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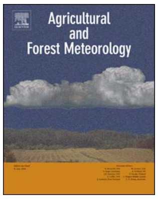

Water response of ecosystem respiration regulates future projection of net ecosystem productivity in a semiarid grassland

Lingjie Lei[a], Jianyang Xia[b,c,d,*], Xiaona Li[a,e], Kun Huang[b,c,d], Ang Zhang[a], Shiping Chen[f], Ensheng Weng[g], Yiqi Luo[h,i], Shiqiang Wan[a,**]

[a] *International Joint Research Laboratory for Global Change Ecology, College of Life Sciences, Henan University, Kaifeng, Henan 475004, China*
[b] *Research Center for Global Change and Ecological Forecasting, School of Ecological and Environmental Science, East China Normal University, Shanghai, China*
[c] *Tiantong National Station for Forest Ecosystem Research, School of Ecological and Environmental Science, East China Normal University, Shanghai, China*
[d] *Institute of Eco-Chongming (IEC), 3663 N. Zhongshan Rd., Shanghai, 200062, China*
[e] *Yunnan Academy of Biodiversity, Southwest Forestry University, China*
[f] *Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing, 100093, China*
[g] *Center for Climate Systems Research, Columbia University, New York, NY 10025, USA*
[h] *Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, AZ, USA*
[i] *Department of Earth System Science, Tsinghua University, Beijing, China*

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ABSTRACT

Recent evidences show that terrestrial biogeochemical models have large uncertainty in estimating climate-change effect on grassland net ecosystem productivity (NEP), which is defined as the difference between gross ecosystem photosynthesis (GEP) and respiration (ER). It remains unclear that whether GEP or ER limits the model capability to simulate NEP responses to climate change in semiarid grasslands. Given the surrogate CENTURY-type model is widely used for Earth system modeling, we investigated two of them (i.e., DAYCENT and TECO models) and examined which processes dominate their ability to capture the responses of NEP to experimental climate changes in a temperate steppe of northern China. During the simulation from 2006 to 2008, the two models captured the observed mean annual NEP in the control plots when they were validated by the observations from an adjacent eddy-flux tower. However, they failed to capture the treatment effects of experimental warming and increased precipitation on NEP because of the poor estimations of ER responses. DAYCENT model simulated a higher precipitation effect on ER (37.83%) and TECO model overestimated the warming effect on ER by 8.18%. The simulation of treatment effects on ER and therefore NEP can be improved by an optimized parameterization of the water-related decay functions for soil organic carbon (C). The simulated cumulative loss of total ecosystem C stock during 2010–2100 were decreased when the TECO model used experiment-fitted parameters ($0.72\,\mathrm{kg\,C\,m^{-2}}$) instead of using the initial validation with eddy-flux data ($0.96\,\mathrm{kg\,C\,m^{-2}}$). The ecosystem shifted from C sink to source at threshold of 435 mm of annual total precipitation. Our findings indicate that future projection of C cycle in semiarid grasslands could be improved by better understanding of water response of ecosystem respiratory processes.

1. Introduction

Convincing projections of terrestrial carbon (C) feedback to climate change need better understanding of the response of net ecosystem productivity (NEP) to climate change. NEP represents the balance between gross ecosystem photosynthesis (GEP) and ecosystem respiration (ER) (Oberbauer et al., 2007; Niu et al., 2008). Despite their importance, large projection uncertainties of those ecosystem CO_2 fluxes and their sensitivities to climate change still remain in current Earth system models (Arora et al., 2013; Friedlingstein et al., 2006, 2014; Jones et al., 2013). Semi-arid grassland is one large contributor to the trend and inter-annual variability of global land CO_2 sink (Ahlström et al., 2015). Thus, an improved simulation of grassland NEP and its two components is particularly important for accurately predicting global land C dynamics under future climate change.

The responses of terrestrial NEP to climate change have been

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* Corresponding author at: Research Center for Global Change and Ecological Forecasting, School of Ecological and Environmental Science, East China Normal University, Shanghai, China.
** Corresponding author.
E-mail addresses: jyxia@des.ecnu.edu.cn (J. Xia), swan@henu.edu.cn (S. Wan).

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studied by many field manipulative experiments (Wu et al., 2011; Lu et al., 2013), so results from these studies have been increasingly used to evaluate model performance on terrestrial C cycle. Some studies evaluate the model performance indirectly using the meta-analysis results of multiple experiments. For example, Piao et al. (2013) used the weighted response of multiple global-change experiments from a meta-analysis to assess the modeled response of GEP to climate change. In that study, the averaged response ratios among experiments were used to evaluate the regression coefficients derived from the time-series analysis of GEP against climate factors. This approach is useful to explore the systematic bias of the models, but is hard to tell which processes or parameters of the models could be improved. Also, the application of this approach is strongly challenged by the large difference in the spatial scale between field experiments (10^1–10^2 m^2) and global land models (0.5°–1° of latitude-longitude degree). Some recent studies have tried to use field experiments to improve model performance at the site level. One excellent example is the FACE Model-Data Synthesis (FACE-MDS) project (e.g., De Kauwe et al., 2013; Medlyn et al., 2016), which runs multiple models at different FACE experimental sites to explore the research needs for current terrestrial ecosystem models. For example, they found the models were unable to replicate the observed aboveground net primary productivity from both ambient and treatment plots in the Prairie Heating and CO_2 Enrichment (PHACE) experiment in the semiarid grassland in Wyoming, USA (De Kauwe et al., 2017). As suggested by that study, using multi-model comparisons in advance of ecosystem-scale experiments need to become normal practice in grassland. However, the ecosystem-level CO_2 fluxes (i.e., GEP and ER) are difficult to measure directly, thus it remains unclear that how their observations could improve the model performance in the semiarid grassland.

The temperate steppe in arid and semiarid regions of northern China is one of dominant grassland types on the Eurasian continent (Li et al., 2003; Niu et al., 2011). With the large diurnal temperature difference and uneven distribution of precipitation, ecosystem C cycle in this area is sensitive to climate warming and changing precipitation regimes (Christensen et al., 2004; Xia et al., 2009; Niu et al., 2011). Many ecosystem manipulative experiments have been done to investigate the response of CO_2 exchange to warming and increased precipitation in this grassland (Niu et al., 2008; Xia et al., 2009; Zhao et al., 2016). Most of them have demonstrated that soil water availability plays a predominant role in mediating ecosystem CO_2 response to climate change (Song et al., 2012; Xia and Wan, 2012; Liu et al., 2016). For example, water availability regulates the responses of ecosystem C uptake (Niu et al., 2008, 2011) and soil respiration (Liu et al., 2009) to experimental warming. In addition, previous analysis has already shown that precipitation non-linearly regulates C cycle in semiarid grassland of Inner Mongolia (Peng et al., 2013). Thus, it is important to examine which model processes can be improved and thus better predict C feedback to climate changes in this area.

In this study, we used data from a field manipulative experiment with warming and increased precipitation to evaluate the performance of two ecosystem models. The field experiment has been run since 2005 in the Mongolian Plateau and has four treatments, including control, warming, increased precipitation, and warming plus increased precipitation. DAYCENT and TECO models as the representative of CENTURY-type model have been used to simulate response of C cycle to climate change in grassland (Shi et al., 2014; Ryals et al., 2015). We force the two models with the climate conditions from different treatments, and then evaluate (1) how the models perform in simulating the observed NEP response to climate change in the experiment, and (2) whether the photosynthetic or respiratory processes limit the model estimates of NEP responses to future climate change in this region.

2. Materials and methods

2.1. Experimental description

The experiment was conducted in Duolun County, Inner Mongolia, China (42°02′ N, 116°17′ E, 1324 m). The mean annual temperature is 2.1 °C, with monthly average temperature ranging from −17.5 °C in January to 18.9 °C in July. The mean annual precipitation is 385.5 mm, with approximately 90% occurring from May to October. The soil type is classified as Haplic Calcisols according to the FAO classification, with 62.75 ± 0.04% sand, 20.30 ± 0.01% silt, and 16.95 ± 0.01% clay. This typical temperate steppe is dominated by *Stipa krylovii*, *Artemisia frigida*, *Potentilla acaulis*, *Cleistogenes squarrosa*, *Allium bidentatum*, and *Agropyron cristatum*.

The field experiment used a nested design with increased precipitation as the main factor, and warming as subplot level. Thus, four treatments in the experiment were control, warming, increased precipitation, and warming plus increased precipitation with six replicates. The warming subplots were heated by infrared radiators (Kalglo Electronics Inc., Bethlehem, PA, USA). In the increased precipitation plots, 15 mm of water was supplied weekly in July and August by sprinklers. Therefore, totally 120 mm precipitation was added in each year, which was equivalent to about 30% of mean annual precipitation at the study site. The detailed experimental design has been provided by Liu et al. (2009).

ER and NEP were measured using a transparent chamber (0.5 m × 0.5 m × 0.5 m) attached to an infrared gas analyzer (IRGA; LI-6400, LiCor, Lincoln, NE, USA). The chamber was placed on the permanent square aluminum frame in each plot during measurement (Steduto et al., 2002; Huxman et al., 2004c; Niu et al., 2011; Ganjurjav et al., 2016). GEP was calculated as the sum of ER and NEP. All measurements were taken during 9:00–12:00 in the sunny morning during the growing season (from May to October). The details of the measuring method have been described in Niu et al. (2008, 2011) and Xia et al. (2009). The daily estimate of the CO_2 fluxes were derived from their relationships between hourly observations and daily averages in an adjacent experiment (Xia et al., 2009; Wan et al., 2009; Fig. A1). In this paper, NEP represented the net CO_2 exchange between ecosystem and atmosphere. The CO_2 flux from atmosphere to biosphere was defined as a positive value and from biosphere to atmosphere was defined as a negative value.

2.2. DAYCENT model

The DAYCENT model is the version of the CENTURY model with daily time step, which has been widely used for simulating ecosystem processes in grasslands and croplands (Abdalla et al., 2010; Lee et al., 2012; Chang et al., 2013; Lugato et al., 2014). The input parameters include daily climate data (e.g., precipitation, the maximum and minimum air temperature, relative humidity, solar radiation, and wind speed), site latitude and longitude, soil properties, and plant growth characteristics (Table A1). Net primary productivity (NPP) (Fig. 1a) is calculated by a function of plant potential growth rate, which is limited by solar radiation, temperature, soil water, and vegetation type. C flow is affected by many factors, such as C sources, temperature, soil water content, and soil physical properties. Decomposition rate (k) of litters or soil organic C (SOC) is calculated by a nonlinear function, which is expressed as:

$$k = d\ \xi_C\ \xi_T\ \xi_W \tag{1}$$

where d is intrinsic decomposition rate of surface or soil. ξ_C, ξ_T, and ξ_W are soil texture or litter, temperature, and water response function, respectively. ξ_T and ξ_W are calculated by:

$$\xi_T = 0.65 + 0.5\ \mathrm{atan}(0.097\ (T_s - 21.5)) \tag{2}$$