ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

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To cite this article: Ranjeet John *et al* 2009 *Environ. Res. Lett.* **4** 045010

Environ. Res. Lett. **4** (2009) 045010 (9pp) doi:10.1088/1748-9326/4/4/045010

Land cover/land use change in semi-arid Inner Mongolia: 1992–2004

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Received 13 March 2009
Accepted for publication 10 August 2009
Published 15 October 2009
Online at stacks.iop.org/ERL/4/045010

Abstract
The semi-arid grasslands in Inner Mongolia (IM) are under increasing stress owing to climate change and rapid socio-economic development in the recent past. We investigated changes in land cover/land use and landscape structure between 1992 and 2004 through the analysis of AVHRR and MODIS derived land cover data. The scale of analysis included the regional level (i.e. the whole of IM) as well as the level of the dominant biomes (i.e. the grassland and desert). We quantified proportional change, rate of change and the changes in class-level landscape metrics using the landscape structure analysis program FRAGSTATS. The dominant land cover types, grassland and barren, 0.47 and 0.27 million km^2, respectively, have increased proportionally. Cropland and urban land use also increased to 0.15 million km^2 and 2197 km^2, respectively. However, the results further indicated increases in both the homogeneity and fragmentation of the landscape. Increasing homogeneity was mainly related to the reduction in minority cover types such as savanna, forests and permanent wetlands and increasing cohesion, aggregation index and clumpy indices. Conversely, increased fragmentation of the landscape was based on the increase in patch density and the interspersion/juxtaposition index (IJI). It is important to note the socio-economic growth in this fragile ecosystem, manifested by an increasing proportion of agricultural and urban land use not just at the regional level but also at the biome level in the context of regional climate change and increasing water stress.

Keywords: Inner Mongolia, LULC, MODIS, AVHRR, IGBP, FRAGSTATS

1. Introduction

Semi-arid and arid regions have been undergoing severe stresses due to the combined effects of growing population and climate change (Ojima *et al* 1998). The degradation of grasslands will have a significant impact on ecosystem service (e.g. its carbon sequestration) and local economy as well as the regional climate (Angell and McClaran 2001). For example, carbon sequestration in Inner Mongolia (IM) varies spatially from a mean annual gross primary production (GPP) of about 100 g^{-2} yr^{-1} in desert regions in the west to about 4000 g^{-2} yr^{-1} in the northeast which is mostly under forest cover (Brogaard *et al* 2005). The grasslands in northern China, a greater portion of which are in IM, make up 41% of the land area, are prone to degradation owing to warming trends in northeast Asia over the last 50 years (Chase *et al* 2000), and intensification of anthropogenic land use practices (Kang *et al* 2007). The climatic changes (Zhai *et al* 1999, Hu *et al* 2003, Zhai and Pan 2003) have influenced not only the ecosystem dynamics, productivity, and stability of the Eurasian steppes, but are also coupled with the accelerated impacts of land use associated with rapid socio-economic growth. This growth is characterized by increasing population pressure combined with grazing pressure, resulting in increased degradation (Jiang *et al* 2006, Kang *et al* 2007). Consequently, these degraded

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arid/semi-arid ecosystems have become prone to wind erosion and are considered to be the cause of frequent sandstorms with a subsequent loss of biodiversity (Ye *et al* 2000, John *et al* 2008). For example, intensive land use of semi-arid grasslands has resulted in the replacement of dominant herbaceous grass communities by invasive shrubs, which are less efficient in water use but more tolerant to heat stress (Cheng *et al* 2006, 2007).

A practical and cost-effective method to successfully map and monitor land cover/land use (LCLU) change within a large region like IM is to use land cover datasets derived from remotely sensed earth observation (EO) data that provide regional coverage with moderate (∼1 km) spatial resolution (Loveland *et al* 2000, Friedl *et al* 2002). LCLU change studies often employ landscape metrics that measure spatial attributes such as landscape pattern and structure to determine effects of fragmentation.

Landscape patterns produced as a result of the fragmentation and loss of natural habitat might affect the sustainability of diverse flora and fauna (Turner *et al* 2001). Aware of the link between ecological pattern and processes at varying scales, land managers have long sought out measures of landscape change in order to monitor changes, e.g. in forest cover and beyond, to aid their decisions (Noss 1999, Lindenmayer *et al* 2002). Landscape metrics are therefore important tools through which management plans can be framed (Baskent and Jordan 1996, Herzog *et al* 2001), especially if they are able to track changes in the ecological or socio-economic variables (McAlpine and Eyre 2002).

In the recent past, multiple scale forest fragmentation studies using landscape metrics such as patch size have been conducted for the continental United States between 1992 and 2001 using the National Land Cover Dataset (Riitters *et al* 2002, Wickham *et al* 2008). The use of metrics to track LCLU change on the Tibetan plateau found a 20% increase in croplands driven by socio-economic changes with a subsequent decrease in cover types with high ecological value such as montane grasslands (Wang *et al* 2008). Landscape metrics have also been used to track LCLU change trajectories in the Tarim Basin, northwest China (Zhou *et al* 2008). The 1973–2000 study showed that anthropogenic modification was responsible for altering water resources as indicated by the interspersion and juxtaposition index (IJI) indicating greater aggregation and increased homogeneity with simpler, larger patches (Zhou *et al* 2008).

Recent landscape metrics studies in IM include quantification of landscape structure in the Heihe river basin (Li *et al* 2001) and the increasing road density between 1990 and 2002 (Li *et al* 2005). However, these studies were made at the basin or watershed scales and failed to capture landscape structure and LCLU at the regional scale. The objective of this study is to quantify changes in LCLU as well as landscape structure in semi-arid IM through the use of AVHRR and MODIS derived IGBP classification between 1992 and 2001/2004 at the regional and biome scales. We confine our study area to semi-arid IM and exclude the forested northeast part of IM as it is not representative of the dominant steppe vegetation. Based on the theory in landscape ecology that LCLU changes are scale-dependent, and that management plans differ by cover type, our study is organized by two hierarchical levels, the region and biome. Thereby the study combines analysis of fragmentation and LCLU change trajectories with two specific hypotheses: (1) Whereas land use practices across the entire region have intensified in recent decades, there exist significant differences in LCLU change across the region and among biomes. (2) We expect an increase in homogeneity synonymous with increasing dominance of the main natural land cover types (i.e. grassland, barren) despite the increase in agricultural and urban land use.

2. Methods

2.1. Study area

The Inner Mongolia Autonomous Region is the third largest province in China, lies between 37°01′–3°02′N, 95°02′–123°37′E (figure 1), and has a mean elevation of 1014 m. IM lies along the southeastern fringes of the Northern Eurasian Earth Science Partnership Initiative (NEESPI, http://neespi.org/) study area. The NEESPI domain of approximately 28.6×106 km^2 accounts for 60% of Eurasia north of 40°N, and was formed to understand the nature of global climate feedbacks (both biogeophysical and biogeochemical) to land processes and anthropogenic activities in the region (Groisman *et al* 2009). The ecosystems within this vast region include tundra in the north to semi-arid grassland and desert in the south. The NEESPI region is undergoing rapid changes resulting both from a warming climate and socio-economic factors (Groisman *et al* 2009).

Inner Mongolia has a semi-arid to arid continental climate (Yu *et al* 2003) with a significant proportion of cropland and urban land use (figure 1). This region includes three biomes: the arid desert in the west, grassland in the center and forest in the northeastern region (Olson *et al* 2001, http://www.worldwildlife.org/science/data/item6373.html) (figure 1). The major mountain ranges are the Greater Hingaan in the east and the Yinshan and Langshan in the center. The arid regions include the Gobi Desert in the northwest, the Mu Us and Hobq deserts south of the Yellow River, and the Tengger and Badain Jarian deserts in the west, which, in total, cover 40.03% of the province (figure 1). The climate is characterized by a decrease in precipitation (400–100 mm) and an increase in temperature as one moves from east to west (Ellis 1992, Kang *et al* 2007). The precipitation in the northeast section of IM exceeds 400 mm (Ellis 1992, Yu *et al* 2003) to support deciduous forest (0.23 million km^2, 19.7% of the region) and irrigated agriculture (Yu *et al* 2003). The north central region of IM borders the Gobi Desert and is dominated by the semi-arid steppe with annual rainfall <100 mm.

2.2. Data

MODIS derived LCLU data for 2001 and 2004 with 1 km resolution (MOD12Q1; Strahler *et al* 1999) were downloaded from the EOS data gateway (https://wist.echo.nasa.gov/api/), while 1 km AVHRR derived International Geosphere Biosphere

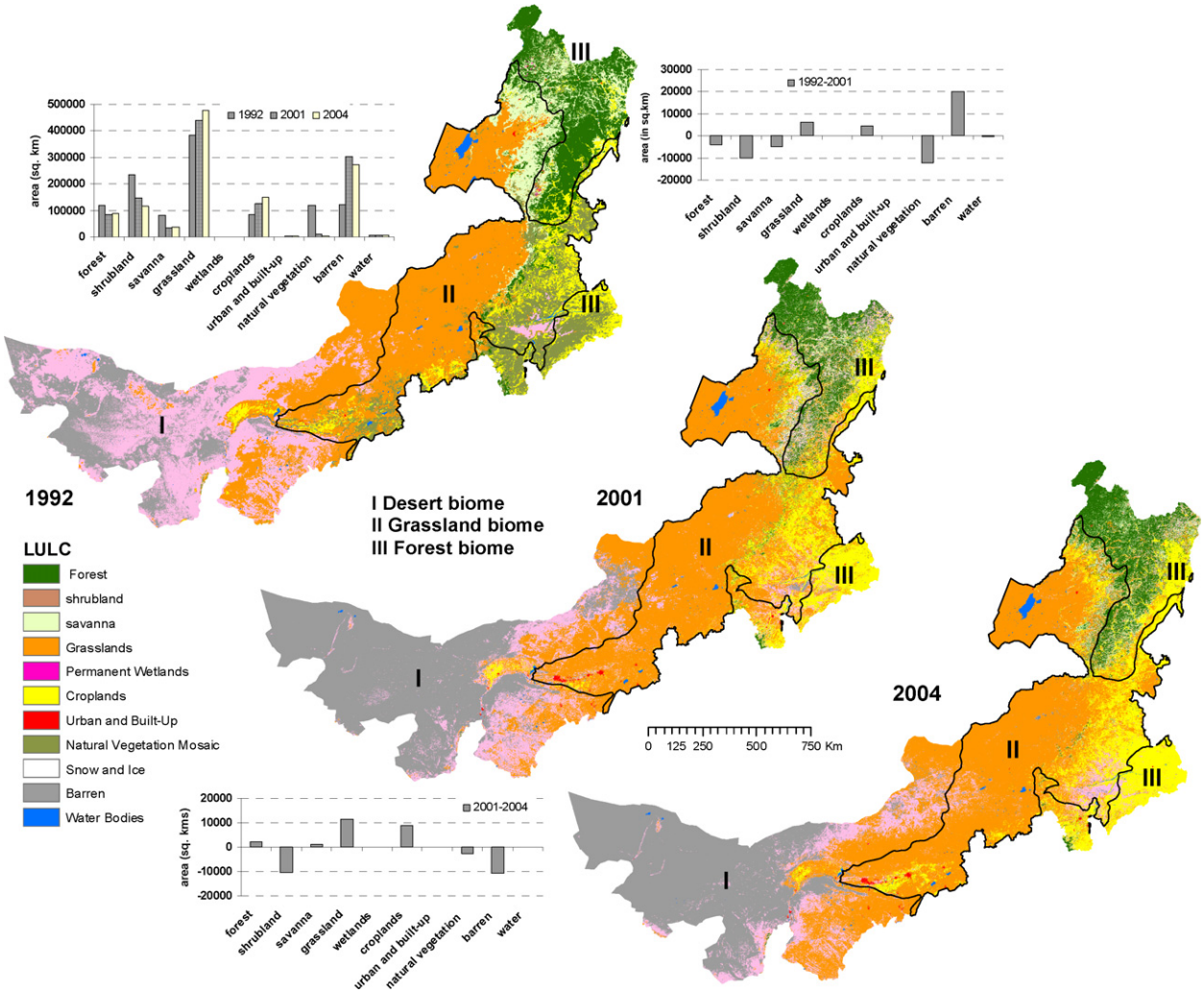

Figure 1. Changes in LCLU in Inner Mongolia between 1992 and 2001/2004 based on AVHHR (1992) and MODIS (2001 and 2004) derived IGBP classification, modified through recoding for forest, shrubland and savanna classes. Graphs denote proportions and changes in LCLU between 1992 to 2001 and 2004.

Program (IGBP) DISCover LCLU data for 1992 were obtained from the Global Land Cover Characterisation database (http://eros.usgs.gov/products/landcover/glcc.php). These data were projected to the Albers equal area projection with datum WGS 84, allowing an easy overlay of the two datasets for intercomparison. Both land cover datasets were classified according to the standard definitions of the IGBP which makes them comparable (Loveland *et al* 2000, Friedl *et al* 2002). The IGBP classification has 17 LCLU classes, out of which only a few were dominant in IM, suggesting a need for map generalization. For example, out of the five forest cover types in the IGBP classification scheme, only mixed forests cover was significant in areal extent. Some of the land cover classes, especially those in the minority, needed to be recoded (i.e. aggregated) to forest, shrubland and savanna so that the final classifications included 10 of the 17 IGBP classes (table 1). Evergreen needleleaf, deciduous needleleaf, deciduous broadleaf and mixed forests were recoded to forest; closed and open shrublands were recoded to shrubland, whereas woody savanna and savanna were recoded to savanna. In addition, the recoded IGBP datasets were overlaid (figure 1) with desert, grassland and forest biomes derived from WWF terrestrial ecoregion boundaries (http://www.worldwildlife.org/science/data/terreco.cfm).

2.3. Accuracy estimates of land cover data

The IGBP DISCover is a second generation land cover dataset and was derived from 1 km AVHRR 10 day composites for April 1992 to March 1993 and had 17 classes based on the IGBP standard (Loveland and Belward 1997, Loveland *et al* 2000). IGBP DISCover original accuracy estimates range from sample point accuracy of 59.4% and area weighted accuracy 66.9% (Scepan 1999): these accuracy figures were based on random sample stratified sampling by land cover type (Belward *et al* 1999). Higher resolution Landsat/SPOT images were independently interpreted for validation, with the majority of the three agreeing on the land cover type (Scepan 1999). The revised accuracy figures based on majority rule ranged from 73.5% to 78.7%, the area weighed estimate (Scepan 1999).

A parallel validation approach investigated the accuracy of the dataset in climate modeling (Defries and Los 1999). The

Table 1. Change in IGBP LULC at regional level between 1992 and 2001/2004 in km^2 (%). Δ denotes rate of change.

LULC type	1992	2001	2004	Δ1992–2001	Δ2001–2004	Δ1992–2004
Forest	118 438 (10.28)	83 443 (7.24)	89 651 (7.78)	−34 995 (−3.03)	6208 (0.53)	−28 787 (−2.49)
Shrubland	235 747 (20.46)	145 333 (12.61)	114 281 (9.92)	−90 414 (−7.84)	−31 052 (−2.69)	−121 466 (−10.54)
Savanna	80 351 (6.97)	35 422 (3.07)	38 254 (3.32)	−44 929 (−3.89)	2832 (0.24)	−42 097 (−3.65)
Grassland	383 102 (33.52)	439 938 (38.19)	474 754 (41.21)	56 836 (4.93)	34 816 (3.01)	91 652 (7.95)
Wetland	548 (0.04)	211 (0.01)	317 (0.02)	−337 (−0.02)	106 (0.00)	−231 (−0.02)
Cropland	84 845 (7.36)	124 448 (10.80)	150 991 (13.10)	39 603 (3.43)	26 543 (2.30)	66 146 (5.74)
Urban	620 (0.05)	2167 (0.18)	2197 (0.19)	1547 (0.13)	30 (0.00)	1577 (0.13)
Crop/natural vegetation	120 098 (10.42)	11 778 (1.02)	4197 (0.36)	−108 320 (−9.40)	−7581 (−0.65)	−115 901 (−10.06)
Barren	120 951 (10.42)	303 612 (26.35)	271 741 (23.58)	182 661 (15.86)	−31 871 (−2.77)	150 790 (13.08)
Water	7257 (0.63)	5452 (0.47)	5565 (0.48)	−1805 (−0.15)	113 (0.00)	−1692 (−0.14)
Sum	1151 957	1151 806	1151 957			

IGBP classes were aggregated into two groups corresponding to key variables in climate modeling, leaf area index (LAI) and surface roughness. The accuracy figures were reported to be 84.5% and 82.4% for LAI and surface roughness, respectively. The area weighed accuracy of the two variables was higher at 90.2% and 87.8%, respectively (Defries and Los 1999).

The MODIS global land cover product was derived from MODIS 1 km resolution data using a state of the art supervised classification system with a decision tree classifier and is representative of third generation land cover product technology (Friedl *et al* 2002). The MODIS dataset is equivalent to the IGBP DISCover global 1 km land cover dataset and distinguishes the same 17 classes (Wu *et al* 2008). Globally, an area weighed accuracy of 71.6 (±0.25)% has been reported (Friedl 2002, Wu *et al* 2008). Accuracy estimates for continental regions vary, with Eurasia reported to have 67.8 (±0.40)% overall accuracy. Global accuracy estimates for the dominant IGBP classes in IM were grassland 66%, cropland 58%, open shrubland 85%, mixed forest 65% and barren 74.5%.

2.4. Quantifying landscape structure

The FRAGSTATS program was used to compute quantitative metrics for describing landscape structure (McGarigal *et al* 2002). We chose the metrics most appropriate to our research based on previous large-scale, multi-temporal landscape fragmentation/LCLU change trajectory studies conducted on the Tibetan Plateau (Wang *et al* 2008), in the Tarim Basin, northwest China (Zhou *et al* 2008) and in the Heihe river basin (Lu *et al* 2003).

The metrics chosen for this study were: (1) area metrics (e.g. the number of patches, patch density), (2) contagion/interspersion metrics such as the aggregation index (AI), the IJI and the clumpy index, and (3) cohesion to represent connectivity metrics. FRAGSTATS was run using signed 8 bit IGBP classification in ERDAS format. In addition, the Shannon and Simpson diversity indices were calculated to measure heterogeneity in the landscape (McGarigal *et al* 2002, Lu *et al* 2003).

3. Results

3.1. Regional scale

The changes in IM's LCLU between 1992 and 2001/2004 are most obvious in the dominant cover types (i.e. grassland, shrubland, agriculture and barren cover types) (figure 1). Grassland, the most dominant cover, increased from 0.38 to 0.47 million km^2 (33.25% in 1992 to 41.21% of the total area in 2004) (table 1). Cropland, the major land use class, increased from 0.08 to 0.15 million km^2 (7.36% in 1992 to 13.10% in 2004). The largest increase in LCLU for all types was for barren cover, from 0.12 to 0.27 million km^2 (10.49% in 1992 to 23.58% in 2004). A decreasing trend was found in shrubland, from 0.23 in 1992 to 0.11 million km^2 in 2004 (20.46–9.92%). The proportion of forest and savanna also decreased from 0.11 to 0.08 million km^2 and 0.08 to 0.03 million km^2 (by 3%) between 1992 and 2004. An increasing trend was found in urban/built-up land from 620 km^2 in 1992 to 2197 km^2 in 2004 (from 0.05% to 0.19% in 2004) (table 1).

The number of patches between 1992 and 2001/2004 increased for all cover types, with the single exception of natural vegetation mosaic class (i.e. regrowth or crop rotation) (figure 2). The increase was the greatest for shrubland, followed by grassland, savanna, cropland, forest and barren (figure 2). The barren cover, however, showed a maximum increase in patch density between the two time periods, followed by forest. We also detected decreasing cohesion, especially in the minority classes (e.g., savanna, permanent wetland, and natural vegetation mosaic classes). However, the increase in urban land was coupled with no changes for cohesion in the dominant cover types between 1992 and 2001/2004. We found a significant decrease in the AI for

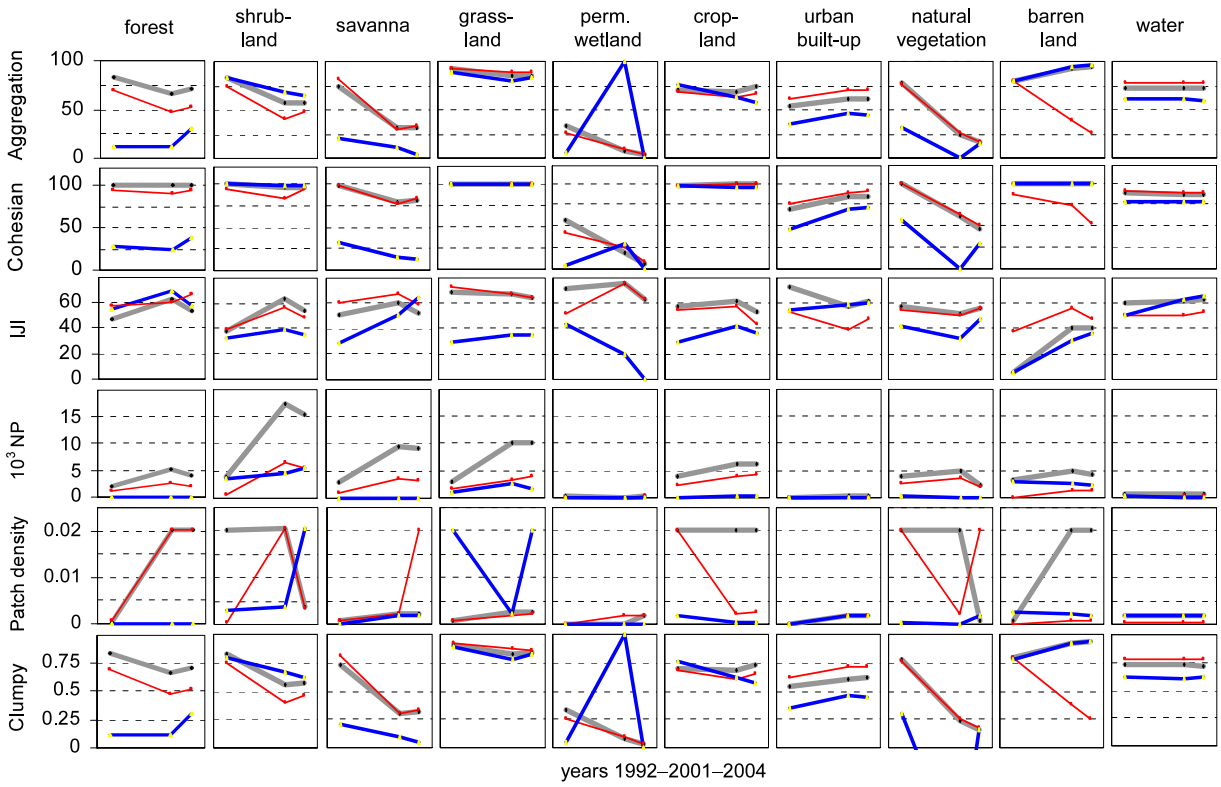

Figure 2. Changes in landscape metrics for regional scale (gray), grassland biome (red) and desert biome (blue) for the 1992 AVHRR derived and 2001/2004 MODIS derived IGBP classification.

shrubland, savanna, permanent wetland and natural vegetation mosaic types, but an increase in the AI for the barren class type and, to a lesser extent, the urban type (figure 2).

The IJI increased for barren (maximum increase) and natural cover types (e.g. shrubland and forest), but remained constant for other dominant cover types such as grassland and cropland. At the same time, there was a decrease in the IJI for the urban/built-up class. The clumpy index, akin to the AI, showed a decreasing trend in the natural vegetation mosaic, followed by forest, shrubland, savanna, permanent wetland and also to a small extent in grassland cover. However, the barren cover and urban/built-up land use indicated an increase in clumpiness. Decreasing landscape heterogeneity was measured by Shannon's and Simpson's diversity and evenness indices (table 3).

3.2. Grassland biome

Within the grassland biome, grassland cover increased from 0.25 to 0.32 million km^2 (54.76–69.89%) between 1992 and 2004, followed by the shrubland cover, which increased from 9975 to 25 973 km^2 (from 2.14% to 5.59%) (table 2). The savanna decreased from 44 620 to 12 809 km^2 (9.6–2.7%), while cropland increased from 49 105 to 75 816 km^2 (10.57–16.32%) between 1992 and 2004 (table 2). Urban land use increased from 384 to 1363 km^2 (0.08–0.28%) while barren cover increased from 129 to 2796 km^2 (0.02–0.60%).

The number of patches increased between 1992 and 2001/2004, with maximum increase in the shrubland class, followed by the grassland, savanna and forest. There was also an increase in the cropland and barren cover type. The patch density index showed a maximum increase in barren cover between 1992 and 2001/2004, followed by forest and savanna cover types. The patch density of the cropland for the same period decreased, while that of other cover types showed no obvious change.

The cohesion index decreased in the savanna, permanent wetland and natural vegetation mosaic classes but increased in the urban land use class. There were no changes for cohesion in the dominant cover types between 1992 and 2001/2004. However, there was a decrease of bare cover class within the grassland biome. There was a significant decrease in the AI for shrubland, savanna, permanent wetland and barren and natural vegetation mosaic types. On the other hand, there was an increase in the AI for the urban land use class (figure 2).

The IJI increased for barren cover type and, to a lesser extent, natural cover types (e.g. shrubland and forest), but did not change for grassland. There was a slight decrease in the IJI for cropland and urban/built-up cover. There was a decrease in the clumpy index, especially with the natural vegetation mosaic (maximum decrease), followed by forest, shrubland, savanna and permanent wetland. However, the barren cover and urban/built-up land use showed an increase in clumpiness. There was a decrease in landscape heterogeneity in the grassland biome, indicated by decreasing the Shannon and Simpson diversity and evenness indices (table 3).

3.3. Desert biome

The desert biome had an increase in barren cover from 0.11 to 0.26 million km^2 (25.82–56.61%) and urban land use from

Table 2. Change in IGBP LULC at biome level between 1992 and 2001/2004 in km^2 (%). Δ denotes rate of change.

LULC type	1992	2001	2004	Δ1992–2001	Δ2001–2004
			Desert biome		
Forest	13 (0.00)	12 (0.00)	10 (0.00)	−0.11 (0.00)	−0.22 (0.00)
Shrubland	212 702 (46.02)	87 345 (18.90)	70 975 (15.35)	−13 928.56 (−3.01)	−1818.89 (−0.39)
Savanna	51 (0.01)	83 (0.01)	85 (0.01)	3.56 (0.00)	0.22 (0.00)
Grassland	123 457 (26.71)	82 544 (17.86)	125 737 (27.20)	−4545.89 (−0.98)	4799.22 (1.04)
Wetland	13 (0.00)	2 (0.00)	0	−1.22 (0.00)	−0.22 (0.00)
Cropland	4392 (0.95)	3216 (0.69)	2177 (0.47)	−130.67 (−0.03)	−115.44 (−0.22)
Urban	51 (0.01)	454 (0.09)	451 (0.09)	44.78 (0.01)	−0.33 (0.00)
Crop/natural vegetation	725 (0.15)	2 (0.00)	109 (0.02)	−80.33 (−0.02)	11.89 (0.00)
Barren	119 320 (25.82)	287 478 (62.21)	261 604 (56.61)	18 684.22 (4.04)	−2874.89 (−0.62)
Water	1379 (0.29)	961 (0.20)	955 (0.20)	−46.44 (−0.01)	−0.67 (0.00)
Sum	462 103	462 097	462 103		
			Grassland biome		
Forest	20 592 (4.43)	12 573 (2.70)	13 306 (2.86)	−891.00 (−0.19)	81.44 (0.02)
Shrubland	9975 (2.14)	30 734 (6.61)	25 973 (5.59)	2306.56 (0.50)	−529.00 (−0.11)
Savanna	44 620 (9.60)	11 246 (2.42)	12 809 (2.75)	−3708.22 (−0.80)	173.67 (0.04)
Grassland	254 348 (54.76)	326 834 (70.38)	324 639 (69.89)	8054.00 (1.74)	−243.89 (−0.05)
Wetland	101 (0.02)	138 (0.02)	240 (0.05)	4.11 (0.00)	11.33 (0.00)
Cropland	49 105 (10.57)	63 729 (13.72)	75 816 (16.32)	1624.89 (0.35)	1343.00 (0.29)
Urban	384 (0.08)	1320 (0.28)	1363 (0.29)	104.00 (0.02)	4.78 (0.00)
Crop/natural vegetation	79 660 (17.15)	10 007 (2.15)	3232 (0.69)	−7739.22 (−1.67)	−752.78 (−0.16)
Barren	129 (0.02)	3596 (0.77)	2796 (0.60)	385.22 (0.08)	−88.89 (−0.02)
Water	5558 (1.19)	4190 (0.90)	4289 (0.92)	−152.00 (−0.03)	11.00 (0.00)
Sum	464 472	464 367	464 463		

51 to 451 km^2 (0.01–0.09%) between 1992 and 2004 (table 2), while the proportion of grassland cover remained unchanged (table 2). On the other hand, there was a significant decrease in shrubland cover from 0.21 to 0.07 million km^2 (46.02% in 1992 to 15.35% in 2004) (table 2).

The number of patches in the desert biome showed a maximum increase in the shrubland class between 1992 and 2001/2004, followed by the grassland and the barren cover. There was an increase between 1992 and 2001/2004 in the shrubland cover type while other covers showed little or no change.

Cohesion decreased in the savanna and natural vegetation mosaic cover types while there were no changes in grassland, cropland and shrubland types between 1992 and 2001/2004. However, there was an increase in cohesion in the urban land use class. The AI decreased for the shrubland, savanna, cropland and natural vegetation mosaic types but increased for forest, barren and urban land use types (figure 2). The IJI increased for the barren, savanna and, to a small extent, urban cover, between the two decades. There was a marked decrease in the clumpiness for the shrubland, savanna and cropland classes with little or no change in the grassland cover type. The clumpy index increased in the barren cover, forest and urban/built-up cover types. There was a decrease in the Shannon diversity index between 1992 and 2001/04, indicating increasing homogeneity in the desert landscape (table 3).

4. Discussion

The dominant grassland cover had increased in proportion from 1992 to 2004; however, it was more fragmented as indicated by the increasing number of patches at the regional and biome scales. At the same time, the increase in proportion of barren cover along with increasing patch density at both the regional and biome scales between 1992 and 2001/2004 is evidence for the growing desertification caused by overgrazing (Wu and Ci 2002). The shrublands, which occupy a transitional belt between the grassland and the desert, have decreased in proportion, with a subsequent increase in patchiness at the regional scale and patch density in the desert biome. However,

Table 3. Measure of landscape diversity for IM between 1992 and 2001/2004.

	SHDI[a]	SIDI[b]	SHEI[c]	SIEI[d]
		Regional		
1992	1.1355	0.4829	0.4735	0.5312
2001	1.0737	0.4783	0.4321	0.5217
2004	1.0651	0.4774	0.4286	0.5208
		Grassland biome		
1992	1.1241	0.5826	0.4688	0.6408
2001	1.0605	0.5659	0.4422	0.6225
2004	1.0758	0.5718	0.4672	0.6353
		Desert biome		
1992	0.9713	0.4499	0.4051	0.4949
2001	0.8857	0.437	0.3693	0.4807
2004	0.8771	0.4371	0.3658	0.4808

[a] SHDI—Shannon's diversity index.
[b] SIDI—Simpson's diversity index.
[c] SHEI—Shannon's evenness index.
[d] SIEI—Simpson's evenness index.

in the grassland biome, the proportion of shrubland cover increased, offering further evidence of gradual desertification eastward, along the desert–grassland ecotone (Cheng *et al* 2007). Within the desert–grassland ecotone, shrubland species such as *Artemisia halodendron* are sand dune stabilizing plants which play a key role in preventing sand blowout (Zhang *et al* 2004), whereas *Artemisia ordosica* is an indicator species for mid-level desertification (Cheng *et al* 2007). Studies conducted in the Heihe Basin, suggest that increasing homogeneity within the grassland/desert biomes might be a manifestation of the intensive anthropogenic modification of landscape as evidenced by the increase in irrigated farmland in an area with limited water resources (Lu *et al* 2003). Landscape homogeneity potentially threatens the loss of biodiversity and native patch types that have evolved to resist desertification (Li *et al* 2001) and facilitates the ingress of invasive shrub species (Cheng *et al* 2007).

We found an increase in the proportion of cropland cover and number of patches at the regional level—a possible consequence of a growing population and economy (Wang *et al* 2008). A nationwide study carried out at the 30 m Landsat scale suggested a per capita increase of croplands in the northeast and northwest provinces, including IM (Liu *et al* 2005). However, these regions (e.g. the Hetao irrigation basin in IM) are also under severe water stress, with depleting groundwater levels leading to nitrate leaching and increased soil salinity due to the increased irrigation demands of the growing population (Feng *et al* 2005). The Hetao irrigation basin is one of the three largest irrigation districts in China (Feng *et al* 2005) and the primary cereal crop is wheat, which has high water use and evapotranspiration (He *et al* 2007) in an increasingly drier climate (Zhai and Pan 2003).

Some of the minority cover types such as savanna, permanent wetland and natural vegetation mosaic showed a decrease in the cohesion index with no change in the dominant cover types. This could be attributed to the landscape becoming more homogeneous, characterized by the dominant land cover types (Zhou *et al* 2008). The increased cohesion for the urban/built-up cover at the regional scale and in both the grassland and desert biome offers evidence of a growing population driven by a growing economy and subsequent urban sprawl (Qi and Chopping 2007). Studies using night-time light data derived from the defense meteorological satellite program (DMSP) operational linescan system (OLS) have also found increases in the extent of urban areas in the Yellow River watershed and confirm our findings (Qi and Chopping 2007).

The general decrease in the AI for the vegetated cover classes such as shrubland, savanna, wetland and natural vegetation mosaic from 1992 to 2001/2004 is consistent with the fragmented minority classes within the dominant landscape matrix (grassland and desert cover types). On the other hand, the increase in the AI for the barren cover offers further proof that the desert matrix is more homogeneous than in the past. The increase in the AI for urban cover corroborates with increasing cohesion and suggests expanding urban settlements (Zhou *et al* 2008). This increase in urban areas has led to an increasing non-agricultural water demand and transfer from agricultural use to municipal and industrial needs, further adding to regional water stress and compounding the problems of efficient water management (Cai 2008).

It is important to note the increase in the AI for forest cover in the desert. In the recent past, attempts have been made by the authorities to stem the tide of advancing desertification through the use of poplar plantations serving as shelter belts (Chang *et al* 2006, Hu *et al* 2008). Such large-scale plantations may significantly alter the water budget in this fragile semi-arid region, with higher evapotranspiration than the native species and therefore are of limited utility as regional climate predictions suggest a drier climate with lower water availability (Wilske *et al* 2009). An experimental study in dune stabilization, conducted in 1997 in the Horqin Sandy Land to evaluate different methods, found that the most successful combination was planting *Artemisia halodendron* as well as corn and wheat straw fencing (Zhang *et al* 2004).

The increase in the IJI between the two time periods for natural cover types such shrubland, forest and savanna (desert biome) is consistent with the results for cohesion, and the AI and offers proof for the interspersion of minor classes leading to a homogeneous matrix (Zhou *et al* 2008). At the same time, greater interspersion of the barren cover in the grassland biome as compared to the regional and desert biome corroborates with increasing proportion of shrubland and suggests desertification (Cheng *et al* 2007).

The segregation in natural cover classes such as forest, shrubland, savanna, permanent wetland, natural vegetation mosaic and, to a small extent, grassland cover is characteristic of a fragmented landscape brought about through a combination of intensive land use practices and climate change in a semi-arid region (Wang *et al* 2008, Zhou *et al* 2008). The increased aggregation of the urban and built-up LCLU type offers proof that urban sprawl has occurred in the last decade. Further proof of desertification is obtained from the increase in the clumpy index for barren cover both at the regional scale and in the desert biome.

Our findings need to be viewed in the context of the accuracy of the two land cover datasets. Some of the uncertainty in the 1 km AVHRR derived IGBP DISCover dataset, is owing to the resolution of the 1 km data set, which is also a first generation product. The dataset has artifacts owing to a variety of factors which include cloud cover, gaps in data acquisition and misregistration. Unlike the MODIS land cover, the dataset does not have a quality assurance/quality control flag layer (Hansen and Reed 2000).

Recently, Wu *et al* (2008) carried out a comparative validation of four land cover datasets of 1 km resolution across China. This study compared the IGBP DISCover and MODIS land cover with the higher resolution Landsat derived National Land Cover Dataset 2000 produced by the Chinese Academy of Sciences (Wu *et al* 2008). The analysis found discrepancies in total area estimates as well as spatial disagreement in cropland cover.

The MODIS land cover dataset was most representative of cropland cover in China with a bias of 2.9% from the National Land Cover Dataset (Wu *et al* 2008). On the other hand, IGBP DISCover overestimated cropland cover by 26% and had the highest bias (37.4%). At the provincial level, cropland estimates for IM by IGBP DISCover and MODIS land cover differed from the National Land Cover Dataset with a bias of 67% and 18.2%. However, it must be noted that the IGBP DISCover dataset is based on AVHRR data acquired between April 1992 and March 1993 and the MODIS data represent 2004 acquisition. Therefore any discrepancy might indicate change in LCLU over time rather than misclassification error. The study also reported higher accuracies in cropland cover estimates for all land cover datasets in north and northeastern China (including IM) which were largely homogeneous and had large contiguous areas under cultivation as compared to the northwest and southeast regions which were more heterogeneous and had smaller land holding (Wu *et al* 2008).

Our study is limited by the non-availability of IGBP level classification at a resolution of <1 km in the AVHRR era before the advent of MODIS. A comparison of the currently available 500 m resolution IGBP data with a similar dataset in the 1990s would have greatly improved and validated our understanding of changes in LCLU and landscape structure. In order to evaluate the LCLU change trajectories over the past decade, we propose to continue monitoring them in the present to see if they are consistent. The MODIS 500 m LCLU dataset can be used to monitor LCLU change trajectories in IM in the present decade (2000–2010) and monitor structural changes in critical cover types such as shrubland that indicate water stress. The higher resolution will allow better characterization of ecotone shifts, e.g. as at the desert–grassland transition as well as increasing cropland and agricultural land use in the context of climate change. In addition to categorical change, we are also monitoring continuous changes in biophysical variables such as GPP, evapotranspiration, vegetation water content and stress in response to climate drivers. At present we have extended the domain of our study across the international border in to neighboring Outer Mongolia to compare LCLU trajectories. Preliminary results suggest significant differences in LCLU and GPP as Outer and Inner Mongolia, although part of the Mongolian grasslands ecoregion, differ in ethnicity (Mongolian and Han Chinese), economic policy, land management, population growth and density which have implications for policy makers.

5. Conclusions

Our analysis at the regional and biome scales offers proof of a fragmented landscape characterized by the increase in the number of patches, especially in the dominant land cover types such as grassland, shrubland and barren. Furthermore, the increase in portions of dominant grassland and barren cover within the decade suggests that the landscape is becoming more homogeneous and water stressed. The decrease in proportions of rare cover types corroborates this finding. The effects of increasing socio-economic growth are manifested in increasing cohesion and aggregation of urban/built-up patches as well as an increasing number of patches and interspersion of cropland cover in this fragile semi-arid region.

Acknowledgments

This study was supported by the National Aeronautics and Space Administration (NASA grant NEWS 2004 NRA: NN-H-04-Z-YS-005-N) as part of the Energy and Water Cycle Study. Partial support was received from the Institute of Botany, Chinese Academy of Sciences.

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