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Inter-annual rainfall variability in Central Asia – A contribution to the discussion on the importance of environmental stochasticity in drylands

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A B S T R A C T

Drylands are characterised by pronounced climatic fluctuations, especially in regard to precipitation. We tested the relationship between mean precipitation and variability values using monthly data from climate stations in both arid and semi-arid parts of Central and High Asia. Total annual and growing season precipitation values were also compared in order to produce results relevant to plant biomass productivity and thus land use. Our study confirmed the well known observation that variability increases with lower overall precipitation levels. The observed correlation indicated that growing season precipitation variability increased dramatically where mean precipitation levels fell below ~100 mm. This sheds new light on the transition between regimes with more regular rainfall patterns and those with episodic rainfall; a focus on the growing season indicates a stronger relation between rainfall sums and rainfall variability compared to annual values. We therefore encourage future analysis for other parts of the world to improve our understanding of the relationship between climatic conditions and productivity in drylands.

1. Introduction

Drylands cover some 47% of the terrestrial surface, where rainfall represents the most limiting factor for primary productivity (L'Houréou, 1984; Nicholson et al., 1998). Since rainfall variability tends to increase with decreasing precipitation, arid environments have greater precipitation variability compared to semi-arid and sub-humid ecosystems (Davidowitz, 2002; Vetter, 2005). A number of ecological functions in drylands are driven by precipitation variability (e.g. wildlife numbers & migration, seed recruitment of plants, biomass productivity). Ongoing discussions in rangeland ecology also emphasise the importance of environmental variability, which suggests that fodder production and thus livestock numbers are mainly driven by the variable climate conditions, with numbers often collapsing during droughts (Ellis and Swift, 1988; Illius and Connor, 1999). Therefore numerous fields in dryland ecology benefit from analyses of variability patterns.

Inter-annual variability is often described with respect to annual precipitation totals. However, timing of rain events in the course of the given year is also important. Lack or absence of rain at the beginning of the growing season has been recognized as a crucially limiting factor (e.g. for vegetation growth in the Chinese Gobi (Yu et al., 2003). The onset of vegetation growth and the duration of the growing season have been used as proxies for the analysis of rangeland dynamics (e.g. Saether, 1997; Walker and Wilson, 2002).

There have been several studies on the climatic patterns of Central and High Asia, but most have been based on the analysis of daily climatic records (e.g. Liu et al., 2006), of which there are overall relatively few. Most papers on this subject focus on climate change (e.g. Li and Zheng, 2002; Linderholm, 2006; Thomas, 2006). Here, we analysed the variability of total annual and total growing season precipitation in Central and High Asia based on monthly totals, which allowed using a much broader dataset. To the best of our knowledge, such a broad analysis has not been conducted for this region.

Our working area is one of the largest arid to semi-arid ecosystems in the world. The continental climate produces strong seasonality: most precipitation falls in the warm summers, whilst the cold winters are mainly dry. Thus, summer precipitation is the main driver of biomass productivity. We analysed climate station

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data for regions with ≤300 mm annual precipitation in Central and High Asia (see map 1 in Supplementary data Fig. S1); since environmental variability is thought to be crucial for plant performance and thus land use below this threshold, the border between equilibrium and non-equilibrium conditions is thought to lie below this threshold within our working area (e.g. Fernandez-Gimenez and Allen-Diaz, 1999; Retzer and Reudenbach, 2005). Our analysis focused on the following questions:

- What is the relationship between the variability and the mean for annual precipitation values?
- What is the relationship between the variability and the precipitation values in the growing season?
- What is the relationship between both the variability of the annual and the growing season precipitation values?

2. Methods

We obtained climate records from the GHCN (Global Historical Climatology Network, http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php) climate database for all 150 climate stations in Central Asia (with at least more than 10 years of data, see Supplementary data S. 3) that received less than 300 mm annual precipitation, as derived from a global extrapolated climate dataset (Hijmans et al., 2005). For each station, we extracted mean monthly precipitation and mean monthly temperature values (see Supplementary data S. 1). Based on the mean monthly precipitation values we calculated the mean annual precipitation totals and the inter-annual variability of the precipitation. Variability was calculated as the coefficient of variation (standard deviation*100/mean) between the years (inter-annual). Temperature was already confirmed as a determinant for the timing of the onset of the growing season in China (Piao et al., 2006). From the mean monthly temperature values we thus estimated the day of the thermally controlled potential onset and conclusion of the growing season through fitting a generalized additive model (GAM) for each year and station. Cutting points of the fitted GAM with a threshold of 8 °C are taken as the onset (function inclines; earlier in the year) and offset (function declines; later in the year); other thresholds (e.g. 5 °C) were initially tried but did not influence the general pattern. The period between onset and offset is hereafter referred to as the growing season. For each year we calculated the duration of the growing season; this allowed us to calculate mean precipitation sums and the coefficient of variance (CV) for each climate station solemnly for the growing season. The relation between precipitation sums and variability was correlated using local polynomial regression models.

All statistical analyses and the plotting were performed with the R software (R Development Core Team, 2008); the package mgcv was used in addition to the standard packages.

3. Results

There is a clear relationship between mean precipitation and the CV of the precipitation (Fig. 1a). This relationship is even more pronounced where data from the growing season are analysed separately (Fig. 1b; see also pseudo-r^2 for both relations in Fig. 1). Here, the slope of the modelled relationship between precipitation and CV is much steeper. For the growing season, the slope increases strongly at around 120 mm rainfall (Fig. 1b). Almost all CV values of the growing season are higher than those derived for the annual totals (Fig. 2). Dry periods therefore have particularly unreliable precipitation during the most relevant time, the growing season. Of course, growing season precipitation totals are lower than annual totals, but the difference is not great, highlighting the fact that Central Asia experiences predominantly summer rains.

4. Discussion

The well known relation of increased precipitation variability with a lower mean precipitation (Boone and Wang, 2007; Davidowitz, 2002) was confirmed by our data. A comparable pattern has also been described for Asian drylands on a larger scale (e.g. Gintzburger et al., 2005). However, our data clearly show that focussing on annual totals may underestimate the variability in the ecological more crucial summer season.

Our approach represents an improved method to describe the precipitation variability of the vegetation period in temperate arid and semi-arid rangelands. This seems necessary because several aspects of the relationship between precipitation variability and its ecological consequences are still poorly understood (e.g. Gillson and Hoffman, 2007). Previous studies examined increasing

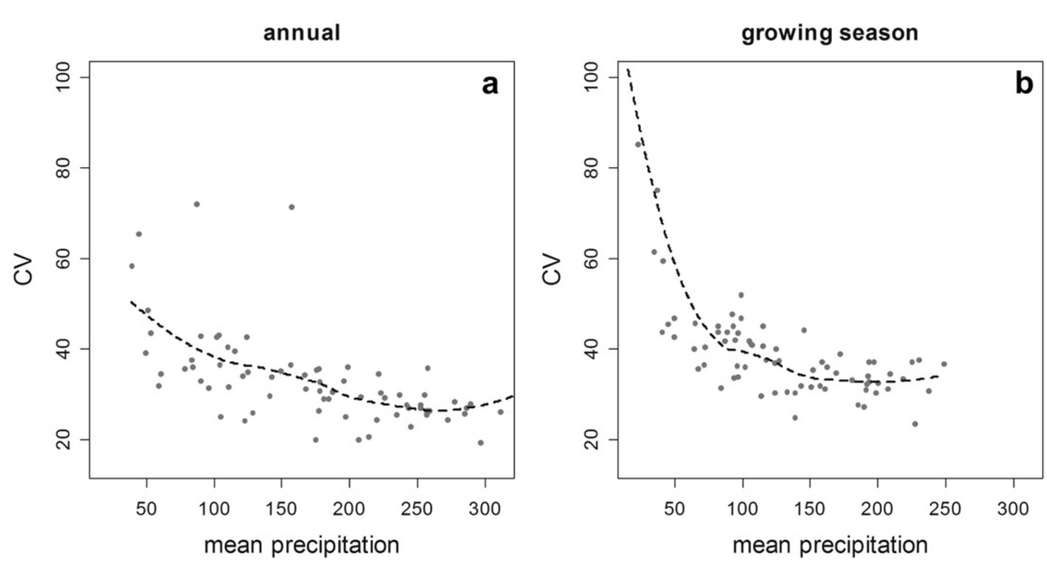

Fig. 1. Inter-annual coefficient of variation (CV, in %) versus the mean precipitation sum (*x*-axes, in mm/a) of (a) the year and (b) the growing season. The dashed lines indicate a local polynomial regression model fitted through all points. Note that for the annual precipitation a pseudo-r^2 was 0.38, while the growing season precipitation had an r^2 of 0.7, indicating a much stronger relation.

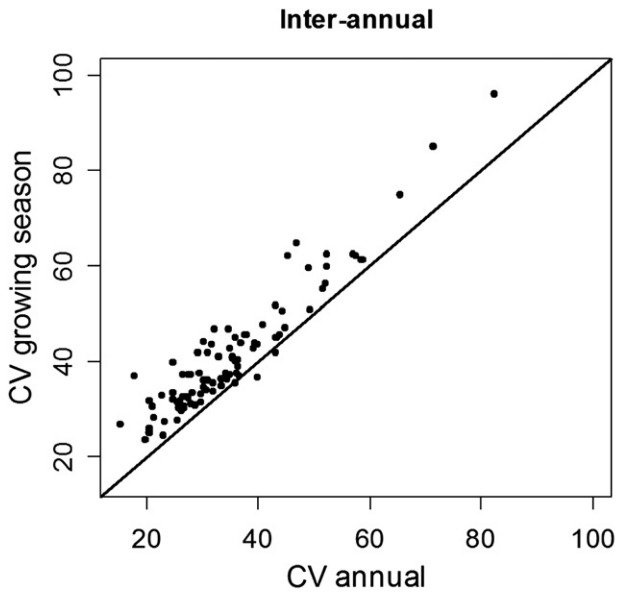

Fig. 2. CV of the annual precipitation (*x*-axis) plotted against the CV of the precipitation of the growing season (*y*-axis). The solid line indicates a hypothetical linear model with the slope of 1, while an actual correlation of a linear model between both parameters is r^2: 0.74***; estimate: 1.19.

variability of growing season precipitation along mean precipitation gradients, yet differentiation was often solemnly based on a general and static designation of several months as summer period (e.g. Davidowitz, 2002). Our GAM-based approach for identifying the growing season is somewhat limited since it assumes a constant temperature threshold for plant growth (8 °C). The conventional standardized interval duration, which is usually used to determine the growing season (e.g. Davidowitz, 2002; Henkin et al., 2007; Jeltsch et al., 1997; Walker and Wilson, 2002), is even more limited due to the high inter-annual climatic variability in arid and semi-arid environments. A more dynamic approach to modelling the potential growing season might include potential evapotranspiration among other parameters, however, such an approach would be infeasible not only because of the lack of such data, but also due to constraints regarding the parameterisation.

The precipitation within Central and High Asia shows an unimodal seasonal pattern (Ho, 2001); winter precipitation is low (Fernandez-Gimenez and Ellis, 2003). Winter snow may also contribute to vegetation growth through spring-melt (e.g. Ren et al., 2007). However, within Central Asia winter snow is rather erratic (Ho, 2001) and often evaporates quickly. Our approach may therefore reveal clearer patterns for rangelands with pronounced or mainly snow-based precipitation (e.g. Patagonia, see Jobbagy et al., 2002).

The increasing slope of the relationship between the CV and the mean of precipitation below 100 mm (Fig. 1b) indicates more strongly episodic precipitation in the crucial summer season. The steep increase in the relation between precipitation sums and precipitation variability occurs around 90 mm of precipitation within the growing season; due to the relation between annual sums and growing season sums (see Fig. 2, estimate of the relation 1.19), this would equal 107 mm of annual sums. The steep rise in the relation between precipitation sums and precipitation variability is however not reflected in the annual values (Fig. 1a). The failure to detect episodic rainfall events was already recognized in other continental rangelands (Milchunas et al., 1989). For Mongolia, 220 mm of annual precipitation has been described as a threshold distinguishing the relatively grazing-sensitive stable environments from so-called non-equilibrium conditions – where grazing impact becomes negligible compared to effects of climatic variability (Fernandez-Gimenez and Allen-Diaz, 1999; Retzer and Reudenbach, 2005). This corresponds to a mean of some 185 mm for the growing season precipitation. Given that CVs in growing season precipitation are higher, thresholds for the CV, which were originally set at 30–33%, for annual sums (Boone and Wang, 2007; see Fig. 2), should also be different for analyses focused on the growing season. Moreover, our data show that even at precipitation totals below 220 mm, a large number of stations have low CVs of precipitation and thus still gain periodic rather than episodic rains. Given that climatic variability is more important for rangeland dynamics than mean values, such regions may be able to sustain larger herds of livestock and may as a result be more sensitive to degradation.

5. Conclusion and outlook

It has been suggested that the CV of the productivity is superior compared to the CV of the precipitation in defining dryland variability (Cingolani et al., 2005). However, long-term data on biomass productivity over larger areas are scarcely available for drylands: only remote sensing data might fill this gap, yet these products are often unreliable where vegetation cover is low (e.g. NDVI). In addition records are rather short-termed, i.e. less than 20 years (Tucker et al., 2005).

Nevertheless, the general relationship between annual primary productivity (ANPP) and climatic variability has already been examined on a global scale (Knapp and Smith, 2001), and numerous detailed studies from other regions confirm the general pattern (e.g. Boone and Wang, 2007; Davidowitz, 2002; Jobbagy et al., 2002). Existing examples from Central Asia include observations of fluctuating productivity in the Gobi based on analyses of NDVI values (Yu et al., 2004); however, in most of the drier parts of that working area the NDVI signal was too low to detect any vegetation growth. Studies from other regions of the world, however, successfully examined the relationship between the precipitation and productivity inferred from remote sensing data (e.g. Evans and Geerken, 2004; Geerken et al., 2005; Potter and Brooks, 1998; Prince et al., 2007), and analyses of variability may benefit from such an approach (e.g. Jobbagy et al., 2002). However, regarding remote sensing data no valid thresholds for the demarcation of rangelands encountering variable dynamics and rather stable environments has so far been suggested, while rainfall dynamics are much better understood. Using the CV of the vegetation period is an improved proxy for the variability in biomass productivity, since rainfall outside the vegetation period is hardly important regarding plant growth. Therefore the relationship between the variability and the total annual precipitation is less pronounced than it is between the variability and the total precipitation for the growing season.

In the future, the relation between the annual CV of the precipitation, the CV of the precipitation solely within the growing season and the ANPP (as derived from remotely sensed data or field measurements) needs to be analysed, because the only threshold between stable and variable drylands regarding precipitation variability has so far been proposed within the non-equilibrium paradigm, which is based on the CV of the annual precipitation.

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Appendix. Supplementary data

Supplementary figures associated with this article can be found, in the online version, at doi:10.1016/j.jaridenv.2010.03.011.

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