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

Ranjeet John¹,³, Jiquan Chen¹,², Nan Lu¹ and Burkhard Wilske¹

¹ Department of Environmental Sciences, University of Toledo, Toledo, OH 43606, USA
² Institute of Botany, Chinese Academy of Sciences, Xiangshan, Beijing 100093, People’s Republic of China
³ Address for correspondence: Department of Environmental Sciences, University of Toledo, 2801 West Bancroft Street, Toledo, OH 43606-3390, USA.

E-mail: ranjeet.john@utoledo.edu

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 km², respectively, have increased proportionally. Cropland and urban land use also increased to 0.15 million km² and 2197 km², 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 C−2 yr−1 in desert regions in the west to about 4000 g C−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
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 km2 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 km², 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 AVHRR (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 of 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 weighted estimate (Scepan 1999).

A parallel validation approach investigated the accuracy of the dataset in climate modeling (Defries and Los 1999). The
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. 2003). 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/interpersion 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 km² (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 km² (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 km² (10.49% in 1992 to 23.58% in 2004). A decreasing trend was found in shrubland, agriculture and barren cover types (figure 1). 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

| LULC type  | 1992 | 2001 | 2004 | Δ1992–2001 | Δ2001–2004 | Δ1992–2004 |
|-----------|------|------|------|------------|------------|------------|
| Forest    | 118,438 | 83,443 | 89,651 | −34,995 (−3.03) | 620,8 (0.53) | −28,787 (−2.49) |
| Shrubland | 235,747 | 145,333 | 114,281 | −90,414 (−7.84) | −31,052 (−2.69) | −121,466 (−10.54) |
| Savanna   | 80,351 | 35,422 | 38,254 | −44,929 (−3.39) | 283,2 (0.24) | −42,097 (−3.65) |
| Grassland | 383,102 | 439,938 | 474,754 | 56,836 | 34,816 | 91,652 |
| Wetland   | 548 (0.04) | 211 (0.01) | 317 (0.02) | −337 (−0.02) | 106,0 (0.00) | −231 (−0.02) |
| Cropland  | 84,845 | 124,448 | 150,991 | 39,603 | 26,543 | 66,146 |
| Urban     | 620 (0.05) | 2167 (0.18) | 2197 (0.19) | 154,7 (0.13) | 30,0 (0.00) | 1577 (0.13) |
| Barren    | 120,098 | 11778 | 4197 | −108,320 (−9.40) | −758,1 (−0.65) | −115,901 (−10.06) |
| Water     | 7257 | 5452 | 5565 | −1805 (−0.15) | 113,0 (0.00) | −1692 (−0.14) |
| Sum       | 1151,957 | 1151,806 | 1151,957 | 0 | 0 | 0 |
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 km² (54.76–69.89%) between 1992 and 2004, followed by the shrubland cover, which increased from 9975 to 25 973 km² (from 2.14% to 5.59%) (table 2). The savanna decreased from 44 620 to 12 809 km² (9.6–2.7%), while cropland increased from 49 105 to 75 816 km² (10.57–16.32%) between 1992 and 2004 (table 2). Urban land use increased from 384 to 1363 km² (0.08–0.28%) while barren cover increased from 129 to 2796 km² (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 km² (25.82–56.61%) and urban land use from
1992 to 15.35% in 2004) (table 2). On the other hand, there was a significant decrease while the proportion of grassland cover remained unchanged 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).

### Table 2. Change in IGBP LULC at biome level between 1992 and 2001/2004 in km² (%). 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                   | 212702 (46.02) | 87345 (18.90) | 70975 (15.35) | −13928.56 (−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                   | 123457 (26.71) | 82544 (17.86) | 125737 (27.20) | −4545.89 (−0.98) | 4799.22 |
| Wetland                     | 13 (0.00)  | 2 (0.00)   | 0          | −1.22 (0.00) | −0.22 (0.00) |
| Crop                        | 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) |
| Desert biome                |            |            |            |            |            |
| Barren                      | 119320 (25.82) | 287478 (62.21) | 261604 (56.61) | 18684.22 (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                         | 462103     | 462097     | 462103     |            |            |
| **Grassland biome**         |            |            |            |            |            |
| Forest                      | 20592 (4.43) | 12573 (2.70) | 13306 (2.86) | −891.00 (−0.19) | 81.44 (0.02) |
| Shrubland                   | 9975 (2.14) | 30734 (6.61) | 25973 (5.59) | 2306.56 (0.50) | −529.00 (−0.11) |
| Savanna                     | 44620 (9.60) | 11246 (2.42) | 12809 (2.75) | −3708.22 (−0.80) | 173.67 (0.04) |
| Grassland                   | 254348 (54.76) | 326834 (70.38) | 324639 (69.89) | 8054.00 (1.74) | −243.89 (−0.05) |
| Wetland                     | 101102 (2.70) | 138004 (2.61) | 240005 (2.59) | 411.00 (0.00)  | 11.33 (0.00) |
| Crop                        | 49105 (10.57) | 63729 (13.72) | 75816 (16.32) | 1624.89 (0.35) | 1343.00 (0.29) |
| Urban                       | 38408 (3.02) | 132008 (2.61) | 136300 (2.62) | 10400.00 (0.02) | 4.78 (0.00) |
| Crop/natural vegetation     | 79660 (17.15) | 100007 (2.15) | 3232 (0.69) | −7739.22 (−1.67) | −752.78 (−0.16) |
| Barren                      | 129002 (1.19) | 359606 (0.90) | 279600 (0.92) | 385.22 (0.08)  | −88.89 (−0.02) |
| Water                       | 5558 (0.90) | 4190 (0.92) | 4289 (0.92) | −152.00 (−0.03) | 11.00 (0.00) |
| Sum                         | 464472     | 464367     | 464463     |            |            |

51 to 451 km² (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 km² (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,
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: NNH-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.

References

Angell D L and McClaran M P 2001 Long-term influences of livestock management and a non-native grass on grass dynamics in the Desert Grassland J. Arid Environ. 49 507–20

Baskent E Z and Jordan G A 1996 Designing forest management to control spatial structure of landscapes Landsc. Urban Plan. 34 55–74

Belward A S, Estes J E and Kline K D 1999 The IGBP-DIS 1-Km Land-Cover Data Set DISCover: a project overview Photogramm. Eng. Remote Sens. 65 1013–20

Brogaard S, Runnstrom M and Seaquist J W 2005 Primary production of Inner Mongolia, China, between 1982 and 1999 estimated by a satellite data-driven light use efficiency model Glob. Planet. Change 45 313–32

Cai X 2008 Water Stress, water transfer and social equity in Northern China—implications for policy reforms J. Environ. Manage. 87 14–25

Chang X, Zhao W, Zhang Z and Su Y 2006 Sap flow and tree conduitance of shelter-belt in arid region of China Agric. Forest Meteorol. 138 132–41

Chase T N, Piepke R A, Knaff J, Kittel T and Eastman J 2000 A comparison of regional trends in 1979–1997 depth-averaged troposphere temperatures Int. J. Climatol. 20 503–18

Cheng X L, An S, Li B, Chen J, Lin G, Liu Y, Luo Y and Liu S 2006 Summer rain pulse size and rainwater uptake by three dominant desert plants in a desertified grassland ecosystem in northwestern China Plant Ecol. 184 1–12

Cheng X L, An S, Chen J, Li B, Liu Y and Liu S 2007 Spatial relationships among species, above-ground biomass, N, and P in degraded grasslands in Ordos Plateau, northwestern China J. Arid Environ. 68 652–67

Defries R S and Los S O 1999 Implications of land-cover misclassification for parameter estimates in global land-surface...
models: an example from the simple biosphere model (SiB2)

Ellis J 1992 Key issues in grassland studies Grasslands and Grassland Sciences in Northern China and J Ellis (Washington, DC: National Academy Press) pp 183–98

Feng Z Z, Wang X K and Feng Z W 2005 Soil N and salinity leaching after the autumn irrigation and its impact on groundwater in Hetao Irrigation District, China Agric. Water Manage. 71 131–43

Friedl M A 2002 Validation of the consistent-year V003 MODIS land cover product, available at http://geography.bu.edu/landcover/ userguide/consistent.htm last accessed 19 June 2009

Friedl M A et al 2002 Global land cover mapping from MODIS: algorithms and early results Remote Sens. Environ. 83 287–2

Grossman P Y et al 2009 The Northern Eurasia earth science partnership: an example of science applied to societal needs Bull. Am. Meteorol. Soc. 90 671–88

Hansen M and Reed B 2000 A comparison of the IGBP DISCover and University of Maryland 1 km global land cover products Int. J. Remote Sens. 21 1365–73

He B, Ose H, Wang Y and Takase K 2007 Measurement and modeling of evapotranspiration from an irrigated wheat field in the Hetao irrigation district of the Yellow River basin J. Japan Soc. Hydro. Water Resour. 20 8–16

Herzog F, Lausch A, Muller E, Thulke H H, Steinhardt U and Lehmann S 2001 Landscape metrics for assessment of landscape destruction and rehabilitation Environ. Manage. 29 1–7

Hu Y L, Zeng D H, Fan Z P, Chen G S, Zhao Q and Pepper D 2008 Changes in ecosystem carbon stocks following grassland afforestation of semiarid sandy soil in the southeastern Keerqin Sandy Lands, China J. Arid Environ. 72 2193–200

Hu Z Z, Yang S and Wu R 2003 Long-term climate variations in China and global warming signals J. Geophys. Res. 108 4614

Jiang G, Han X and Wu J 2006 Restoration and management of the Inner Mongolia Grassland require a sustainable strategy Ambio 35 269–70

John R, Chen J, Lu N, Liang C, Wei Y, Noormets A, Jiang G, Han X and Wu J 2006 Restoration and management of the Inner Mongolia Grassland require a sustainable strategy Ambio 35 269–70

John R, Chen J, Lu N, Guo K, Liang C, Wei Y, Noormets A, Ma K and Han X 2008 Predicting plant diversity based on remote sensing products in the semi-arid region of Inner Mongolia Remote Sens. Environ. 112 2018–32

Kang L, Han X, Zhang Z and Sun O J 2007 Grassland ecosystems in China: review of current knowledge and research advancement Phil. Trans. R. Soc. B 362 997–1008

Li S, Zhou Q and Wang L 2005 Road construction and landscape fragmentation in China J. Geol. Sci. 15 123–8

Li X, Lu L, Cheng G and Xiao H 2001 Quantifying landscape structure of the Heihe River Basin, north-west China using FRAGSTATS J. Arid Environ. 48 521–35

Lindemayer D B, Cunningham R B, Donnelly C F and Lesslie R 2002 On the use of landscape surrogates as ecological indicators in fragmented forests Forest Ecol. Manage. 159 203–16

Liu J, Liu M, Tian H, Zhuang D, Zhang Z, Zhang W, Tang X and Deng X 2005 Spatial and temporal patterns of China’s cropland during 1990–2000: an analysis based on Landsat TM data Remote Sens. Environ. 98 442–56

Lu L, Li X and Cheng G 2003 Landscape evolution in the middle Heihe River Basin of north-west China during the last decade J. Arid Environ. 53 395–408

Loveland T R and Belward A S 1997 The IGBP-DISCover global 1 km land cover data set, DISCover: first results Int. J. Remote Sens. 18 3289–295

Loveland T R, Reed B C, Brown J F, Olenh D O, Zhu Z, Yang L and Merchant J W 2000 Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data Int. J. Remote Sens. 21 1303–30

McAlpine C A and Eyre T J 2002 Testing landscape metrics as indicators of habitat loss and fragmentation in continuous eucalypt forests (Queensland, Australia) Landsc. Ecol. 7 711–28

McGarigal K, Cushman S A, Neel M C and Ene E 2002 FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps Computer software program produced by the authors at the University of Massachusetts, Amherst, available at www.umass.edu/landeco/research/fragstats/fragstats.html

Noss R F 1999 Assessing and monitoring forest biodiversity: a suggested framework for indicators Forest Ecol. Manage. 115 35–46

Ojima D S, Xiao X, Chuluun T and Zhang X S 1998 Asian Change in the Context of Global Climate Change: Impact of Natural and Anthropogenic Changes in Asia on Global Biogeochemistry ed J Galloway and J M Melillo (Cambridge: Cambridge University Press)

Olson D M et al 2001 Terrestrial ecoregions of the world: a new map of life on earth Bioscienc 51 933–8

Qi X and Chopping M 2007 Expansion of urban area in the Yellow Riverzone. Inner Mongolia Autonomous Region, China, from DMSP OLS nighttime lights data Proc. IEEE Int. Geoscience and Remote Sensing Symp. 2007 (Barcelona, July 2007) doi:10.1109/IGARSS.2007.4423222

Riitters K H, Wickham J D, O’Neill R, Jones K B, Smith E R, Coulston J W, Wade T G and Smith J H 2002 Fragmentation of continental United States forests Ecosystems 5 815–22

Scepan J 1999 Thematic validation of high-resolution global land-cover data sets Photogramm. Eng. Remote Sens. 65 1051–60

Strahler A, Muchoney D, Borak J, Friedl M, Gopal S, Lambin E and Moody A 1999 MODIS land cover product algorithm theoretical basis document (ATBD) Version 5.0 MODIS Land Cover and Land-Cover Change, available at http://modis.gsfc.nasa.gov/data/atbd/atbd_mod12.pdf

Turner M G, Gardner R H and O’Neill R V 2001 Landscape Ecology. Theory and Practice: Pattern and Process (New York: Springer)

Wang X, Zheng D and Shen Y 2008 Land use change its driving forces on the Tibetan Plateau during 1990–2000 Catena 72 56–66

Wickham J D, Riitters K H, Wade T G and Homer C 2008 Temporal change in fragmentation of continental US forests Landsc. Ecol. 23 891–8

Wilske B et al 2009 Poplar plantation alters water balance in semiarid Inner Mongolia J. Environ. Manage. 90 2762–70

Wu B and Ci L J 2002 Landscape change and desertification development in the Mu Us Sandland, Northern China J. Arid Environ. 50 429–44

Wu W, Shibasaki R, Yang P, Ongaro L, Zhou Q and Tang H 2008 Validation and comparison of 1 km global land cover products in China Int. J. Remote Sens. 29 3769–85

Ye D Z, Zhou J F and Liu J Y 2000 Causes of sandstormy weather in northern China and control measures Acta Geogr. Sin. 55 513–20

Yu F, Price K P, Ellis J and Shi P 2003 Response of seasonal vegetation development to climatic variations in eastern central Asia Remote Sens. Environ. 87 42–54

Zhang T H, Zhao H L, Li S G, Li F R, Shirato Y, Ohkuro T and Taniyama I 2004 A comparison of different measures for stabilizing moving sand dunes in the Horqin Sandy Land of Inner Mongolia, China Acta Geogr. Sin. 59 123–8