas of artificial grasslands' can significantly improve grasslands overall.

iii) Management measures for livestock, such as reducing the grazing pressure on grasslands through zoned rotational grazing or free grazing. Different grazing practices and different grazing intensity vary in effect on soil carbon storage. Li (2013) compared the amount of carbon sequestered in grasslands before ($181.50 \sim 294.80 \text{ t hm}^{-2}$) and after (362.60 t hm^{-2}) grazing management in Aba Pastoral Areas of the QTP.

Therefore, a reasonable goal is to adopt appropriate ecological management measures in the future that positively influence the potential of carbon sequestration in alpine grasslands on the QTP (Liu et al., 2022; Yu et al., 2022a). Protecting, consolidating and enhancing the functions of carbon pools and carbon sinks, will effectively bring into play the advantages of ecological resources on the QTP and contribute to the achievement of the carbon neutrality target in China and the other countries in the post-Paris agreement era (Wei et al., 2020; Yu et al., 2022b).

5. Conclusion

The magnitude, trend, and stability of carbon sink contributions of grasslands in Qinghai Province were predicted and climate influences were diagnosed under alternative future climate scenarios in this study. Alpine grasslands will contribute to carbon sink capabilities at almost the same magnitude under both climate scenarios studied, with grasslands the dominant regional contributor, above 80%. However, its uptake trend will likely peak around the end of the 2060 s, followed by a decline. Compared to a "medium emissions" scenario, the carbon sink of

Table 4

Impact of ecological restoration and conservation measures in QTP.

Strategy	Specific measures	Effects	Reference
Perspectives on the protection and restoration of natural grasslands	Establishment of national park protected reserves	Enhancing grassland aboveground biomass, coverage and diversity, improving the ecosystem service function of grassland	(Zeng et al., 2023; Zhao et al., 2020)
	Closed fencing of grasslands	Increasing soil organic matter and nutrients, improving the productivity, diversity of vegetation	(Chen et al., 2021; Shang et al., 2014; Yan and Lu, 2015; Yu et al., 2019)
	Restoration of degraded grasslands	Increasing coverage and productivity of vegetation	(Hu et al., 2022; Török et al., 2021)
Perspectives on increasing yields of grass	Returning cropland back to grassland	Increasing grassland area and production	(Lu, 2018; Yu et al., 2022a)
	Establishment of perennial mixture grasslands	Increasing species diversity and above- and below-ground biomass, improving community structure and community stability	(Laubach et al., 2023; Tian et al., 2023)
	Establishment of high-yield artificial grasslands	Improving the productivity and quality of grassland	(Li et al., 2023; Ma et al., 2017; Qian et al., 2022)
Perspectives on grazing and livestock	Reasonable control of grazing intensity	Improving productivity and diversity of grasslands	(Lai et al., 2021; Liu et al., 2021b; Wu et al., 2022)
	Zoned rotational grazing/rest grazing	Increasing the height, cover and species diversity, above-ground biomass of vegetation and soil organic matter, optimization of species communities	(Lawrence et al., 2019; Li et al., 2018; Ma et al., 2016)
	Adjustment of livestock structure	Improving slaughter rates and reducing grazing pressure on winter pastures	(Shi et al., 2022; Zhao, 2010)

the alpine grasslands will be more unstable under a "high emissions" scenario with a faster rate of decline after the peak. This change may be explained by the fact that the variability of carbon sinks in alpine grassland ecosystems will be more sensitive to temperature even with insignificant variability in precipitation. Warming and drying of the climate can explain the major variability of carbon sinks in the future, with temperature and precipitation dominating the trend and stability of carbon sinks respectively. To promote the stability of carbon sinks, the restoration and protection of grassland ecosystems is needed as an effective way for the region to slow down and adapt to global warming in the future, which is also an inevitable choice to achieve the strategic goal of carbon neutrality advocated by governments worldwide in the post-Paris agreement era.

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CRediT authorship contribution statement

Chan Zuo: Methodology, Software, Writing – original draft, Writing – review & editing. **Junbang Wang:** Conceptualization, Writing – review & editing, Funding acquisition. **Xiujuan Zhang:** Writing – review & editing. **Hui Ye:** Software, Data curation. **Shaoqiang Wang:** Writing – review & editing. **Alan E. Watson:** Writing – review & editing. **Yingnian Li:** Writing – review & editing. **Xinquan Zhao:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2023.110823>.

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