Non-climatic component provoked substantial spatiotemporal changes of carbon and water use efficiency on the Mongolian Plateau

Gang Dong\(^1\), Fangyuan Zhao\(^1\), Jiquan Chen\(^6\), Yaoqi Zhang\(^7\), Luping Qu\(^8\), Shicheng Jiang\(^9\), Batkhishig Ochirbat\(^10\), Jingyan Chen\(^2\), Xiaoping Xin\(^2\) and Changliang Shao\(^2\)

\(^1\) School of Life Science, Shanxi University, Taiyuan 030006, People's Republic of China
\(^2\) National Hulunber Grassland Ecosystem Observation and Research Station & Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, People's Republic of China
\(^3\) Institute of Loess Plateau, Shanxi University, Taiyuan 030006, People's Republic of China
\(^4\) Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, People's Republic of China
\(^5\) University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
\(^6\) Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing 48824, United States of America
\(^7\) School of Forestry and Wildlife Sciences, Auburn University, Auburn 36824, United States of America
\(^8\) Forest Post-Doctoral Station, Forest Ecology Stable Isotope Center, Forestry College, Fujian Agriculture and Forestry University, Fuzhou 350002, People's Republic of China
\(^9\) Key Laboratory of Vegetation Ecology, Ministry of Education, Northeast Normal University, Changchun 130024, People's Republic of China
\(^10\) Institute of Geography, Mongolian Academy of Sciences, Ulaanbaatar 210620, Mongolia
\(^11\) These authors contributed equally to this work
\(^12\) Author to whom any correspondence should be addressed

E-mail: shaochangliang@caas.cn

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Abstract
Understanding the joint impact of anthropologic and climatic changes on ecosystem function and dynamics is among the frontiers in global environmental change studies. Carbon and water balances are especially crucial to the sustainable ecosystem and functional returns in sensitive regions such as the Mongolian Plateau. In this study, the significance of non-climatic component (NCC) on carbon and water use efficiency (CUE and WUE) is quantified among the ecosystem types on the Mongolian Plateau. We mapped the spatial gradients of carbon/water balance and delineated the hotspots of NCC-driven CUE and WUE for 2000–2013 using gross and net primary production (GPP and NPP) and evapotranspiration (ET) products derived from the MODIS databases. Significantly higher CUE and WUE values were found in Mongolia (MG) than in Inner Mongolia (IM) due to both climatic forcing (CF) and NCC. NCC was found to dominate the changes in CUE and WUE in the steppes on the plateau by over 16% and 22%, respectively, but with spatially uneven distributions. NCC-driven WUE values were much higher than those driven by CF. The hotspots for NCC-driven CUE did not overlap with those of WUE, with CUE hotspots concentrated in the east of MG and northeast of IM; WUE hotspots were found in the central and Khangai regions of MG and eastern regions of IM. The NCC-driven CUE area in MG was from population growth and the industrial shares in gross domestic product, while the NCC-driven WUE area was due to livestock growth in MG but driven by the growth of cultivated lands in IM. In sum, we conclude that NCC provoked substantial spatiotemporal changes on carbon and water use. CF and NCC effects on carbon and water balance varied in space, by ecosystem type, and between the two political entities.
1. Introduction

Climatic changes and anthropogenic activities jointly and extensively alter the function and dynamics of social-ecological systems (SES). In recent decades there has been an increasing interest within the scientific community in the effect of non-climatic component (NCC) (e.g. land use and land cover change, management practices) on SES performance, primarily focusing on sensitive regions such as the Mongolian and Tibetan plateaus, Arctic and Boreal regions, Amazon basin, etc. As in all sensitive environments and regions, we found that escalating land degradation, wild fires, urbanization, pollution, land use for industry, etc can significantly increase the complexity in modeling direct climatic influences on landscapes and societies (Groisman et al 2017, 2018, Qi et al 2017, Chen et al 2018, Gutman et al 2020). The influence of NCC endures to exert heavy pressure on biodiversity and water, nutrient and ecosystem stability (Smith et al 2016). NCC, together with intensive climatic forcing (CF), such as extreme climate events, not only exerts pressure on ecosystems, affecting their functional returns, but also alters underlying processes such as carbon and water cycling (IPCC 2007, Liu et al 2013, Elmhagen et al 2015, Le Quéré et al 2018).

The Mongolian Plateau (MP), a major region of dryland East Asia, includes two distinct political systems: Inner Mongolia (IM) in China and Mongolia (MG) (Chen et al 2015b). These two political entities have gone through very different changes in their landscapes and societies since their separation in early 1920s (Chen et al 2015b, Gutman et al 2020). Both IM and MG have experienced massive land degradation due to higher-than-global warming trends, population increases, economic progress, heavy land-use intensity, great changes in nomadic lifestyle, booming industry and international trade (Chen et al 2013, Groisman et al 2017). Climatic extremes (e.g. drought and dzuds), urbanization and livestock changes, policy implementation, and other circumstances are thought to have contributed to the socioecological differences between IM and MG (Allington et al 2018). Today, these regions exhibit significant dissimilarity in vegetation, net primary production (NPP), biological diversity, water balance, livestock cultivation, and landscape features (John et al 2008, 2013, Fernández-Giménez et al 2012, Wang et al 2013, Park et al 2017). In Mongolia a market-driven economy replaced a planned economy since the Mongolian revolution started in 1990, which led to land and livestock privatization, changes in rangeland management, a shift from nomadism to sedentary pastoralism, expansion of the mining industry, and development of highly aggregated urban areas (Fernández-Giménez and Batbayan 2004, Fan et al 2016a, Fernández-Giménez et al 2017, Park et al 2017, John et al 2018, Xu et al 2019).

Changes in socioeconomic sectors also have exacerbated the heterogeneity of grasslands in the region through intensive grazing (John et al 2018). In contrast, large ecological restoration programs were initiated in IM (e.g. the Three North Belt and Grain for Green projects, rapid installation of roads and other infrastructure) to combat desertification and restore vegetation through land enclosure, grazing control, restoration of native grasslands in agricultural areas, and replanting of degraded lands (Chen et al 2015a). Since 1999 these actions have led to substantial greening and have mitigated desertification.

Logically, large-scale revegetation in IM and altered nomadic lifestyles in MG would directly influence ecosystem carbon stock and water balance. Indeed, the past two decades have witnessed an increasing number of scientific investigations (e.g. much research under the NEESPI and the NEFI initiatives) (Groisman et al 2017) that explore a wide range of topics regarding the influences of climatic changes, spatiotemporal changes in ecosystem productivity, livestock and herder societies (Allington et al 2017, Groisman et al 2018, Tian et al 2018, Gutman et al 2020, Zhang et al 2020). Among the remaining unknowns about ecosystems are questions such as: (1) How have carbon and water use efficiency in the grasslands been altered in space and over time? and (2) What are the contributions of CF and NCC in different types of steppes across the plateau? Answering these fundamental questions is critical to developing adaptive management plans on the plateau, as well as for modelling of carbon-water cycling for the changing climate (Allington et al 2018).

Carbon use efficiency (CUE), the ratio of NPP to GPP (gross primary production), describes the efficiency of carbon retention from photosynthesis, which varies by ecosystem and climatic conditions (Chambers et al 2004, Delucia et al 2007). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017). CUE values decline when plants consume more photosynthetic capacity than the NEESPI and the NEFI initiatives) (Groisman et al 2017).
Figure 1. Land cover, administrative boundaries and major cities (a), mean annual precipitation—MAP (b), mean annual temperature—MAT (c), elevation (d), long term changing trend of population density (PD Trend, $10^4$ person km$^{-2}$ yr$^{-1}$) (e), and long-term changing trend of livestock density trend (LD Trend, $10^6$ km$^{-2}$ yr$^{-1}$) (f) of the Mongolian Plateau during 2000–2013. Linear trend of PD and LD trend in 2000–2013 were calculated based on the governmental statistics of Inner Mongolia (at meng level) and Mongolia (at aimag level). Land cover includes: coniferous forest (FC), broadleaf forest (FB), meadow steppe (MS), typical steppe (TS), desert steppe (DS), shrubland (SH), the Gobi Desert (GOBI), sandy land (SL), cropland (CR), water (W) and Alpine meadow and tundra (AM).

Ecosystem functions are jointly regulated by CF and NCC, with NCC traditionally regarded as an ‘additional regulator’ on ecosystem-climate relationships. Yet with increasing intensity and extent of human activities, NCC is gradually recognized as having the larger influence in shaping ecosystem processes and functions (Chen et al. 2013, Liu et al. 2013, Le Quéré et al. 2018), including carbon assimilation and losses, water and nutrient use, etc. Teasing apart the contributions of CF and NCC has become a major challenge to both the scientific community and the general public (IPCC 2007, 2014).

The overall objective of this study, therefore, was to quantify the importance of these two broadly defined driving forces on CUE and WUE. We used the moderate-resolution imaging spectroradiometer (MODIS) products of annual NPP, GPP and ET and long-term meteorological observations over a 14-year period (2000–2013) to calculate annual CUE and WUE across the MP, and applied residual analysis to isolate the contributions of CF and NCC at three dominant types of steppes in IM and MG. Specifically, our study objectives were to: (1) quantify the significance of NCC on ecosystem carbon and water use efficiency, as well as their spatial and temporal variations in three grassland ecosystem types: desert steppe (DS), typical steppe (TS) and meadow steppe (MS); (2) delineate spatial hotspots of CUE and WUE during the study period; and (3) identify the major biophysical and socioeconomic variables that were responsible for the magnitude and changes of CUE and WUE. Additional attention was given to the differences between IM and MG.

2. Methods

2.1. Study area

The Mongolian Plateau (MP) is a $2.6 \times 10^6$ km$^2$ landlocked highland in east-central Asia between $37^\circ 46'$–$53^\circ 08'$ N and $87^\circ 40'$–$122^\circ 15'$ E (figure 1). The plateau is bounded by the Altai mountains in the southwest; the Tannu-Ola, Sayan and Yablonoviy Ranges in the north; the Greater Khingan mountains in the east; the Yin mountains and the Hetao Plain in the south. The average elevation of the plateau is 1285 m (a.s.l.), ascending from the Altai mountains in the east to the Khangai mountains in the west. The Gobi Desert sits in the southwest of the plateau. The MP has a mean annual temperature range of $-4.5$ °C to
8.6 °C (John et al. 2018) and mean annual precipitation from 50 mm to 400 mm (Bao et al. 2016). Steppe types on the MP are classified according to precipitation gradients into three major types: meadow steppe (MS), typical steppe (TS) and desert steppe (DS). Canopy cover declines from MS (60% ~ 90%) to TS (25% ~ 100%) and DS (10% ~ 25%) (John et al. 2018).

MG has an undeveloped economy that traditionally relies on livestock production of sheep, goat, cattle and horses, but its mining industry has boomed over the last two decades (Chen et al. 2015a, Hoffmann et al. 2016, John et al. 2018). The urban population in MG is highly concentrated in three major cities, and the entire population numbers three million (Park et al. 2017). IM has undergone rapid economic and technological development in agricultural and livestock industries since the Reform and Opening Policy was instituted in 1979, with escalated growth after China became a member of the World Trade Organization in 2001 (Chen et al. 2018).

2.2. Climate, land-use and socioeconomic data
Annual precipitation (P), temperature (T), solar radiation (Rn) and vapor pressure deficit (VPD) from state-level meteorological stations on the MP were acquired from the China Meteorological Data Service Center (CMDC) (http://data.cma.cn/) and Mongolian Meteorological Bureau from 2000–2013. These data were interpolated to the plateau level using digital elevation model (DEM) through smoothing splines (ANUSPLIN 4.1) to 1 km resolution. Land-use maps of IM and MG were acquired from the Institute of Geographic Sciences and Natural Resources Research, CAS (http://www.gscloud.cn) and the Mongolian Academy of Sciences, respectively. Due to the focus on grassland cover change, other land-use types (e.g. forests, water body, urban areas) were not included in this study. Annual population density of the plateau at 100 m resolution was acquired from the WorldPop (https://www.worldpop.org/) and then used to calculate the trend. Land-use maps from 2000–2013 were applied to identify land conversion of grassland and cropland. The annual socio-economic data of subdivisions were taken from the Inner Mongolia Statistical Yearbooks for IM and National Statistical Office (https://www.en.nso.mn), including population, livestock, cultivated areas (ha) and gross domestic product (GDP). The average industry share in GDP (2000–2013) was calculated as the average annual ratio of industry gross product to GDP in 2010 constant prices.

2.3. Satellite data
Annual NPP, GPP and ET of the MP during 2000–2013 were acquired from the MODIS portal (https://modis.gsfc.nasa.gov/data/), including MOD17A3 v055, MOD17A2 v005 and MOD16A3 v006, and resampled to 1-km resolution. The annual grass cover during the study period was represented by non-tree vegetation cover from MODIS Vegetation Continuous Fields product (VCF, MOD44B v006). Normalized Difference Vegetation Index (NDVI) from MOD13A2 v005 was averaged annually to match other data at 1-km resolution. Land-use maps were re-projected to UTM WGS-1984 at 1-km resolution. Finally, CUE and WUE were calculated by dividing annual NPP by GPP and ET, respectively.

2.4. Partitioning the non-climatic and climatic affected areas
Temperature and precipitation were considered as the primary indicators of climatic forcing on the MP because annual precipitation had shown a greater linear control on the interannual variations of dry-land ecosystem production than seasonal precipitation variation and plant phenology (Bao et al. 2019). Temperature and the warming trend are other phenomenal changes on the plateau, which have significantly increased carbon loss on the MP (Liu et al. 2018). The impacts of CF and NCC are both independent and synchronized. In this study we applied residual analysis to first remove the direct effect of CF on WUE and CUE. The remaining variations (i.e. the residuals after CF variables) are model errors, caused by random errors, anthropologic effects and human-nature interactions (i.e. NCC). In our linear modeling of carbon-water use efficiencies with climate factors (annual precipitation and temperature), the residuals around 0 are assumed to be insignificant errors that are not caused by NCC. In contrast, extreme high/low residuals are hypothesized as the results of NCC influence. In this study, residuals (δ) beyond the upper or lower quantiles of residual distribution are used to identify NCC and CF:

\[
\text{CUE} = \alpha_1 \cdot P + \beta_1 \cdot T + \delta_{\text{cue}} \tag{1}
\]

\[
\text{WUE} = \alpha_2 \cdot P + \beta_2 \cdot T + \delta_{\text{wue}} \tag{2}
\]

where P and T are annual total precipitation (mm) and annual mean temperature (°C). Specifically, for each year, areas with residuals (δ_{\text{cue}}, δ_{\text{wue}}) above the upper quartile or below the lower quartile of the entire plateau were regarded as driven by NCC, while those that fell within the 25% ~ 75% quantiles of the residuals were regarded as predictive errors and the sign of CF-dominated areas. Partial correlation coefficients of P and T with CUE and WUE were calculated to articulate explanatory power of CF and NCC on CUE and WUE across the plateau. The spatial hot-spots of CF-driven and NCC-driven CUE and WUE were delineated according to the occurrence of CF and NCC in multi-year series using ‘majority’ function in ArcGIS.

Path coefficient analysis in structural equation modeling (SEM) (Fan et al. 2016b) was applied to evaluate the influence of CF and vegetation cover on...
Figure 2. Average CUE (a) and WUE (gC kg\(^{-1}\) H\(_2\)O) (b) in 2000–2013 for meadow steppe (MS), typical steppe (TS) and desert steppe (DS) on the Mongolian Plateau.

CUE and WUE for CF-driven and NCC-dominated areas, by steppe type and between IM and MG.

3. Results

3.1. Spatiotemporal variations of CUE and WUE

CUE showed an increasing trend from east to west on the plateau (figure 2(a)). The mean ± STD of CUE in TS (0.616 ± 0.032 in MG, 0.582 ± 0.033 in IM) and DS (0.614 ± 0.036 in MG, 0.595 ± 0.030 in IM) were higher than MS (0.585 ± 0.045 in MG, 0.563 ± 0.032 in IM). The overall CUE was higher in MG (0.611 ± 0.036) than in IM (0.583 ± 0.034) during the study period. The lowest CUE on the MP was found in the MS near the Greater Khingan mountains of IM. Most steppes in MG had a CUE of >0.550 and reached 0.700 in west Khangai mountains.
Figure 3. Trends of CUE (a) and WUE (gC kg$^{-1}$ H$_2$O yr$^{-1}$) (b) in 2000–2013 for meadow steppe (MS, blue), typical steppe (TS, green) and desert steppe (DS, red). The decreasing trend is represented by light color, and increasing trend by dark color.

Steppes with increasing CUE were mostly found around Ulaanbaatar, Bulgan, Selenge, Darkhan-Uul, Tov, Khentii, Dornogovi, Dundgovi, Ovorkhangai, Arkhangai and Dornod aimags in MG, and TS in the western part of Hulunbuir in IM. Conversely, steppes at lower latitudes of the MP showed a decreasing trend of CUE, especially in IM (figure 3(a)).
WUE increased from the southeast (i.e. Xilin-gol league in IM) to the northwest (i.e. TS around the Khangai mountains) on the plateau, but there were two low-WUE zones (<0.400 gC kg$^{-1}$ H$_2$O) dotted in the DS in the eastern part of the Gobi Desert and MS around the Greater Khingan mountains (figure 2(b)). The overall WUE in MG ($0.741 \pm 0.255$ gC kg$^{-1}$ H$_2$O) was higher than that in IM ($0.561 \pm 0.133$ gC kg$^{-1}$ H$_2$O). WUE was the highest in TS ($0.762 \pm 0.262$ gC kg$^{-1}$ H$_2$O in MG, $0.566 \pm 0.135$ gC kg$^{-1}$ H$_2$O in IM), followed by MS ($0.717 \pm 0.212$ gC kg$^{-1}$ H$_2$O in MG, $0.577 \pm 0.136$ gC kg$^{-1}$ H$_2$O in IM), and DS ($0.638 \pm 0.238$ gC kg$^{-1}$ H$_2$O in MG, $0.524 \pm 0.113$ gC kg$^{-1}$ H$_2$O in IM). TS around the Khangai mountains had a relatively higher WUE value (>1.000 gC kg$^{-1}$ H$_2$O) than other steppes. TS along the Kherlen River of MG had a higher WUE than TS in the south. WUE showed an increasing trend in Dundgovi, Govi-Sumber, eastern Tov and northern Dornogovi (i.e. the geographic center of MP) and northern of Xilingol, Ulanqab, Baotou and Bayannur in IM (figure 3(b)).

3.2. Climatic and non-climatric forcing
Steppe CUE driven by NCC was found mostly in eastern MG (e.g. Dornod, Sukhbaatar, Khentii and Dornogovi aimags). Another CUE hotspot under NCC was found in the TS to the north of Ulaanbaatar (including Tov, Bulgan, Selenge, Darkhan-Uul and Khovsgol aimags). A few large patches in IM and smaller patches in the MS of the Greater Khingan mountains, as well as in the TS in the east of Xilingol league and the DS along the border of IM and MG (i.e. Baotou, Bayannur and Ordos) in the west (figure 4(a)), had NCC-driven CUE hotspots.
Table 1. Mean (STD) of annual WUE (gC kg\(^{-1}\) H\(_2\)O) and CUE driven by climatic forcing (CF) and non-climatic component (NCC) in meadow steppe (MS), typical steppe (TS) and desert steppe (DS) in Inner Mongolia (IM) and Mongolia (MG) during 2000–2013.

| Type  | IM CF     | NCC | MG CF     | NCC |
|-------|-----------|-----|-----------|-----|
| WUE   | 0.561 (0.123) | 0.592 (0.147) | 0.695 (0.194) | 0.741 (0.227) |
|       | 0.551 (0.118) | 0.582 (0.149) | 0.734 (0.251) | 0.791 (0.269) |
|       | 0.513 (0.106) | 0.535 (0.119) | 0.586 (0.205) | 0.686 (0.255) |
| CUE   | 0.563 (0.031) | 0.562 (0.034) | 0.392 (0.036) | 0.582 (0.048) |
|       | 0.585 (0.03)  | 0.580 (0.035) | 0.621 (0.027) | 0.613 (0.032) |
|       | 0.599 (0.028) | 0.593 (0.031) | 0.619 (0.033) | 0.612 (0.037) |

Figure 5. Inter-annual variability of CUE (red and pink circles) and WUE (black and grey squares) driven by climatic forcing (CF) (solid line) and non-climatic component (NCC) (dash line) in meadow steppe (MS), typical steppe (TS) and desert steppe (DS) of IM and MG during 2000–2013.

Hotspots of NCC-driven WUE were distributed largely around the Khangai mountains in western MG, which includes Uvs, Zavkhan, Khovsgol, Arkhangai, Bulgan and Tov aimags, and there appeared several such patches in Dornod aimag in the east. In IM, steppes of NCC-driven WUE were scattered in the TS of eastern Hulunbuir and the northern part of the leagues (figure 4(b)).

Areas with both CUE and WUE driven by NCC were found in only a few places on the plateau, including TS in the middle of Dornod, Khovsgol, Bulgan, Selenge aimags of MG, and around the Haila and Gen rivers in IM. Clearly, hotspots for both CUE and WUE were extensively driven by CF on the plateau, especially in MS and TS near the Gobi Desert areas of MG, and in Xilingol league and DS west of IM (figure 4(c)).

There was no significant difference between NCC-driven and CF-driven CUE despite some major differences among the three ecosystem types (i.e. higher in TS and DS than those in MS) (table 1, figure 5). NCC had an impact on CUE for 16.60% (72,222 km\(^2\)) and 16.49% (142,103 km\(^2\)) of steppes in IM and MG, respectively (table 2). CUE in IM was 0.563 ± 0.031, 0.585 ± 0.030 and 0.599 ± 0.028 for MS, TS and DS under CF, and 0.562 ± 0.034, 0.580 ± 0.035, 0.593 ± 0.031 for MS, TS and DS under NCC, respectively. CUE in MG was 0.592 ± 0.036, 0.621 ± 0.027 and 0.619 ± 0.033 for MS, TS and DS under CF, and 0.582 ± 0.048, 0.613 ± 0.032, 0.612 ± 0.037 for MS, TS and DS under NCC, respectively (table 1). WUE driven by NCC was higher than that by CF on the plateau, especially in MG (table 1, figure 5). Within any ecosystem type, much larger differences existed between CF-driven and NCC-driven WUE in MG. WUE driven by NCC in IM (0.592 ± 0.147 gC kg\(^{-1}\) H\(_2\)O, 0.582 ± 0.149 gC kg\(^{-1}\) H\(_2\)O and 0.535 ± 0.119 kg\(^{-1}\) H\(_2\)O for MS, TS and DS, respectively) and MG (0.741 ± 0.227 gC kg\(^{-1}\) H\(_2\)O, 0.791 ± 0.269 gC kg\(^{-1}\) H\(_2\)O and 0.686 ± 0.255 gC kg\(^{-1}\) H\(_2\)O for MS, TS and DS, respectively) appeared much
Table 2. Percentage of land areas that are driven by non-climatic component (NCC) on CUE and WUE in meadow steppe (MS), typical steppe (TS) and desert steppe (DS) of Inner Mongolia (IM) and Mongolia (MG).

| Type  | CUE (%) | WUE (%) | Land area (km²) |
|-------|---------|---------|-----------------|
|       | IM      | MG      | IM              | MG              |
| MS    | 24.15   | 17.67   | 22.88           | 26.11           |
| TS    | 13.77   | 16.50   | 22.30           | 27.04           |
| DS    | 13.58   | 15.25   | 22.73           | 30.05           |

Figure 6. Spatial changes in partial correlation coefficient of CUE with annual mean temperature (T) (a) and annual total precipitation (P) (b), and WUE with T (c) and P (d) on the Mongolian Plateau in 2000–2013.

3.3. Complex regulations of CUE and WUE

3.3.1. Partial correlation of CF with CUE and WUE on the plateau.

CUE in TS was positively influenced by temperature and negatively influenced by precipitation at lower latitudes of the MP (e.g. Xilingol league of IM), but negatively influenced by temperature and precipitation in the northeast of the MP (e.g. the Hulunbuir grassland of IM, and eastern part of MG) and positively affected by precipitation in the west of the MG (figures 6(a) and (b)). Precipitation had a positive effect on CUE of DS and MS (figure 6(b)). WUE of TS and DS was negatively correlated with temperature in the east of MG, and positively correlated with precipitation in the central and western parts of MG (figures 6(c) and (d)). WUE of TS was negatively correlated with precipitation in Xilingol league, IM and the southeast of MG (figure 6(d)).

3.3.2. Vegetation cover and climatic controls on CUE.

CUE was negatively influenced by precipitation in all three steppes except in MS of IM (figure 7). Precipitation had a much stronger negative influence on CUE in NCC-driven areas than in CF-driven areas in MG and in TS of IM. A positive influence of precipitation on CUE was only found in MS in IM, which was stronger in NCC-driven areas. CUE was mostly driven by the negative effect of precipitation in TS in...
Figure 7. Structural Equation Modeling (SEM) on CF-driven and NCC-driven CUE and WUE in meadow steppe (MS), typical steppe (TS) and desert steppe (DS) of IM and MG in 2000–2013. Solid black arrows and solid grey arrows indicate the significant positive and negative paths, respectively ($p < 0.05$).

IM and temperature in DS in both IM and MG. The negative effect of temperature on CUE was strongest in DS, weakest in MS and medium in TS, and it was much stronger in MG than in IM. However, CUE in MS was primarily promoted by temperature in IM, especially in CF-driven areas. Increase in vegetation cover (VCF) had a strong negative impact on CUE in CF-driven TS across the MP, but a positive effect in NCC-driven area in MS of IM.

3.3.3. Vegetation cover and climatic controls on WUE. For all the steppe types on the plateau, temperature had a substantial impact on WUE, but this was positive in IM and negative in MG. The effects of temperature on WUE were stronger in NCC-driven areas than in CF-driven MS of MG, DS of IM and TS across the plateau. Temperature had a more powerful effect on WUE in MG than in IM (figure 7). Precipitation had the strongest negative impact on NCC-driven WUE of MS in MG, and was insignificant on DS in IM and TS in both IM and MG. The positive effect of VCF was strongest for WUE in NCC areas on MS and medium in CF on TS in IM, which counteracted the negative effect of precipitation on DS in MG. Correlations of CUE and WUE were positive in most cases, and much higher in NCC-driven steppes, such as MS on the plateau and TS in IM. CUE showed an even tighter negative correlation with WUE in CF-driven TS than in NCC-driven TS in IM.

3.3.4. Grass cover and climatic controls on GPP, NPP and ET. GPP was closely associated with NDVI on the plateau, with higher correlation in MG than in IM for MS (figure 7). Temperature was negatively correlated with GPP in MS and TS of IM; precipitation was predominant to NPP on the MP. The impact of precipitation on NPP was higher than ET, except in NCC-driven steppes in MG, where precipitation had a greater impact on ET in DS. VCF had greater impact on NPP in CF-driven TS and DS than in NCC-driven areas in both IM and MG. In MG, precipitation had a larger effect on NPP in MS and TS compared to VCF's dominance in DS.

Precipitation and temperature were more tightly coupled with ET on the plateau than VCF and other climate variables. The positive effect of precipitation on ET was much larger in MG than IM for MS. ET was negatively correlated with temperature in IM and net radiation in MG, but positively affected by temperature in MG and net radiation in IM. Temperature had a much stronger relationship with vapor pressure deficit in NCC steppes than CF steppes in MG. ET in IM DS and MS was negatively influenced by precipitation on the plateau, while VCF in MS was negatively correlated with precipitation in IM.

3.4. Social-economic regulations of CUE and WUE
3.4.1. Grazing and cultivated area controls on WUE. The percentage of NCC-driven WUE grassland in each aimag increased significantly with the growth rate of livestock among MG aimags ($p < 0.05$) (figure 8(c)), albeit this relationship was not found for the mengs of IM. In MG, WUE was mostly driven by NCC in 50.46% grasslands of Khangai region (Arkhangai, Bayankhongor, Bulgan, Khovsgol)
Figure 8. Trends of population density (a), land-use change between cropland and grassland on the Mongolian Plateau (b). Changes in the percentage of NCC-driven WUE grassland (%) in subdivisions of IM and MG with livestock capita growth rate (10^3 heads per year) (c) and cultivated area growth rate (10^3 ha per year) (d). Changes in the percentage of NCC-driven CUE grassland (%) in subdivisions of IM and MG with population growth rate (persons per year) (e) and percentage of industrial gross value in GDP (%) (f). The significance level of population density trends in (a) was p < 0.01.

3.4.2. Population and industrial GDP controls on CUE. Due to the extraordinarily high population growth rate in Ulaanbaatar (45,518 persons yr⁻¹), the percentage of NCC-driven CUE grasslands in an aimag increased significantly with population growth rate in MG (p < 0.05), but this showed asymmetrical and insignificant responses in IM (figure 8(e)). The grasslands were converted to other land-use types (e.g. residency and factories) across MG (e.g. Sukhbaatar TS) (figure 8(b)). The percentage of NCC-driven grassland CUE showed a predominantly positive correlation with average industry shares in GDP among MG aimags, but was insensitive to GDP changes in IM (figure 8(f)).

4. Discussion

4.1. CUE and WUE among steppe types of the Mongolian Plateau

Grassland CUE and WUE on the plateau varied spatiotemporally among steppe types, water availability and energy input in IM and MG. This study showed higher CUE and WUE in MG than in IM.
(table 1, figure 5), indicating a more efficient carbon accumulation than respiratory loss and less water consumption in MG than in IM. Ecosystem carbon balance is generally influenced by the counteractive effects of temperature that enhance carbon uptake capacity or increase respiratory carbon loss and drought under different hydrological conditions (Niu et al. 2008, Liu et al. 2019). Here, our results on CUE in MG are in agreement with previous reports that NPP/GPP ratio was negatively correlated with temperature at global scale (Zhang et al. 2014). In the plateau, the lower annual temperature in MG, together with water vapor from the Arctic Ocean (Groisman et al. 2017), favored photosynthesis for biomass build-up because lower temperatures would considerably reduce water stress via evapotranspiration, stomatal closure and respiration in MG rangelands (Cen and Sage 2005, Dusenge et al. 2019). Overall, regulators for CUE on the plateau varied spatially with temperature that negatively affected CUE in MG and the desert steppes of IM, but precipitation reduced CUE in the typical steppes of IM (figure 7). Through examination of the relation between climate variability and CUE, it appears that elevated temperature can potentially reduce the carbon sink strength of cold ecosystems (e.g. those in MG) due to its disproportional activation of ecosystem respiration (Monson et al. 2006), whereas carbon assimilation is suppressed by water stress in the dry desert steppes. In contrast, CUE of IM typical steppes declined with increasing precipitation (figure 7)—the most dominant climate factor in semiarid ecosystems, because increases in precipitation not only promote carbon assimilation but also stimulate ecosystem respiration (i.e. more carbon loss). In this study, annual CUE during 2000–2013 on the plateau differed by steppe type and between IM and MG (table 1, figure 2(a)), though approximation of the medium-high CUE level (0.45 ~ 0.7) falls in the range of modeled CUE for grassland (0.45 to 0.75 for MP in 2000–2013) by Liu et al. (2019). In sum, NPP and GPP across the plateau were limited by drought and rainfall distribution (Bai et al. 2008, Bao et al. 2019). A more active metabolic rate and respiration in humid ecosystems (MS) than that in dry ecosystems (TS and DS) might be responsible for its lowered carbon assimilation than in TS and DS (table 1).

Higher WUE in MG than in IM is partially attributable to the overall lower ET in MG, suggesting that carbon assimilation consumes more water in IM grasslands. The long-term ET of IM and MG is 310 mm and 259 mm, respectively (Gutman et al. 2020). In Mongolia, waterlogging and replenishment from permafrost melting are frequent events; rangeland productivity is more strongly affected by low temperature than by water scarcity because of long winters and cool summers. Contrarily, water stress is more severe in relatively warmer IM, where water use has proliferated to support the increasing population, tree plantations, and agriculture (Chen et al. 2018). Currently, IM has ten times the population density and twice the livestock density of MG. A recent increase in precipitation stimulated NPP in water-limited IM and had no impact on ET in less water-restrained MG. The most obvious difference between IM and MG lies in the relation of temperature and ET (figure 7). Geographically speaking, warming in MG tends to reduce WUE because elevated temperature can greatly stimulate ET by accelerating soil evaporation from permafrost and snow melt, while photosynthesis remains restrained by the long non-growing season (Dusenge et al. 2019). In water-limited IM, the negative correlation between temperature and ET was attributed to limited water supply, high Bowen ratio and temperature in sparse vegetated dry steppes (i.e. low NPP). The decreasing portion of soil evaporation in ET with vegetation coverage and rainfall would cool the environment and elevate NPP in IM (Laurenroth and Bradford 2006, Li et al 2007, Hu et al 2008, Bao et al 2014). These findings suggest that ecosystem water availability is an important regulator to the asymmetric response of carbon and water use to climatic forcing in IM and MG.

4.2. Non-climatic effects

The positions of NCC-driven hotspots and relations with population, livestock, GDP and land-use change showed the contrasting responses of CUE and WUE to the socioeconomic conditions in IM and MG. The NCC dominated CUE over larger areas in MG (142 103 km²) than in IM (72 222 km²) but did not cause significant changes to the carbon balance (table 2, figure 4(a)). The tight relation between NCC hotspot, population growth rate and industry in MG indicated that agricultural and non-agricultural land-use change had a predominant effect on CUE as a consequence of political and economic changes. Two possible regulatory mechanisms of non-agricultural land-use change may explain how NCC impacted CUE of MG steppes. First, the grazing pressure remained too high in many soums where ecosystem carbon balance was severely altered by larger herder populations and livestock husbandry (figure 9(c)). In some regions it was relieved by shifts from nomadic lifestyle to sedentary households, immigration to urban cities, or moves to well-fertilized forest-steppe. These land-use changes in MG became a major driving force for ecosystem primary production, with the carbon balance of intensively grazed pastureland reduced. Second, land conversion of grasslands to industrial lands (i.e. mining plants) removed vegetation in eastern and central MG, such as Dornod, Sukhbaatar and Selenge (Eckert et al. 2015, John et al. 2018). Our results regarding the relationships between population growth and percentage of NCC-driven CUE areas indicate that the
rising population and demands for food had direct influences on ecosystem production. They also confirmed the dominant effect of NCC on grassland degradation and NPP decline in MG steppes (Yang et al. 2016). Contrarily, CUE of IM typical steppes appeared mostly driven by CF in 2000–2013, partially due to the grazing prohibition policies that have substantially decreased livestock density and human interferences in most pasturelands (figure 9(e)). Take Xilingol league as an example, the policy of restricting mowing and nomadism in all ecologically fragile areas made carbon-water uses more dependent on climate. From the divergent abundance of NCC hotspots, we suspect that the effectiveness of environmental protection determines the CF dominance to CUE in IM, while the strength of land and resource explorations establishes the NCC dominance to CUE in MG.

Overexploitation of pasturelands and cultivated land use changes strengthened the influence of NCC on WUE in MG and IM steppes, and weakened the control of climate changes on WUE (Huxman et al. 2004, Gang et al. 2016). The NCC affected WUE for 27.32% of steppes in MG (235 297 km$^2$), which is 2.4-fold the area of that in IM (98 134 km$^2$, 22.56% of steppes). Most NCC hotspots of WUE spanned the central and Khangai regions of MG, or were distributed along the Kherlen River and extend eastward to the Hulunbuir grasslands, where population density decreased (figure 8(a)) but the livestock growth rate was much higher than other regions (figure 1(f)). Clearly, the changes in livestock exacerbated ecosystem degradation and water crises, while increasing population immigrated into urban centers (Pederson et al. 2014, Lee and Ahn 2016). Recent
studies on grassland dynamics and land use change also confirmed the dominant role of anthropogenic influence on MG grassland degradation we found in NCC-driven WUE areas (Yang et al. 2016, Zhang et al. 2020). In the central and Khangai regions of MG, the coupling of overgrazing and arid environment aggravated vegetation degradation and soil desertification. The massive land degradation led to increased dominance of high-WUE plants and significantly higher ecosystem WUE in NCC-driven grasslands in response to the severe water shortage. In contrast, the explaining power of cultivated land change to NCC hotspot of WUE is largely attributable to strict land-use policies in IM that effectively preserved the water resources and primary productivity of grassland ecosystems by returning cultivated lands to grasslands, fencing and grazing prohibition. Correlation between the extent of NCC-driven area and growth rate of cultivated lands demonstrate the positive effect of converting croplands to grasslands on ecosystem functions in IM.

Our findings of how NCC affects ecosystem functions in contrasting socioeconomic systems of similar ecological environment elucidate the asymmetric responses of carbon-water cycling to policy shift and anthropogenic exploitation. Livestock and grassland tenure reform have a direct effect on regulating the spatial-temporal variations of vegetation coverage, water resource and carbon turnover on the Mongolian Plateau. In this study, the NCC effects on CUE and WUE were investigated, but future efforts are still needed to explore the constraints and interactions of human and climate influences on varying components of carbon and hydrologic cycles so that better management decisions could facilitate ecosystem services and sustainable socioeconomic development.

5. Conclusions

In this study, non-climatic forcing on the CUE and WUE of divergent socioeconomic systems of MG and IM were investigated by steppe type. CUE and WUE values were significantly higher in MG than in IM during 2000–2013. The opposite influences of temperature on ET (decreased ET in IM but increased ET in MG) were determined to reflect the contrasting impacts of warming on WUE. CUE values were similar between CF-driven and NCC-driven steppe, but NCC-driven WUE values were much higher than those driven by CF. Hotspots for NCC-driven CUE did not overlap with those of WUE, with CUE hotspots concentrated in the southeast of MG and WUE in the central and Khangai regions of MG. The NCC-driven CUE areas in MG were driven by population growth and the industrial shares in GDP, while the NCC-driven WUE areas were associated with livestock growth in MG and growth of cultivated lands in IM. In sum, we conclude that the NCC stimulated substantial changes in carbon and water use. CF and NCC were the key factors in both CUE and WUE but varied in space, by ecosystem type, and between the two political entities.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

Gang Dong https://orcid.org/0000-0002-9515-6643
Fangyuan Zhao https://orcid.org/0000-0002-6063-8730
Jiquan Chen https://orcid.org/0000-0003-0761-9458
Luping Qu https://orcid.org/0000-0002-2498-5065
Changliang Shao https://orcid.org/0000-0002-4968-8577

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