Three-decadal destabilization of vegetation activity on the Mongolian Plateau

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Abstract

Steppes on the Mongolian Plateau, mainly within the Republic of Mongolia and the Inner Mongolia Autonomous Region (IMAR) of China, have been subjected to widespread degradation as a result of climate change and human utilization. Field experiments and long-term observations suggest that the productivity of degraded grassland ecosystems might show greater instability, i.e. stronger interannual variation in vegetation activities, when driven by climate change. However, it remains unknown whether this hypothesized destabilization of steppe vegetation activity has occurred in the past three decades and how this destabilization has fed back to livestock production on the plateau. Herein, we define temporal instability of vegetation activity using three indicators, the start and end of the growing season as indicated by the normalized difference vegetation index (NDVI) and the mean growing-season NDVI, and examine their trends between 1983 and 2015. Our results show a significant destabilization of vegetation activity over a large proportion of the total steppe area. Compared with the IMAR, vegetation destabilization has occurred to a significantly higher extent in Mongolia. Climate warming, drying and interannual climate variability accounted for approximately 60%–80% of the vegetation destabilization. The destabilization of steppe productivity was significantly associated with the interannual variability of livestock production in Mongolia, while the interannual variability of steppe productivity and livestock production were decoupled in the IMAR. Our findings highlight the need to improve livestock production systems and conserve degraded grasslands for sustainable development in view of the destabilization of steppe productivity on the Mongolian Plateau.

1. Introduction

Grasslands cover more than a third of the terrestrial surface area of the globe and make an essential contribution to climate and food security (Lemaire et al. 2005, O’Mara 2012, Ahlström et al. 2015). Due to decades of climate change and human utilization (e.g. livestock grazing), global grassland ecosystems in arid and semi-arid regions have undergone significant degradation (Gang et al. 2014). Grassland degradation is usually characterized by a reduction in productivity, a shift in species composition and a reduction in species richness (van der Merwe and Kellner 1999, Wang and Wang 2001, Akiyama and Kawamura 2007), which can further increase the temporal instability of grassland productivity, indicated as the magnitude of interannual variation (Naeem and Li 1997, Bai et al. 2004, Tilman et al. 2006, Isbell et al. 2009, Gross et al. 2014, Donohue et al. 2016). Such an increase in vegetation instability is likely to threaten the forage supply for sustainable livestock production (Bouwman et al. 2005, Sloat et al. 2018) and amplifies the interannual variation of global carbon sinks (Ahlström et al. 2015). However, current understanding of the trends in grassland ecosystem instability and their key drivers is still lacking at both regional and global scales.
Field experiments and long-term ecological research have improved our understanding of the instability of grassland ecosystems in response to climate change (Tilman et al. 2006, Isbell et al. 2009, Gross et al. 2014, Gherardi and Sala 2015). For instance, field experiments show that the temporal instability of grassland productivity generally increases with warming and drought (Hautier et al. 2015, Ma et al. 2017, Zhang et al. 2017). Field experiments and long-term monitoring data both indicate that increased interannual variability of mean temperature and total precipitation can increase ecosystem instability, whereas the accompanying shift in species composition and plant diversity can potentially either ameliorate or enhance the negative effect of climate variability (Hallett et al. 2014, Gherardi and Sala 2015, Zhang et al. 2018, Ma et al. 2020). These findings observed at the plot scale suggest that climate change may potentially increase grassland ecosystem instability at regional and global scales.

The Mongolian Plateau steppes are a major component of the Eurasian grasslands and include a majority of Mongolia and the Inner Mongolia Autonomous Region (IMAR) of China (figure 1). These steppes have experienced widespread degradation over the past three decades (Liu et al. 2013, Hilker et al. 2014). In addition to the occurrence of intensive grazing, the Mongolian Plateau has been subjected to climate warming and drying in recent decades (Zhao et al. 2015). Using a long-term (from 1982 to 2014) field data set from steppes in the IMAR, Zhang et al. (2018) showed that climate variability decreased species richness and increased community instability. A biome-scale analysis found that along a precipitation gradient in IMAR steppes ecosystem instability decreased with mean annual precipitation (MAP) within a range below 230 mm, but increased at higher MAP (Hu et al. 2018). In Central Asia, vegetation instability decreased with higher MAP but increased with increasing mean annual temperature (MAT) (Bai et al. 2019). A global analysis has highlighted the increasing importance of interannual variability in precipitation on livestock grazing lands (Sloat et al. 2018). However, it remains unknown whether an increase in temporal instability, i.e. destabilization, of vegetation activity has occurred over time across the Mongolian Plateau. This information is essential if we are to elucidate the vegetation dynamics and guide sustainable livestock production to adapt to future climate variability.

Long-term satellite-based products, such as the normalized difference vegetation index (NDVI), make it possible to evaluate the temporal instability of vegetation activity from regional to global scales (de Keersmaecker et al. 2014, García-Palacios et al. 2018, Bai et al. 2019). Previous studies have usually employed the temporal instability of plant productivity or its proxy (Tilman 1999, Hautier et al. 2015, Zhang et al. 2017), but this indicator only reflects one dimension of vegetation activity. For instance,
temporal instability of vegetation phenology is often relevant because it may cause a mismatch in the timing of feed source supply for herbivores (Post et al 2008, Renner and Zohner 2018). To gain a better understanding of the vegetation dynamics on the Mongolian Plateau, we defined the temporal instability of vegetation activity based on three indicators, including the NDVI-indicated start of the growing season (SOS), end of the growing season (EOS) and mean growing-season NDVI (NDVI_GS). Considering that the livestock management systems and grassland conservation policies are different between Mongolia and the IMAR (Wang et al 2013, Hua and Squires 2015), we evaluated the temporal instability of vegetation activity across three steppe types in Mongolia and the IMAR separately. We further assessed the role of climate variability and climate change in driving the temporal instability of vegetation activity and the feedback of livestock production on the destabilization of vegetation activity in the two regions.

2. Materials and method

2.1. Data set
The Mongolian Plateau comprises Mongolia and the IMAR of China (figure 1). The plateau biogeographically comprises three major steppe types, i.e. meadow steppe, typical steppe and desert steppe, which spread from east to west mainly due to a decrease in annual precipitation (figure 1, table S1 (available online at stacks.iop.org/ERL/16/034049/mmedia)). Species biodiversity and primary productivity also decrease from meadow steppe to typical steppe to desert steppe (Bai et al 2008, Shen et al 2016). Across the plateau, MAT ranges from −0.04 °C to 3.28 °C and MAP ranges from 209 mm to 362 mm (figures 1(c) and (d)). Precipitation occurs predominantly during the summer (June–August) in synchrony with peak temperatures. The spatial distribution of these steppes was digitized from the Vegetation Atlas of China (1:1000 000, Editorial Committee for Vegetation Atlas of China 2001) and the Ecosystem Map of Mongolia (1:1000 000, which was authorized by Institute of Botany, Mongolia Academy of Sciences 1995), respectively.

The NOAA/AVHRR GIMMS NDVI3g archive (0.083° spatial resolution, bi-monthly frequency, spanning 1983–2015) was used to indicate vegetation activity (https://ecocast.arc.nasa.gov/data/pub/gimms/). The monthly NDVI was obtained via the maximum value composite method (Zhao et al 2015). The Savitzky and Golay smoothing filter was used to perform data filtering. Winter NDVI values were corrected using the mean NDVI between the EOS and the beginning of snow cover to reduce biases resulting from snow cover and melting (Beck et al 2006).

Monthly temperature and precipitation data (0.5° spatial resolution) were derived from the University of East Anglia Climatic Research Unit’s Time Series 3.2 data sets (CRU TS3.2, www.cru.uea.ac.uk/cru/data/) (Harris et al 2013). These CRU climate data were then compared with those from 49 meteorological stations in the IMAR (National Meteorological Information Center of the CMA, www.nmic.gov.cn) to validate the quality of the CRU data set (figure S1). Data on the annual livestock production of cattle and sheep (1983–2015) in Mongolia and the IMAR of China were derived from Food and Agriculture Organization (www.fao.org/faostat) data and the National Bureau of Statistics of China (http://data.stats.gov.cn), respectively. However, these two livestock data sets did not contain specific information for each steppe, which hindered further feedback analysis between livestock production and the destabilization of vegetation activity for each steppe type.

2.2. Quantifying the vegetation activity
NDVI data were used to quantify the three indicators that describe vegetation activities, including the SOS, EOS and mean NDVI_GS. A double logistic function was first fitted using the smoothed and snow-corrected time series NDVI data (Beck et al 2006, Fisher et al 2006). The day corresponding to the maximum (or minimum) value in the first-order derivative of the fitted curve was determined as the start (or end) of the growing season (Studer et al 2007, Busetto et al 2010). The mean NDVI_GS was calculated as the mean NDVI value between the SOS and EOS. NDVI_GS was used as a proxy of aboveground biomass productivity (Tian et al 2016, Huang et al 2017, García-Palacios et al 2018, Thenkabail 2018). These three indicators are relevant because a higher temporal instability of SOS, EOS and NDVI_GS indicates a higher risk of timing and degree of mismatch for the feed supply for grazing livestock.

2.3. Defining temporal instability
The temporal instability of vegetation activity was defined using NDVI_GS, SOS and EOS. First, the temporal instability of NDVI_GS was calculated using equation (1):

\[
TIS = \frac{SD}{Mean} \times 100\%,
\]

where TIS, SD and mean indicate the temporal instability of NDVI_GS, the standard deviation and the mean of NDVI_GS, respectively.

Second, the temporal instability of SOS and EOS was defined as their standard deviation (SD) during a certain period. To calculate the time series data set of the temporal instability of the three indicators for the period 1983–2015 we used different moving windows (e.g. 5, 7 and 9 years) and time steps (e.g. 2, 3 and 4 years), which produced consistent results for vegetation instability trends (figure S2, table S2).
2.4. Climate drivers
Previous studies have indicated that temporal instability of vegetation activity is hypothetically driven by the changing magnitude of the interannual variation of climate variables and/or stressors (e.g. climate warming and drying in semi-arid regions) that affect the resistance of vegetation to interannual climate variability (Donohue et al 2016). We defined interannual climate variability as the coefficient of temporal covariance (CV), that is the SD divided by the mean, using the same moving window (5 years) and time step (2 years) as in the calculation of vegetation instability. To avoid possible bias due to negative or near-zero values in degrees Celsius, we used temperature values in Kelvin to calculate the interannual variability of temperature. Climate warming ($T_i - T_{1983}$) was defined as the difference in temperature between the base year (1983) and year $i$. Climate drying ($P_i - P_{1983}$) was defined as the difference in precipitation between the base year and year $i$. A description of the climate variables that were used for analysis of the temporal instability of vegetation activity is provided in table S3.

2.5. Statistical analysis
Temporal trends in vegetation instability were examined by applying the Theil–Sen (TS) median slope trend analysis, which is a robust trend detection method operating on a non-parametric statistic (Theil 1992). Trends are estimated using the median values and are therefore less susceptible to noise and outliers (Neeti and Eastman 2011). The Mann–Kendall significance test was used to test the significance of the TS median slope value (de Jong et al 2011).

Mann–Kendall tau rank correlation analysis was used to examine the correlations between temporal instability of vegetation activity and temporal instability in the corresponding temperature and precipitation (a description of the variables is given in table S3) for each steppe type in the IMAR and Mongolia, respectively. We further tested the change in temporal instability of vegetation activity with climate warming and drying, respectively. Using the vegan package (https://github.com/vegandevs/vegan), we partitioned the contributions of climate variability, warming and drying to the destabilization of vegetation activity. We also used a 5-year moving window and a 2-year step to calculate the temporal variation coefficients for cattle and sheep livestock production and tested the effect of changing vegetation instability on livestock production on the Mongolian Plateau. Analyses were conducted separately for the IMAR and Mongolia due to their different livestock management strategies and grassland conservation policies. All statistical analyses were conducted in MATLAB for Windows (Version 2016b, MathWorks, Inc., USA) and ArcGIS (Version 10.3, ESRI, Inc., USA).

3. Results and discussion

3.1. Spatial variation of vegetation activity instability
Our results show that vegetation activity became increasingly unstable from the meadow steppe to the typical steppe and finally to the desert (figure 2). This spatial pattern was observed in both Mongolia and the IMAR and for all three indicators (figures 2(b), (d) and (f)). This difference among the three steppe types could be due to the higher plant diversity in the meadow steppe (Shen et al 2016, Wang et al 2019) and the lower interannual temporal variability of the corresponding precipitation conditions (table S4). A similar spatial pattern of vegetation instability was found in Central Asia, where the vegetation instability decreased with higher MAP but increased with increasing MAT (Bai et al 2019). Moreover, the SOS was the most unstable of the three indicators while the EOS was highly stable (figures 2(b), (d) and (f)). This is probably due to the stronger climate sensitivity of vegetation at the SOS (Piao et al 2006) as well as the higher interannual temporal variability of temperature at the SOS (table S4).

3.2. Three-decadal destabilization in vegetation activity
Our analysis revealed that widespread destabilization of vegetation activity has occurred on the Mongolian Plateau over the past three decades (figures 3, S3 and S4). Significant destabilization occurred in a larger percentage of area in the meadow and typical steppes than in the desert steppe (figures 3(b), (d) and (f)). This is probably attributable to the fact that the productivity of desert steppe is relatively low and already highly unstable as a result of high interannual precipitation variability (figure 2, table S4) and thus the temporal instability of desert steppe has a low potential to increase in response to the change of precipitation due to the lower vegetation coverage and plant species that are adapted to high interannual precipitation variability (Otto et al 2016, Hu et al 2018). Overall, the temporal instability of SOS and EOS increased significantly in 23% and 30%, respectively, of the total steppe area on the Mongolian Plateau (figures 3(a) and (c)). Surprisingly, a significantly larger area showed an increase (41%) in temporal instability of the NDVI$_{GS}$ (figure 3(e)). If ignoring the significance ($p$ value) of the trend analysis, destabilization of steppe vegetation activity could have occurred and/or tend to occur to a wider extent across the Mongolian Plateau (figure S3).

Compared with the IMAR, Mongolia showed a higher percentage area with vegetation destabilization across the three steppe types (figures 3(b), (d) and (e)). Specifically, the temporal
instability of SOS and EOS increased in 18% and 20% of the total steppe area in the IMAR from 1983 to 2015, whereas in Mongolia destabilization occurred in 27% (SOS) and 37% (EOS) of the steppe area (figures 3(b) and (d)). Moreover, NDVI\textsubscript{GS} indicated that significant vegetation destabilization occurred in 35% of the total steppe area in the IMAR, whereas the extent was even higher (44%) in Mongolia (figure 3(e)). The relatively lower extent of destabilization in steppe productivity in the IMAR could be attributed to the implementation of grassland conservation programs (e.g. the Returning Grazing Land to Grassland Project and the Grassland Ecological Subsidies Program) and livestock production systems which partially curb grassland degradation and lead to regional vegetation improvements (Li et al. 2012, Hua and Squires 2015).

3.3. Drivers of destabilization in vegetation activity
We first separately analyzed the correlations between the interannual variability (CV) of the climate variables (table S5) and vegetation instability for each steppe type in Mongolia and the IMAR. Mann–Kendall tau rank correlation analysis indicates that the destabilization of SOS in Mongolia is significantly associated with interannual variability of monthly mean temperature prior to the SOS, while destabilization of the EOS in Mongolia is significantly associated with interannual variability of EOS precipitation (figure 4). In addition, destabilization of NDVI\textsubscript{GS} in the meadow and typical steppes in both Mongolia and the IMAR was associated with the interannual variability of the growing-season mean temperature rather than that of precipitation (figure 4). This might be because the interannual
variability of temperature could increase interannual variability of soil moisture supply by regulating evapotranspiration (Zhang et al. 2007), thus resulting in destabilization of NDVI\textsubscript{GS} in the meadow and typical steppes. In a recent global analysis, Sloat et al. (2018) highlighted the risk of increasing interannual variability of precipitation on grassland productivity and livestock grazing. However, our analysis did not reveal any trends in the interannual variability of total precipitation during the growing season (table S5) and thus it contributed only marginally to the destabilization of steppe productivity (figure 4). Nevertheless, a significant increase of variability in interannual precipitation occurred during the late growing season and this is likely to have driven the increase in interannual variability of NDVI\textsubscript{GS} and the EOS.

Our analysis further showed that climate warming (\(\Delta T > 0\) °C) and drying (\(\Delta P < 0\) mm) were significantly associated with the destabilization of steppe productivity in both the IMAR (figures 5(a) and (b)) and Mongolia (figures 5(c) and (d)). This is consistent with the findings of field experiments which show that climate warming and drought tend to increase the temporal instability of biomass production (Hautier et al. 2015, Ma et al. 2017). Long-term field observations also show that climate change, such as a decrease in precipitation and warming, can significantly decrease plant diversity (Harrison et al. 2015, Khishigbayar et al. 2015, Herrero-Jauregui and
Oesterheld 2018) and thus increase the instability of grassland ecosystems. Compared with the interannual variability of growing-season climate variables, our analysis indicates a stronger effect of climate warming and drying on the destabilization of growing-season steppe productivity on the Mongolia Plateau (figures 4 and 5).

Based on variation partitioning, we finally quantified the contributions of interannual climate variability, warming and drying to the destabilization of vegetation activity (figure 6). Specifically, destabilization of the SOS and NDVI GS mainly resulted from interannual climate variability and warming in both the IMAR and Mongolia (figures 6(a), (b), (e) and (f)), whereas temporal destabilization of the EOS is mainly attributable to warming and drying (figures 6(c) and (d)). Experimental results indicate that a decrease in precipitation resulted in an earlier EOS (Wang et al 2020), while climate warming could further aggravate soil moisture deficiency in the late growing season.
Figure 6. Contributions of interannual climate variability, warming and drying to the destabilization of vegetation activity in the Inner Mongolia Autonomous Region (IMAR) ((a), (b), and (c)) and Mongolia ((d), (e), and (f)).

In view of the significant drying and warming during the EOS across the Mongolia Plateau (table S5), climate drivers thus explained a higher proportion of destabilization of the EOS than did SOS and NDVI_{GS} in both IMAR and Mongolia (figure 6). Overall, climate change, climate interannual variability and their interactions explained 76%, 80% and 60% of the variation observed in destabilization of the SOS, EOS and NDVI_{GS} in the IMAR, whereas their contributions (SOS 67%, EOS 88%, NDVI_{GS} 68%) were higher overall in Mongolia. These findings suggest that warming, drying and interannual climate variability have contributed substantially to the destabilization of vegetation activity on the Mongolian Plateau.

3.4. Implications for sustainable livestock production
The widespread destabilization of steppe vegetation activity may significantly affect grazing livestock production in Mongolia and the IMAR. Although the production of cattle and sheep has increased dramatically in Mongolia (figure 7(a)), the interannual variability of livestock production has also increased significantly (figure 7(b)) and shows a positive correlation with the temporal instability of steppe productivity (CV of NDVI_{GS}; figure 7(c)), indicating the significance ($R^2 = 0.53$, $p < 0.01$) of destabilization of steppe productivity for the instability of livestock production in Mongolia. This is probably attributable to the fact that mobile grazing, which is the dominant livestock management strategy in Mongolia (Wang et al. 2013), is highly sensitive to temporal variation of feed yields from natural steppes. Moreover, low standing biomass resulting from overpopulation of livestock during the growing season can further reduce the resistance of livestock production ecosystems to climate hazards (cold temperatures and heavy snow) and increase livestock mortality in the non-growing season (Nandintsetseg et al. 2018).
In turn, the economics-driven increase in livestock production and consequent overgrazing would further aggravate grassland degradation and vegetation destabilization in Mongolia, probably resulting in a positive feedback given the mobile grazing systems and lack of vegetation conservation efforts.

However, the interannual variability of livestock production in the IMAR showed no significant trend over the past three decades ($p = 0.80$; figure 7(b)) and no significant correlation with the temporal instability of steppe productivity ($p = 0.52$; figure 7(c)). The lack of correlation between the interannual variability in livestock production and the temporal instability of steppe productivity is probably due to improved livestock production systems in the IMAR as a result of the ‘household production responsibility system’, whereby pastures are contracted to individual households (Wang et al 2013). Mobile grazing has been banned since the implementation of the Returning Grazing Land to Grassland Project (Fang et al 2016, Jiang et al 2016). Food processing technology has been implemented in place of traditional grazing to intensify forage utilization efficiency and extend the storage time of animal feed (Huang et al 2016). Moreover, livestock sheds have been constructed to protect animals from extreme weather and supplementary feeding is provided for winter and spring. These measures have improved the livestock production system in the IMAR despite the increasing temporal instability of steppe productivity in recent decades. Unfortunately, the lack of spatial data on livestock grazing intensity limited a more detailed comparison of the livestock–vegetation feedbacks between Mongolia and the IMAR. Future efforts are needed to improve inventory data on grazing intensity and assess the livestock–vegetation feedbacks at finer spatial scales.

4. Conclusions

Using three metrics of NDVI-indicated surrogates, we investigated spatial–temporal patterns of vegetation instability on the Mongolian Plateau from 1983 to 2015. Our results indicate that vegetation activity has become increasingly unstable at the plateau scale over the past three decades. Climate warming, drying and interannual climate variability have all contributed substantially to the destabilization of steppe activity over time. Interannual variability in livestock production was decoupled from the temporal instability of steppe productivity in the IMAR, while the increasing temporal instability of steppe productivity is likely to be detrimental to long-term livestock production and food security in Mongolia. Future measures should be implemented to adapt to the changing climate (increased availability of weather information, animal shelter infrastructure, improved winter protection, better feed storage and climate-based livestock insurance) and the livestock numbers should be adjusted according to the carrying capacity to sustain the development of local livestock production systems (Fang et al 2016, Qi et al 2017, Xu et al 2019). In addition to control of livestock numbers, livestock production efficiency and net pastoral income should be increased by producing high-quality animal products (Briske et al 2015, Fang et al 2016).
Data availability statement
The data that support the findings of this study are available upon reasonable request from the authors.

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