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Assessment of changes in the state of the rangelands of Inner Mongolia, China between 1998 and 2007 using remotely sensed data

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Abstract. The spatial annual patterns of aboveground net primary productivity (ANPP) and precipitation-use efficiency (PUE) of the rangelands of the Inner Mongolia Autonomous Region of China, a region in which several projects for ecosystem restoration had been implemented, are described for the years 1998–2007. Remotely sensed normalised difference vegetation index and ANPP data, measured *in situ*, were integrated to allow the prediction of ANPP and PUE in each 1 km^2 of the 12 prefectures of Inner Mongolia. Furthermore, the temporal dynamics of PUE and ANPP residuals, as indicators of ecosystem deterioration and recovery, were investigated for the region and each prefecture. In general, both ANPP and PUE were positively correlated with mean annual precipitation, i.e. ANPP and PUE were higher in wet regions than in arid regions. Both PUE and ANPP residuals indicated that the state of the rangelands of the region were generally improving during the period of 2000–05, but declined by 2007 to that found in 1999. Among the four main grassland-dominated prefectures, the recovery in the state of the grasslands in the Erdos and Chifeng prefectures was highest, and Xilin Gol and Chifeng prefectures was 2 years earlier than Erdos and Hunlu Buir prefectures. The study demonstrated that the use of PUE or ANPP residuals has some limitations and it is proposed that both indices should be used together with relatively long-term datasets in order to maximise the reliability of the assessments.

Additional keywords: aboveground net primary productivity, Inner Mongolia, land degradation, precipitation-use efficiency, temperate grasslands, vegetation restoration.

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Introduction

About 40% of China is covered with grassland which has major significance in the sustainability of livestock production and environmental conservation (Fan *et al*. 2008). Temperate grassland, the predominant type of grassland in China, has experienced serious deterioration during the past decades due to over-grazing (Akiyama and Kawamura 2007). Such deterioration has caused severe environmental issues and poses a challenge to food security (Jiang *et al*. 2006; Akiyama and Kawamura 2007). The Chinese government has invested heavily in planting trees on these grasslands in the Inner Mongolia region in the past 20 years [e.g. the Three-North (north, north-west and north-east) Shelterbelt Forest Program, also known as the Green Great Wall Program]. The Chinese government also provided US $7300 million to combat dust storms from 2001 to 2006 (i.e. the Beijing-Tianjin Sandstorm-Controlling Program). In addition, the Start-up Re-grass Program, which is aimed to protect grasslands from heavy grazing pressures, has also been implemented since 2003 (Jiang *et al*. 2006). Despite the fact that these land restoration projects have been implemented to arrest grassland deterioration in Inner Mongolia, it remains unclear whether the process of deterioration has been arrested or reversed during the past decade. Comprehensive monitoring and assessment of the ecosystem recovery is, therefore, necessary.

Using appropriate indices is critical in monitoring and assessing rangeland deterioration or recovery in these arid regions. Many efforts have been made for this purpose in the past (Le Houérou 1984; Ding *et al*. 2004; Wessels *et al*. 2007; Wang *et al*. 2008; Zhang *et al*. 2008). Conventional indices used for the assessment of rangeland deterioration are vegetation cover, leaf area index, normalised difference vegetation index (NDVI), aboveground biomass and aboveground net primary productivity (ANPP). These indices, however, are mostly correlated with annual precipitation (Hu *et al*. 2007). Therefore, the inter-annual variations in these indices may be not due to land deterioration or recovery but to fluctuations in rainfall. For example, vegetation cover would be high in wet years and low in dry years and thus may underestimate deterioration in wet years and overestimate it in dry years.

Precipitation-use efficiency (PUE), or rainfall-use efficiency, the ratio of vegetation ANPP to annual precipitation, has been widely used to address the relationship between precipitation and vegetation productivity in the evaluation of deterioration or recovery of rangelands in arid regions (Le Houérou 1984; Prince *et al*. 1998; Paruelo *et al*. 1999; Holm *et al*. 2003; Huxman *et al*. 2004; Hu *et al*. 2010). Owing to largely excluding the effect of the fluctuations of annual precipitation, PUE has obvious advantages in evaluating deterioration over conventional indices. For this reason, PUE has been a useful and widely-used index to assess the deterioration of rangelands (Le Houérou 1984; Prince *et al*. 1998; Paruelo *et al*. 1999; Diouf and Lambin 2001; Holm *et al*. 2003; Wessels *et al*. 2007). For example, by analysing changes in PUE using remotely sensed data, Prince *et al*. (1998) investigated the dynamics of desertification of Sahara from 1982 to 1990. Holm *et al*. (2003) assessed land degradation in the arid area of Western Australia during the period from 1992 to 1999. There have been few studies of land degradation of grasslands in China using changes in PUE. Bai *et al*. (2008) and Hu *et al*. (2010) investigated the spatio-temporal variations in PUE along a precipitation gradient in the temperate grasslands of north China although these studies did not address the issue of rangeland deterioration or recovery.

In addition to PUE, the 'Residual Trends (RESTREND)' method is now widely used for the assessments of rangeland deterioration. The RESTREND method was proposed by Evans and Geerken (2004). They described a method that allows individual ANPP–precipitation relationships to be developed for each pixel of a region, after which the trends in the residual (observed production – production predicted from rainfall) through time can be identified. A negative trend indicates deterioration and a positive trend indicates recovery. The RESTREND method accommodates the effects of local variations in slope, soil and vegetation through the analysis of the relationship between rainfall and primary production for every pixel. This makes it more appropriate than the approach which relates ANPP–precipitation for the whole region and not for each pixel. Some attempts have been made to assess rangeland deterioration using this method in recent years (Wessels *et al.* 2007; Zhuo *et al*. 2007).

In this study, by integrating ground-based ANPP data and the remotely sensed NDVI, we investigated the spatial patterns of the relationship between ANPP and PUE in Inner Mongolia, China where several national restoration projects have been implemented in recent years. Furthermore, we used the PUE and RESTREND methods to make a preliminary assessment of the changes in deterioration and recovery of the rangelands in this region in 1998–2007 as an initial attempt to evaluate the effectiveness of the ecosystem restoration projects implemented in the region.

Materials and methods

Data collection

In order to estimate the ANPP from 1998 to 2007, we established the relationship between measured ANPP and yearly peak NDVI using 152 measurements made in Inner Mongolia, and used the relationship and the yearly peak NDVI data at each pixel to estimate the ANPP of each pixel. The measured ANPP was the harvested peak aboveground biomass (including live biomass as well as standing dead biomass produced in the current year) accumulated during the growing season and measured in August, which has been widely used previously to estimate the ANPP of grassland (Scurlock *et al*. 2002). The measured ANPP was from two data sources. The first was based on measurements made on 23 sites made at the peak growing seasons (middle of August) of 2003–06, when vegetation reached its maximum aboveground biomass. Aboveground biomass was measured in three independent 1 × 1-m quadrats harvested at each site. The sampled biomass was dried in an oven at 65°C for 48 h and weighed. The second data source was from sites used to monitor the seasonal and inter-annual dynamics of grassland biomass in Inner Mongolia. Local governments have established permanent plots for the continuous measurement of aboveground biomass, plant community composition and vegetation cover. Five or more quadrats were used as the replicates for the measurements at each of 22 sites. Measurements at these sites were made between 1998 and 2003. For this dataset, the peak aboveground standing biomass in each growing season was used as the measured ANPP. In total, 152 measurements of ANPP were made at 45 sites, which included sites for all the zonal grassland types in the region (i.e. meadow steppe, typical steppe, desert steppe and steppe desert) (Fig. 1), and with a range of biomasses of 17.9–862.4 g m^{-2} $year^{-1}$.

The yearly peak NDVI occurred in August and hence monthly NDVI from August in 1998–2007 was used to establish the relationship between measured ANPP and yearly peak NDVI and then to estimate ANPP for each pixel of the whole region. The NDVI data (1 km^2) were derived from the VEGETATION sensor on board the SPOT satellite platforms. The data were obtained from the Vlaamse Instelling voor Technologisch Onderzock

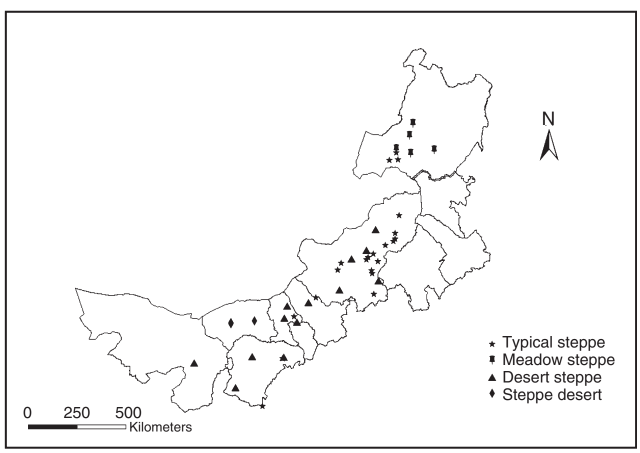

Fig. 1. Distribution of sites used for the measurement of aboveground net primary productivity.

Image Processing centre (Mol, Belgium) (available at: www.vgt.vito.be, accessed 19 January 2012). The data were compositions of 10 days which had been subjected to correction in order to reduce the effects of residual clouds, atmospheric perturbations, variable illumination and viewing geometry (Lasaponara 2006; Telesca and Lasaponara 2006). The average of the three 10-day NDVI compositions in August was calculated as the monthly NDVI of August.

Annual precipitation and mean annual temperature were acquired from the public database of the Chinese National Bureau of Meteorology. The station-specific data were interpolated using three-dimension second-order trend surface analysis (1 km in resolution). Results of a test of the accuracy of the interpolation indicated a relative error of less than 3% for annual temperature, and less than 7% for annual precipitation (Yu *et al*. 2004).

Although most of the territory in Inner Mongolia is covered by grasslands, there is a certain area of forest and crop lands. To exclude the effects of non-grassland land cover, we used the data of Land Use and Cover of China (1 km) developed by Chinese Academy of Sciences to eliminate the pixels covered by other ecosystems (available at: www.geodata.cn, accessed 19 January 2012 (in Chinese)).

Methods of assessing recovery of biomass of rangelands

PUE and the ANPP residuals from 1998 to 2007 were calculated to assess the ecosystem recovery. PUE was calculated as the ratio of ANPP to annual precipitation. For each pixel, the ANPP–precipitation relationship was developed, and the residuals (i.e. estimated ANPP – ANPP predicted by rainfall) were calculated. The trends of PUE and ANPP residuals from 1998 to 2007 were used to assess recovery of the grassland. The mean values of PUE and ANPP residuals for each of the 12 prefectures in Inner Mongolia were also calculated.

Data analyses

The equation in Fig. 3 was fitted using the SPSS statistical package (Version 13.0, SPSS Inc., Chicago, IL, USA) and the standard deviations in Fig. 3 were estimated using Microsoft Excel (Version 2003, Microsoft, Seattle, WA, USA).

Results

Spatial pattern of ANPP and PUE

There was a significant ($P < 0.001$) exponential relationship between measured ANPP and the NDVI in August described by the equation $Y = 11.59e^{5.47x}$ ($R^2 = 0.79$, $n = 152$) (Fig. 2). The average ANPP and PUE values for 1998–2007 for the whole autonomous region of Inner Mongolia were 193.9 g m^{-2} $year^{-1}$ and 0.59 g m^{-2} mm^{-1}, respectively. Generally, both ANPP and PUE were high in the humid eastern area and low in the dry western area. ANPP increased exponentially with mean annual precipitation with a rapid increase when mean annual precipitation was higher than 200 mm (Fig. 3*a*). Similarly, PUE increased rapidly when the mean annual precipitation was above 200 mm (Fig. 3*b*).

Among the prefectures, ANPP increased from the west to the east in association with a higher mean annual precipitation. For the prefectures mainly covered by desert steppe and steppe

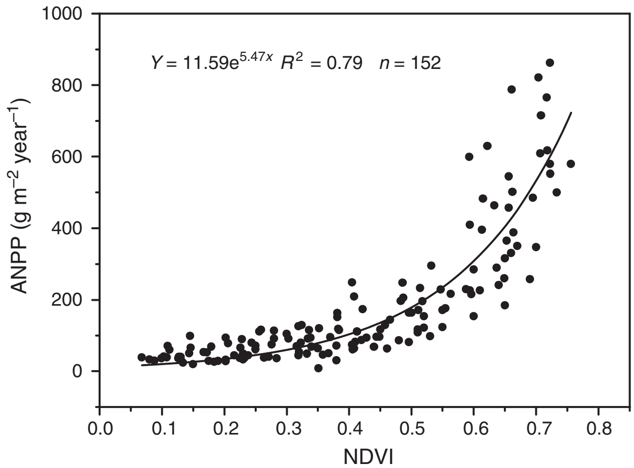

Fig. 2. The relationship between measured aboveground net primary productivity (ANPP) and normalised difference vegetation index (NDVI) for 152 sets of observations.

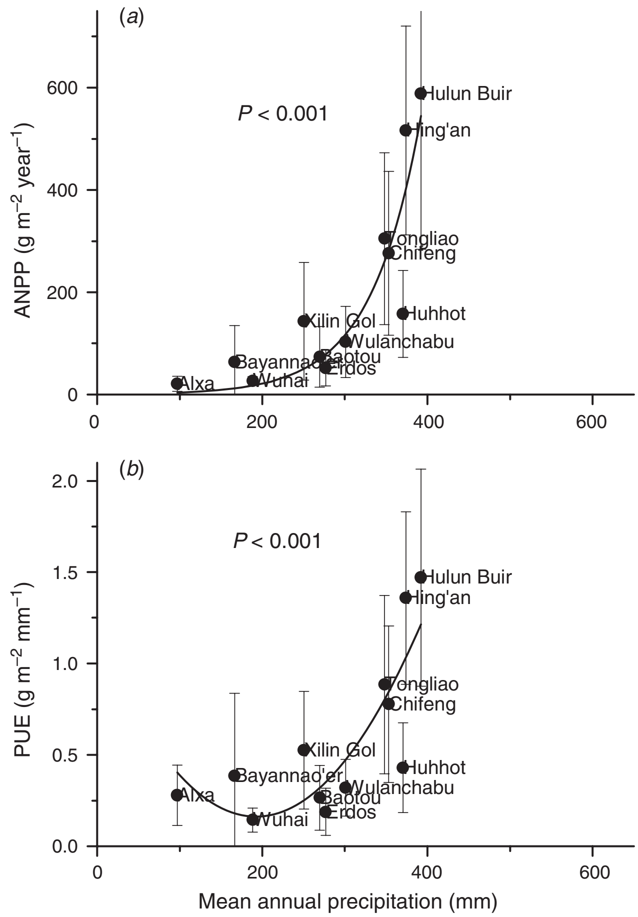

Fig. 3. Relationships between mean annual precipitation and (*a*) aboveground net primary productivity (ANPP) and (*b*) precipitation-use efficiency (PUE) for Inner Mongolian rangelands. Each point was the mean value of ANPP and PUE for each of the 12 prefectures in Inner Mongolia. The error bars indicate the standard deviations of ANPP and PUE for each prefecture.

desert, the ANPP were estimated to be mainly lower than 100 g m^{-2} $year^{-1}$, with values of ANPP (mean ± s.d.) of the western prefectures being Alxa (20.9 ± 14.8 g m^{-2} $year^{-1}$), Wuhai (26.6 ± 8.7 g m^{-2} $year^{-1}$), Erdos (52.2 ± 35.7 g m^{-2} $year^{-1}$), Bayannao'er (63.8 ± 71.1 g m^{-2} $year^{-1}$), Baotou (73.8 ± 59.3 g m^{-2} $year^{-1}$) and Wulanchabu (103.1 ± 69.6 g m^{-2} $year^{-1}$). For the prefectures in the middle part of Inner Mongolia, the land is mainly covered by typical steppe and estimated ANPP values ranged from 100 to 300 g m^{-2} $year^{-1}$. For example, the values of the prefectures were Xilin Gol, 143.2 ± 115.2 g m^{-2} $year^{-1}$, Hohhot, 157.9 ± 85.2 g m^{-2} $year^{-1}$ and Chifeng, 276.4 ± 160.0 g m^{-2} $year^{-1}$. For the prefectures in the eastern part, the land is mainly covered by meadow steppe, and there is a large area of land in Hing'an and Hulun Buir prefectures where lowland meadows are distributed. The estimated ANPP values were much higher in these prefectures than in the other prefectures. For example, the estimated ANPP values were 304.9 ± 167.9 g m^{-2} $year^{-1}$ in Tongliao, 516.1 ± 203.7 g m^{-2} $year^{-1}$ in Hing'an and 588.5 ± 304.6 g m^{-2} $year^{-1}$ in Hulun Buir prefectures, respectively. The pattern of PUE differed slightly from that of ANPP. The prefectures with the lowest PUE included not the driest, i.e. Alax (0.27 ± 0.16 g m^{-2} mm^{-1}) but rather Wuhai (0.14 ± 0.07 g m^{-2} mm^{-1}) and Erdos (0.19 ± 0.13 g m^{-2} mm^{-1}), which have a slightly higher mean annual precipitation than Alxa (Fig. 3*b*). With the increasing mean annual precipitation across the middle to east prefectures, PUE increased steadily from Baotou (0.26 ± 0.18 g m^{-2} mm^{-1}) to Hulun Buir (1.47 ± 0.59 g m^{-2} mm^{-1}) prefecture mean annual precipitation.

Assessment of state of rangelands in Inner Mongolia

The annual changes in PUE and ANPP residuals, together with annual rainfall between 1998 and 2007, were used to assess the recovery in the state of the rangelands in Inner Mongolia and are shown in Fig. 4. Both indices were at their lowest in 1998, the year of the highest rainfall, but had higher values between 1999 and 2002. During the period from 2003 to 2005, the annual PUE and ANPP residual values steadily increased by 30% compared with those in 2002. This period overlapped with the implementation period of three national projects, i.e. the Three North Shelterbelt Forest Program, the Beijing-Tianjin Sandstorm-Controlling Program, and the Start-up Re-grass Program. In 2006 and 2007 there was decline in annual PUE and

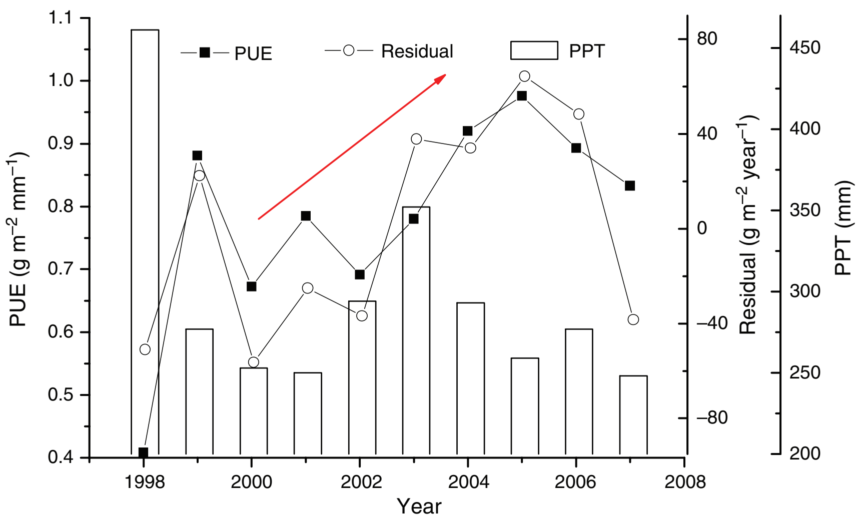

Fig. 4. Precipitation-use efficiency (PUE) and aboveground net primary productivity (ANPP) residual for rangelands of the Inner Mongolia Autonomous Region for each year between 1998 and 2007. PPT is annual precipitation (mm).

Table 1. Inter-annual variations in precipitation-use efficiency (g m^{-2} mm^{-1}) of the rangelands in each prefecture

	Alxa	Bayan-nao'er	Baotou	Chifeng	Huhhot	Hulun Buir	Tongliao	Wulanchabu	Xilin Gol	Xing'an	Erdos	Wuhai
1998	0.21	0.35	0.25	0.45	0.39	0.52	0.46	0.32	0.44	0.53	0.16	0.12
1999	0.21	0.40	0.25	0.83	0.32	1.71	1.03	0.28	0.66	2.01	0.19	0.13
2000	0.37	0.45	0.26	0.48	0.33	1.42	0.73	0.26	0.39	1.29	0.25	0.20
2001	0.40	0.34	0.23	0.87	0.24	1.66	1.03	0.25	0.45	1.49	0.13	0.11
2002	0.26	0.32	0.24	0.78	0.39	1.41	0.83	0.31	0.44	1.15	0.17	0.12
2003	0.25	0.33	0.24	0.86	0.43	1.41	1.19	0.33	0.58	1.54	0.17	0.13
2004	0.37	0.37	0.31	0.99	0.53	1.75	1.07	0.36	0.61	2.19	0.19	0.15
2005	0.36	0.62	0.31	0.92	0.65	2.04	0.91	0.40	0.71	1.43	0.29	0.20
2006	0.36	0.36	0.24	0.99	0.57	1.72	0.95	0.40	0.64	1.79	0.20	0.12
2007	0.24	0.44	0.35	0.82	0.47	1.91	1.05	0.30	0.42	1.24	0.22	0.18

Table 2. Inter-annual variations of the residual of aboveground net primary productivity ($g\,m^{-2}\,year^{-1}$) of the grasslands in each prefecture

	Alxa	Bayannao'er	Baotou	Chifeng	Huhhot	Hulun Buir	Tongliao	Wulanchabu	Xilin Gol	Xing'an	Erdos	Wuhai
1998	–0.4	–3.5	–5.4	–46.3	–13.8	–153.7	–54.7	–3.2	–6.6	–121.8	–2.9	0.2
1999	–0.5	–6.4	–9.3	4.2	–35.4	72.3	14.7	–13.3	19.1	58.3	–7.5	–2.4
2000	–0.1	–2.6	–3.6	–122.3	–34.7	–87.8	–96.2	–20.6	–42.3	–123.2	–0.6	1.1
2001	–1.6	–11.9	–12.9	9.6	–60.7	–52.1	–0.8	–19.9	–19.7	–77.8	–15.6	–5.7
2002	–0.8	–4.2	–3.5	–18.9	–16.3	–89.2	–65.3	–5.3	–23.6	–80.4	0.2	–0.7
2003	1.1	4.8	–1.3	41.3	3.2	66.8	94.6	3.9	19.1	135.8	2.0	–0.7
2004	1.4	3.1	16.2	96.0	41.9	40.8	77.5	16.7	25.4	39.1	3.3	0.7
2005	0.3	8.2	4.1	26.6	59.1	167.7	45.8	22.3	39.7	161.3	7.3	–0.8
2006	–0.2	–1.4	–4.4	31.1	45.6	137.2	3.1	23.3	23.1	134.3	2.3	–1.3
2007	0.7	13.9	20.1	–21.0	11.1	–103.7	–18.8	–3.8	–34.1	–126.7	11.6	9.5

ANPP values such that the values in 2007 were similar to those in 1999.

PUE and ANPP residuals of the prefectures in each year are shown in Tables 1 and 2. The prefectures, which are dominated by grasslands, are Hulun Buir, Xilin Gol, Erdos, and Chifeng and they account for more than 70% of the grasslands in Inner Mongolia. In general, the temporal variations in PUE and ANPP residuals of the four prefectures were in agreement with the whole autonomous region, illustrating an increasing trend between 2000 and 2005 when the PUE and ANPP residuals were normalised as shown in Fig. 5. The trends in the Xilin Gol and Chifeng prefectures, in particular, were associated with the period when the Beijing-Tianjin Sandstorm-Control program was implemented in these prefectures. The increases in normalised PUE and ANPP were greatest in the Chifeng and Erdos prefectures, followed by those in Xinlin Gol and Hunlun Buir prefectures. Xilin Gol and Hulun Buir are the prefectures with the largest area of grassland in Inner Mongolia. The increases in normalised PUE and ANPP in the Xilin Gol prefecture occurred 2 years earlier than that in the Hulun Buir prefecture (Fig. 5).

Discussion

Spatial pattern of ANPP and PUE

A limitation in the method of predicting ANPP from the relationship between values of NDVI and measured ANPP was that only a small number of quadrats were measured within each 1 km^2. In regional-scale studies, it is difficult to command the resources to measure enough quadrats in each 1 km^2 to provide theoretically a more accurate assessment of the ANPP of the area. It is argued that most of the rangeland areas were relatively homogenous at a scale of 1 km^2 since they were comprised of grasslands. The reasonable close relationship found between measured ANPP and NDVI also provides support that the method provided useable results. It is also recognised that NDVI may be a poor indicator of ANPP in environments with highly variable/episodic rainfall because of the growth of ephemerals after rainfall but in rangelands composed mainly of grassland this is less of a problem. NDVI measurements made in August at the peak growing season may also underestimate ANPP, and hence PUE.

The positive relationship between ANPP and mean annual precipitation is consistent with the results of most previous studies in arid and semiarid rangelands (Sala *et al.* 1988; Lauenroth and Sala 1992; Lauenroth *et al.* 2000; Knapp and Smith 2001). The PUE values of the grasslands in Inner Mongolia (0.14–1.47 $g\,m^{-2}\,mm^{-1}$) are within the range reported by Le Houérou (1984) for other rangelands in arid regions of the world (0.05–1.81 $g\,m^{-2}\,mm^{-1}$). In addition, it was found that PUE

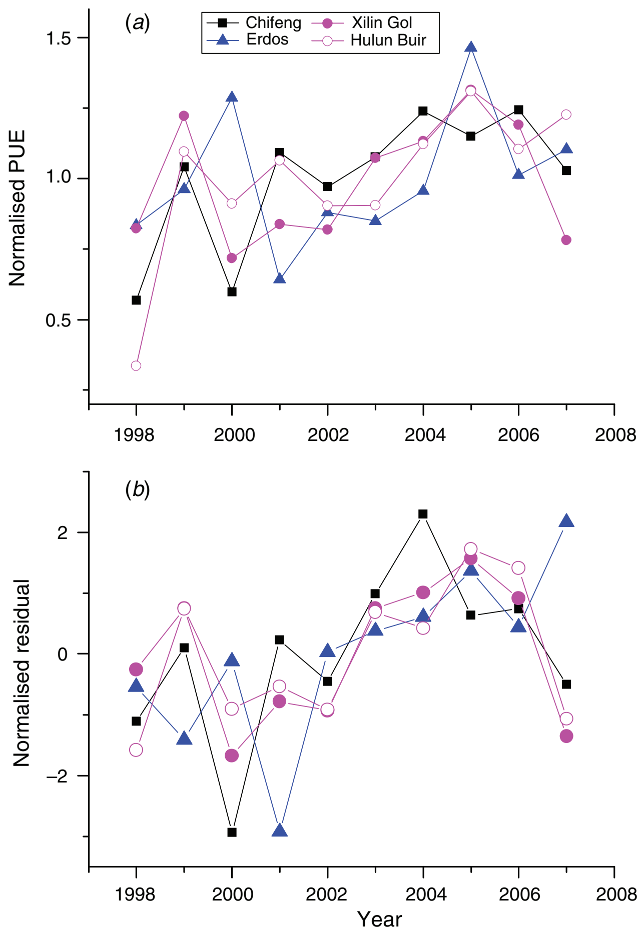

Fig. 5. (*a*) Precipitation-use efficiency (PUE) and normalised aboveground net primary productivity (ANPP) residual of main grassland-dominated prefectures for each year between 1998 and 2007. (*b*) PUE and ANPP residual were normalised by dividing the values by their mean absolute values for each prefecture, owing to the differences between prefectures in their magnitude.

decreased slightly or remained the same at first and then increased with mean annual precipitation along the climate gradient from the dry Alax prefecture to the humid regions in the Hulun Buir prefecture (Fig. 3*b*). This overall trend in PUE might be related to the fact that at lower levels of annual precipitation desert plants have adapted to an extremely dry climate by using the water held in deeper soil layers (Jobbágy and Sala 2000). With increased precipitation, vegetation canopies grow denser and plants have higher growth rates. In these conditions, less precipitation would be lost directly via soil evaporation and runoff, but in the form of transpiration from plant growth, and this allows PUE to increase with increasing mean annual precipitation (Paruelo *et al*. 1999; Hu *et al*. 2008, 2010).

Assessment of recovery in the state of rangelands in Inner Mongolia

Our study indicated that recovery in the state of the rangelands in Inner Mongolia was occurring between 2000 and 2005. This period is consistent with the time when the national ecological projects were being implemented. Our study also indicated that, for Xilin Gol and Hulun Buir, the two prefectures with the largest area of grassland in Inner Mongolia, the state of the former was recovering 2 years earlier than that of the latter (Fig. 5). This may be due to the fact that before the implementation of the Start-up Re-grass Program in 2003, the Beijing-Tianjin Sandstorm-Control Program had already started in Xilin Gol prefecture in 2001. The state of the grasslands declined after 2005 such that by 2007. It is not clear what the reasons for this were but it may have occurred through a combination of drought, insect pests or a rebounding grazing pressure. Future research should address the mechanisms causing this effect. This preliminary assessment of the recovery in grasslands in Inner Mongolia only provides limited evidence of a link between the recovery of the rangelands and the national ecological projects, and long-term *in-situ* monitoring records for a set of control points in the project area are needed to establish such a link conclusively.

Using PUE and ANPP residuals to assess deterioration and recovery of the state of the rangelands has the advantages over conventional indices as they largely exclude the effects of fluctuations in annual precipitation. The results in this study illustrated that the dynamics of the two indices were generally in good agreement, implying their effectiveness and robustness in assessing land deterioration and recovery. It is worthy to note that there was some inconsistence in some cases, despite this phenomenon being only found in very few years and prefectures. For example, in Erdos prefecture the PUE in 1999 was higher in 1998 while the ANPP residual suggested the contrary trend (Fig. 5). Although the effect of precipitation has been largely excluded, negative correlations between PUE and annual precipitation have been found in other studies (Wessels *et al.* 2007). In this study, we found weak relationships between PUE and annual precipitation at the prefecture and regional scales ($R^2 < 0.2$). The significant decline in precipitation in 1999 in Erdos is likely to have contributed largely to the increase in PUE.

The ANPP residuals also have disadvantages in some cases. First it is based on the relationship between ANPP and annual precipitation. To get accurate and robust relationships for each pixel, long-term period of data are required. Second, there is an underlying assumption for the ANPP residuals method, i.e. that the relationship between ANPP and precipitation is fixed for each pixel regardless of vegetation condition. This is obviously not the case since changes in the structure of plant communities may change the response of ANPP to precipitation (Paruelo *et al*. 1999; Huxman *et al*. 2004). To avoid the disadvantages of PUE and ANPP residuals in the assessment of rangeland deterioration or recovery, we suggest the use of both methods simultaneously. We also recommend the use of relatively long-term datasets in order to exclude the effect of extreme rainfall conditions on PUE, and to allow the development of robust relationships between ANPP and precipitation.

Conclusions

Through integrating remotely sensed NDVI and ground-based ANPP data, this study described the spatial pattern of ANPP and PUE across 12 prefectures in Inner Mongolia. By elucidating the dynamics of PUE and ANPP residuals, the changes in the state of the vegetation between 1998 and 2007 were assessed. The results indicated that ANPP and PUE were high in humid regions and low in dry regions. According to the temporal dynamics of PUE and ANPP residuals, the rangelands, mainly grasslands, appear to have been in a recovery phase between 2000 and 2005, especially in 2003 for most grasslands in Inner Mongolia. The recovery was greatest in Chifeng and Erdos prefectures. However, there was a decline in the state of the vegetation in 2006 and 2007 for most rangeland sites in Inner Mongolia. Measurements of PUE and ANPP residuals both have disadvantages in assessing deterioration and recovery in some cases. We suggest that both methods are used simultaneously and with relatively long-term data to overcome their shortcomings.

Acknowledgements

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