



Transitions in land use and cover and their dynamic mechanisms in the Haihe River Basin, China

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Abstract

In this study, 1-km gridded land use maps from 1980, 1990, 1995, 2000, 2005, 2010, and 2015 were used to analyze transitions in the spatial distribution and land use/cover in the Haihe River Basin (HRB) of China. The patterns of changes in land use/cover were characterized by an increase in rural–urban industrial lands and decreases in cropland, forestland, grassland, water, and unused land. Meanwhile, the land use/cover in 93% of the area in the HRB remained unchanged from 1980 to 2015. The results of a multi-temporal analysis of transition pathways from and to different land use/cover classes clearly revealed the transitional process of each class. Further analysis of the dynamic mechanisms underlying the five most common transitions showed that croplands in the areas with better locations (proximal to a city), traffic (near roads), topography (low altitude and flat terrain), and hydrology (close to a river) and rapid economic and population growth were likely to be changed into construction lands. Grasslands in areas at low altitude, over flat terrain, near a city, and with decreasing rainfall were easily changed to croplands, and croplands and forestlands in areas with unfavorable topographic (high altitude and uneven terrain) and hydrological (far from a river) conditions were likely to be converted into grasslands.

Keywords Land use · Land cover · Land use transition · Haihe river basin

Introduction

Land use is defined as the human manipulation of the land to fulfill a need or desire. As a result of land use, land cover refers to the physical conditions of the land surface (Turner and Meyer 1991). Land-use change involves either a shift

from one use to another (e.g., from dry land to rice paddy) or the expansion and intensification of an existing form, such as from subsistence to commercial farming (Matson et al. 1997). The influences of land use on the environment and natural ecology, such as biosphere–atmosphere interactions, biodiversity, surface radioactive forcing, biogeochemical cycles, and the sustainable utilization of environmental resources (Liu et al. 2014a, b), are mainly achieved through land cover; thus, land use and land cover are interrelated (Quan et al. 2006).

In 2005, the Global Land Project (GLP) was launched to deepen the understanding of the coupled human land environmental system in the context of earth system evolution. Then, the “Future Earth” plan (2014–2023), and the Sustainable Development Goals (SDGs) (2015–2030) were sponsored successively by International Council for Science (ICSU), International Social Sciences Council (ISSC), and Sustainable Development Goals (SDGs) (2015–2030), respectively. The impacts and challenges of global environmental change on regions, countries, and societies and sustainable development were the themes of these two plans. Understanding regional land use/cover transitions are vitally important to regional environmental management and

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sustainable development. Thus, the study on land use/cover transitions has been a popular theme of global environmental studies that link human activities to natural ecological processes (Mooney et al. 2013; Fan et al. 2008; Pijanowski and Robinson 2011; Kadioğullari and Baskent 2008).

China has experienced tremendous change in all aspects since the reform and opening of China in the 1980s, and land use/cover transitions have gained increasing attention. Additionally, the increases in both data and projects make the study of land use/cover transitions convenient. Currently, a 1:100,000-scale national land-use change vector database and a 1-km gridded database of component classifiers have been completed for seven periods: the 1980s, 1990, 1995, 2000, 2005, 2010, and 2015. Based on this database and local RS images, along with other related data, land use/cover transition studies have been performed in many regions of China at different spatial scales and temporal ranges. For example, at the national scale, Liu et al. (2003, 2009, 2014a, b, 2018a, b) studied spatiotemporal dynamic changes in land use and the driving forces in China in the early 21st Century, the 2000s, the 1990s, the late 1980s, and from 2010–2015. On the regional scale, Cao et al. (2011) analyzed the quantitative changes in land use in the Three Gorges Reservoir area of China from 1975 to 2005, Wei et al. (2017) obtained information on land-use changes in the Shiyang River Basin from 1986 to 2015 using RS data, and Fan et al. (2008) detected and predicted land use/cover transitions in the Core Corridor of the Pearl River Delta from 1998–2003 using Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) images. At the urban scale, the dynamic processes of the spatiotemporal characteristics of land-use change in several cities have been analyzed in many studies (e.g., Kuming, Changsha, Xiamen, and Shanghai) from the 1980s to recent years (Sun et al. 2016; Chen et al. 2015; Quan et al. 2006; Shi et al. 2012). Most of these studies have revealed that large changes have occurred in land use patterns in China, and these changes are characterized by a decrease in farmland and an increase in urban areas.

The Haihe River Basin (HRB), covers all of Beijing and Tianjin, along with parts of Hebei, Shanxi, Shandong, Henan, Liaoning, and Inner Mongolia. This is a very important basin in China because it is the political center of China, as it contains the capital, Beijing. Therefore, the HRB is the pioneering and demonstration area of various reform measures nationwide, and the pattern of land use/cover changes can represent those across China. Secondly, the HRB is one of the dominant economic centers in China. Beijing is second only to Shanghai as the largest economy in China, and Tianjin, another municipality in the HRB, is the largest port city in northern China. The province of Hebei, with 91% of its area located in the HRB, is one of the important energy and heavy industry bases in China. Since the reform and opening of China in the 1980s, the HRB has experienced

great change and rapid economic development; thus, land use/cover has inevitably been changed in this area. Finally, the HRB is one of the most populated areas in China, with 13.6% of the national population and only 3.3% of the land area, according to statistics from 2015 (Citation). Thus, the higher intensity of human activities may lead to more drastic land use/cover changes than observed in other Chinese basins.

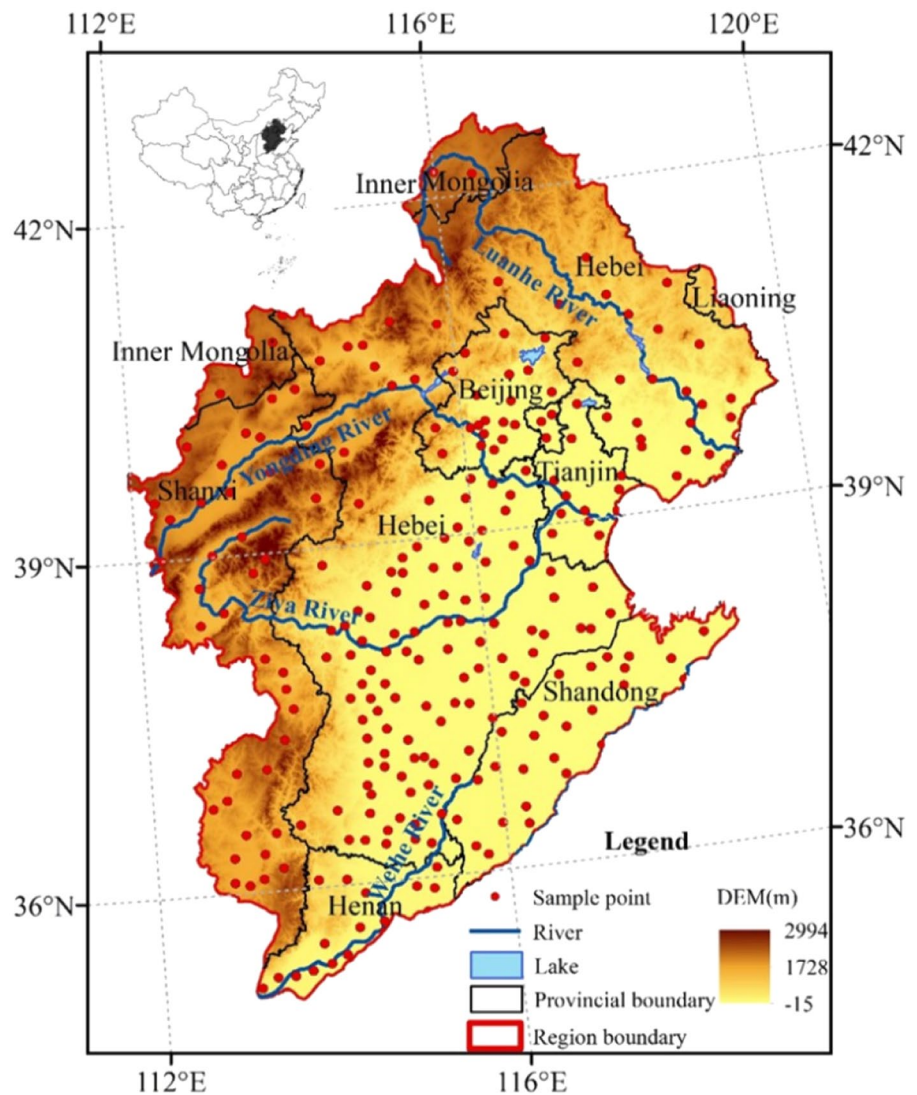
In recent years, many researchers have focused on the HRB to study changes in farmlands (Jiang et al. 2007; Meng et al. 2013), soil nutrients (Shu et al. 2015; Liu et al. 2018a, b), climate (Liu et al. 2011; Shen et al. 2015; Yin et al. 2015; Shi et al. 2014; Zhang et al. 2015), hydrological conditions (Kan et al. 2016; Wang and Zhang 2015), and grain productivity (Yang, 2017; Hong et al. 2014). Moreover, studies of local land use/cover transitions in the HRB have been performed using RS images, topographic data, statistical socioeconomic data, and historical survey data (Han et al. 2015; Li et al. 2016). However, these existing studies have been restricted to the local scale or to a limited timeframe. In short, there has been no comprehensive land use/cover transition study in this region of China to-date. In 2018, the Ministry of science and technology of China launched the national key research and development program "The impact of global change on regional water and land resources", aiming to explore the law of water and land resources change under global climate change and social and economic development. The HRB is one of the research regions of the program, and land use/cover transition is the most direct response to climate change and economic and social development. Thus, in this study, land use/cover transitions from 1980 to 2015 in the HRB were studied using RS data and GIS tools. The characteristics and patterns of land use/cover changes and their driving factors were analyzed quantitatively, and thus provide a scientific basis for decision-making with respect to regional resources and coordinated environmental development.

Materials and methods

Study area and data

The HRB (~ 35 to 43° N, ~ 112 to 120° E; Fig. 1) is located on the northeastern North China Plain, with an area of 318,000 km², and accounting for approximately 3.3% of the total national land area. In 2015, the total population and gross domestic product (GDP) of the HRB were 187 million people and 11,090 billion Yuan (~ \$1612 billion USD), respectively accounting for 13.6% and 16.1% of the total of the nation. In this study, the land use/cover data of the HRB in 1980, 1990, 1995, 2000, 2005, 2010, and 2015 was obtained from the Chinese Resource and

Fig. 1 Location of the Hai River Basin and the spatial distributions of elevation and meteorological stations. *DEM* digital elevation model



Environment Database (<http://www.resdc.cn/>), in which 1-km gridded land use/cover maps were interpreted from Land Satellite (Landsat) TM/ETM, Landsat 8 operation land imager (OLI), and Gaofen-2 (GF-2) images. According to the land classification system for RS interpretation, land use/cover was divided into six classes and 25 subclasses (Liu et al. 2009), and the overall accuracy of the subclasses was greater than 91.2% (Liu et al. 2014a, b). The daily precipitation and temperature data for 250 meteorological stations with data coverage from 1980 to 2015 in and around the HRB were provided by the China National Climate Center, and the data for provincial and city boundaries, roads, and rivers were from the national fundamental GIS from the national database (<http://nfgis.nsd.gov.cn>).

Data processing

In this study, for the convenience of analysis, all subclasses of cropland, forestland, grassland, open water areas, and unused land were combined into the Level I class, and all subclasses of rural–urban industrial land remained in the final chosen classes due to their high values and increasing rates of differences. The final chosen land use/cover classes are shown in Table 1.

Spatial analysis

Land use/cover transition matrices and maps were calculated to quantify and spatialize the land use/cover changes from one class to another between two time periods by using the

Table 1 Codes and names of land use classes, subclasses, and final selected classes

| Classes | Subclasses | Final selected classes |
|-------------------------------|--|--|
| 1 cropland | 11 paddy field 12 dry land | 1 cropland |
| 2 forestland | 21 forest 22 shrubbery 23 sparse woods 24 other woods | 2 forestland |
| 3 grassland | 31 high cover grass 32 moderate cover grass 33 low cover grass | 3 grassland |
| 4 open water area | 41 river and canals 42 lake 43 reservoir pit 44 permanent glacier snow 45 beach 46 lowlands | 4 water |
| 5 rural–urban industrial land | 51 urban and town land 52 rural residential land 53 other built-up land | 5 urban and town land 6 rural residential land 7 other built-up land |
| 6 unused land | 61 sand 62 Gobi 63 saline-alkali land 64 marshlands 65 bare land 66 bare rock land 67 other land | 8 unused land |

ArcGIS 10.2 Spatial Analyst tool. In this study, there were seven time periods of land use/cover data; thus, seven digits for each cell (1 km × 1 km) could be obtained via GIS to present the multiple change pathways for all locations within the study area over time. Additionally, if one cell remained unchanged between two time periods, the cell was categorized as persistent (Pijanowski and Robinson 2011; Pontius et al. 2004); otherwise, the cell was categorized as a transitional cell. The total persistence was then calculated as the proportion of one land use/cover class or all land use/cover classes that remained in their class during the change interval, and the range of persistence was from 0 to 1. The closer the total persistence was to 1, the more the land use/cover remained unchanged between two time periods. For the entire study area, persistence was calculated for both the entire 35-year period and for the two neighboring time periods to compare the proportions from the two steps of different periods and those of the six-step transitions.

Dynamic mechanism analysis

Driving factors

Land use/cover transitions are influenced by the natural and socioeconomic interactions within a certain region (Liu and Long 2016; Long 2015; Chen and Zhang 2011). Thus, in this study, these two driving factors were selected to analyze their impact on land use/cover transitions.

Natural drivers In previous studies, topographic and hydrological variables have usually been selected for driving force analyses because they affect the spatial heterogeneity of hydrothermal conditions and the degree of land surface development. In this study, the topographic factors were expressed by elevation (X_1 , Fig. S1a) and slope (X_2 , Fig. S1b); the hydrological conditions were characterized by the distance to the main river (X_3 , Fig. S1c). Additionally, climatic factors are usually applied to analyze their influences on land use/cover changes (Liu and Long 2016). Thus, the changes in annual rainfall (X_4 , Fig. S1d–i) and mean annual temperature (X_5 , Fig. S1j–p) between two time periods were selected to characterize the change in climatic conditions. The spatial distributions of annual rainfall and mean annual temperature for one year were obtained by the kriging interpolation method, based on the diurnal monitoring data collected at 250 meteorological monitoring stations.

Socioeconomic drivers Spatial heterogeneities in socioeconomic conditions are the result of human activities in a regional geographical environment, leading to spatial differences in land use/cover changes. For example, locations with better economic conditions and higher levels of urbanization have more significant impacts on land use/cover transitions than other regions. In this study, the following factors were selected to express the spatiotemporal heterogeneity of socioeconomic conditions: (1) GDP change (X_6 , Fig. S2a–e) and population change

(X_7 , Fig. S2f–k) for each city between two time periods were selected to characterize the economic conditions; (2) the distance to a municipal-level administrative center (X_8 , Fig. S2l) was chosen to characterize the location; (3) the distance to the main road (X_9 , Fig. S2m) was used to express the impact of traffic conditions.

Relationship between land use/cover transition and driving factors

To analyze the impact of driving factors on the land use/cover transitions in the HRB, each of the nine driving factors were divided into 10 categories based on quantiles. Then, for each driving factor X_k ($k = 1, \dots, 9$ in this study) and each transition period, the study area, D , was divided into many subareas D_i ($i = 1, 2, \dots, 10$; 10 is the number of categories for each driving factor). For each type of land use/cover transition, j , in one subarea, D_i , recorded as $[C_{k,\text{original}}^{i,j}, C_{k,\text{target}}^{i,j}]$, a probability of transition, $P_k^{i,j}$, for the driving factor, X_k in subarea D_i was calculated using the formula:

$$P_k^{i,j} = \frac{\text{Count}_{k,\text{original}-k,\text{target}}^{i,j}}{\text{Count}_{k,\text{original}}^{i,j}} \times 100\%, \quad (1)$$

where $\text{Count}_{k,\text{original}}^{i,j}$ is the total area of the original land use/cover class at the initial time of transition type j in the subarea D_i during all transition periods and $\text{Count}_{k,\text{original}-k,\text{target}}^{i,j}$ is the total area of the original land use/cover class that was transformed into the target land use/cover class at the end of transition type j in the subarea D_i during all transition periods. The Spearman correlation coefficients between i and $P_k^{i,j}$ ($i = 1, 2, \dots, 10$ in this study) were calculated to express the relationship between driving factor X_k and land use/cover transition type j .

Results

Spatial distributions of land use/cover classes in HRB

Figure 2 shows the spatial distribution of the land use/cover classes in the study area in 1980, 1990, 1995, 2000, 2005, 2010, and 2015, and Table 2 shows the proportions and areas of land in each land use/cover category by time period. Croplands, accounting for an average of 50.19% of the total area from 1980–2015, were distributed throughout the HRB, with more coverage in the eastern part of the study area. From 1980 to 2015, croplands exhibited the largest decrease in area, 6507 km² (4.02%). Rural

residential lands were scattered throughout the cropland areas, and accounted for an average of 5.27% of the total area from 1980–2015, and increased by 11.33% over time.

In the HRB, there are 25 large and medium-sized cities, such as Beijing, Tianjin, and Shijiazhuang, along with 223 counties. The urban and town areas are mainly distributed in the plains region within the eastern part of the study area and accounted for an average of 1.52% of the total area from 1980 to 2015. The urban and town land areas increased steadily from 1980 to 2015, with the largest increase being 4164 km² (154.05% of the original area). Other built-up land types, including mines, large industrial areas, oil fields, salt pans, and quarry areas, were mainly distributed on the eastern margin of the study area and accounted for an average of 0.95% of the total area from 1980 to 2015. From 1980 to 2015, the area of other built-up land types increased by 107.33%. The forest and grass areas were distributed in the western and northern parts of the study area, accounting for averages of 19.1% and 19.54% of the total area from 1980 to 2015, respectively. Forestlands and grasslands decreased by 450 and 495 km² from 1980 to 2015, respectively, accounting for only 0.74% and 0.8% of their areas in 1980. Water areas were mainly composed of rivers, reservoir pits, and lowlands, with an average of only 2.3% of the total study area from 1980 to 2015, and decreasing by 1.07% of the original amount from 1980 to 2015. Unused land was mainly composed of sand (north of the study area), saline-alkali lands, and marshlands (east of the study area), and accounted for an average of 1.13% of the total area from 1980 to 2015, which decreased by 16.51% from 1980 to 2015.

Land use/cover persistence

As shown in Table 3, the persistence of each land use/cover class in the study area across all time intervals varied from 0.71 (unused land) to 0.96 (forestland). In all intervals from 1980 to 2015, rural–urban industrial lands, water areas, and unused lands persisted less than the total persistence (0.93) of all land use/cover classes, suggesting that these categories were more dynamic than crop-, forest-, and grasslands. Additionally, unused lands had the lowest persistence of only 0.71 from 1980 to 2015; its greatest decreasing proportion from 1980 to 2015 (–16.51%, Table 2) indicates a higher level of development for unused land. In contrast, forestlands had the greatest persistence of 0.96 from 1980 to 2015, and as the total area decreased by only 0.74% from 1980 to 2015, forest protection efforts in the HRB could be considered effective. The total persistence of the region from was 0.93, indicating that 93% of the total area in the HRB remained unchanged in land use/cover over time.

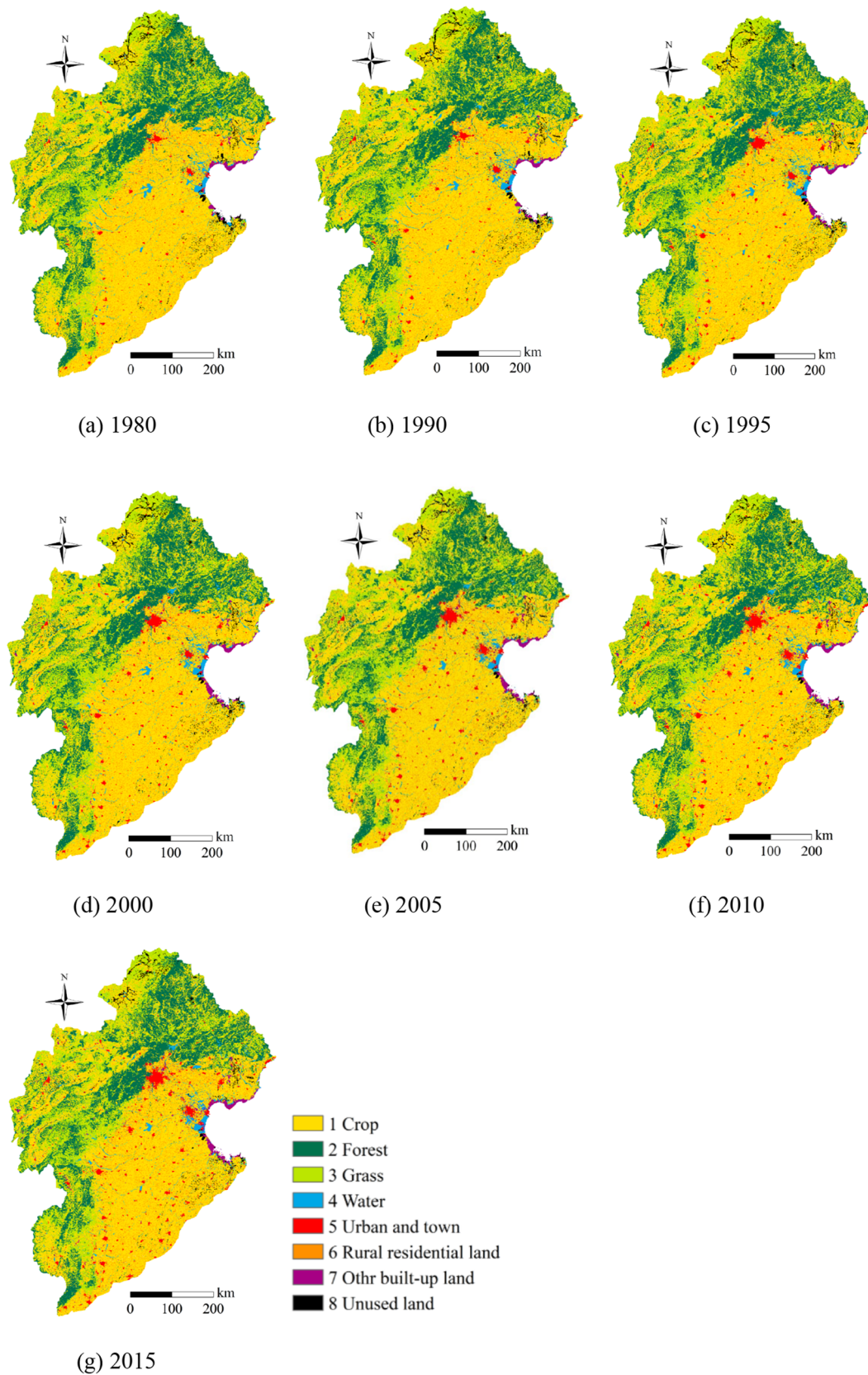


Fig. 2 Spatial distributions of land use and cover classes in **a** 1980, **b** 1990, **c** 1995, **d** 2000, **e** 2005, **f** 2010, and **g** 2015

Table 2 Proportions of land in each land use/cover (LUC) class by time period

| LUC | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------------------------------------|-------|-------|-------|-------|--------|-------|--------|--------|
| % total 1980 | 51.12 | 19.21 | 19.59 | 2.31 | 0.85 | 5.03 | 0.65 | 1.24 |
| % total 1990 | 50.92 | 19.10 | 19.66 | 2.25 | 0.98 | 5.13 | 0.74 | 1.22 |
| % total 1995 | 50.23 | 19.05 | 19.55 | 2.32 | 1.42 | 5.40 | 0.87 | 1.16 |
| % total 2000 | 50.41 | 19.07 | 19.54 | 2.33 | 1.43 | 5.19 | 0.89 | 1.13 |
| % total 2005 | 49.94 | 19.06 | 19.49 | 2.29 | 1.83 | 5.25 | 1.04 | 1.09 |
| % total 2010 | 49.64 | 19.12 | 19.49 | 2.29 | 1.98 | 5.27 | 1.19 | 1.03 |
| % total 2015 | 49.06 | 19.07 | 19.43 | 2.28 | 2.17 | 5.60 | 1.35 | 1.04 |
| % change (1980–2015) | −4.02 | −0.74 | −0.80 | −1.07 | 154.05 | 11.33 | 107.33 | −16.51 |
| % annual change | −0.11 | −0.02 | −0.02 | −0.03 | 4.40 | 0.32 | 3.07 | −0.47 |
| Change (1980–2015) km ² | −6507 | −450 | −495 | −78 | 4164 | 1804 | 2210 | −649 |

1—cropland; 2—forest; 3—grass; 4—water; 5—urban and town land; 6—rural residential land; 7—other built-up land; 8—unused land

Table 3 Persistence values for LUC classes by time interval

| Time period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Regional persistence |
|------------------------|------|------|------|------|------|------|------|------|----------------------|
| 1980–1990 | 0.99 | 0.99 | 1.00 | 0.93 | 1.00 | 1.00 | 0.99 | 0.96 | 0.99 |
| 1990–1995 | 0.98 | 0.99 | 0.99 | 0.96 | 0.99 | 0.98 | 0.94 | 0.91 | 0.98 |
| 1995–2000 | 0.98 | 0.98 | 0.96 | 0.96 | 0.93 | 0.93 | 0.96 | 0.90 | 0.97 |
| 2000–2005 | 0.99 | 1.00 | 0.99 | 0.94 | 0.98 | 0.98 | 0.96 | 0.93 | 0.99 |
| 2005–2010 | 0.99 | 1.00 | 1.00 | 0.98 | 0.99 | 0.99 | 0.98 | 0.93 | 0.99 |
| 2010–2015 | 0.97 | 0.98 | 0.97 | 0.95 | 0.95 | 0.96 | 0.95 | 0.95 | 0.97 |
| 1980–2015 ^a | 0.93 | 0.96 | 0.94 | 0.81 | 0.92 | 0.88 | 0.88 | 0.71 | 0.93 |

1—crop land; 2—forest; 3—grass; 4—water; 5—urban and town land; 6—rural residential land; 7—other built-up land; 8—unused land

^aDenotes persistence from 1980–2015 refers to the ratio of the cells that remained in their class during all change intervals

Land use/cover transitions

The land use/cover transitions in the HRB during different periods using a transition matrix are shown in detail in Table S1. The eight most common transition pathways for each land use/cover class from 1980 to 2015 from the original class and toward the new class are shown in Figs. 3 and 4, respectively. Each land use/cover class in 1980 transitioned to itself most frequently (i.e., persisted), and the percentage of each class that transitioned to itself equaled the persistence of each land use/cover class across all time intervals. Meanwhile, each land use/cover class in 2015 also originated from itself most frequently.

For croplands, most of the lost area in 1980 ultimately transitioned into urban and town lands or rural residential lands (Fig. 3a) in 1995, followed by in 2005; however, the gained area mainly originated from grasslands, water areas, and forestlands (Fig. 4a) in 1990 and 1995. Meanwhile, we noticed that part of croplands transitioned into grasslands, rural residential lands, forestlands, and water areas in 2000. And then, in 2015, those lost areas were transitioned back into croplands.

For forestlands, 95.85% of the original forest remained forest in 2015. Most of the lost forest eventually transitioned to grassland (Fig. 3b) in 1990, 1995, and 2000. And, a small amount of forest in 2015 originated from cropland or grassland in 1990, 1995, and 2010 (Fig. 4b). Meanwhile, part of forestlands transitioned into grasslands and croplands in 2020, transitioned back into forestlands in 2015. A total of 93.94% of the grasslands in 1980 remained unchanged from 1980 to 2015, and 1.67% and 1.16% of the original grasslands transitioned to cropland and forestland in 2000, respectively, before finally transitioning back into grasslands in 2015 (Fig. 3c). Additionally, a small amount of grasslands in 2015 originated from forestlands and croplands at different periods (Fig. 4c). Similarly, part of grasslands transitioned into croplands and forestlands in 2020, transitioned back into grasslands in 2015. A total of 80.77% of the original water area in 1980 remained unchanged in 2015, and most of the lost water area was transitioned to cropland in 1990, 1995, 2000, and 2005 (Fig. 3d). Meanwhile, most of the gained water areas were came from cropland at different periods (Fig. 4d).

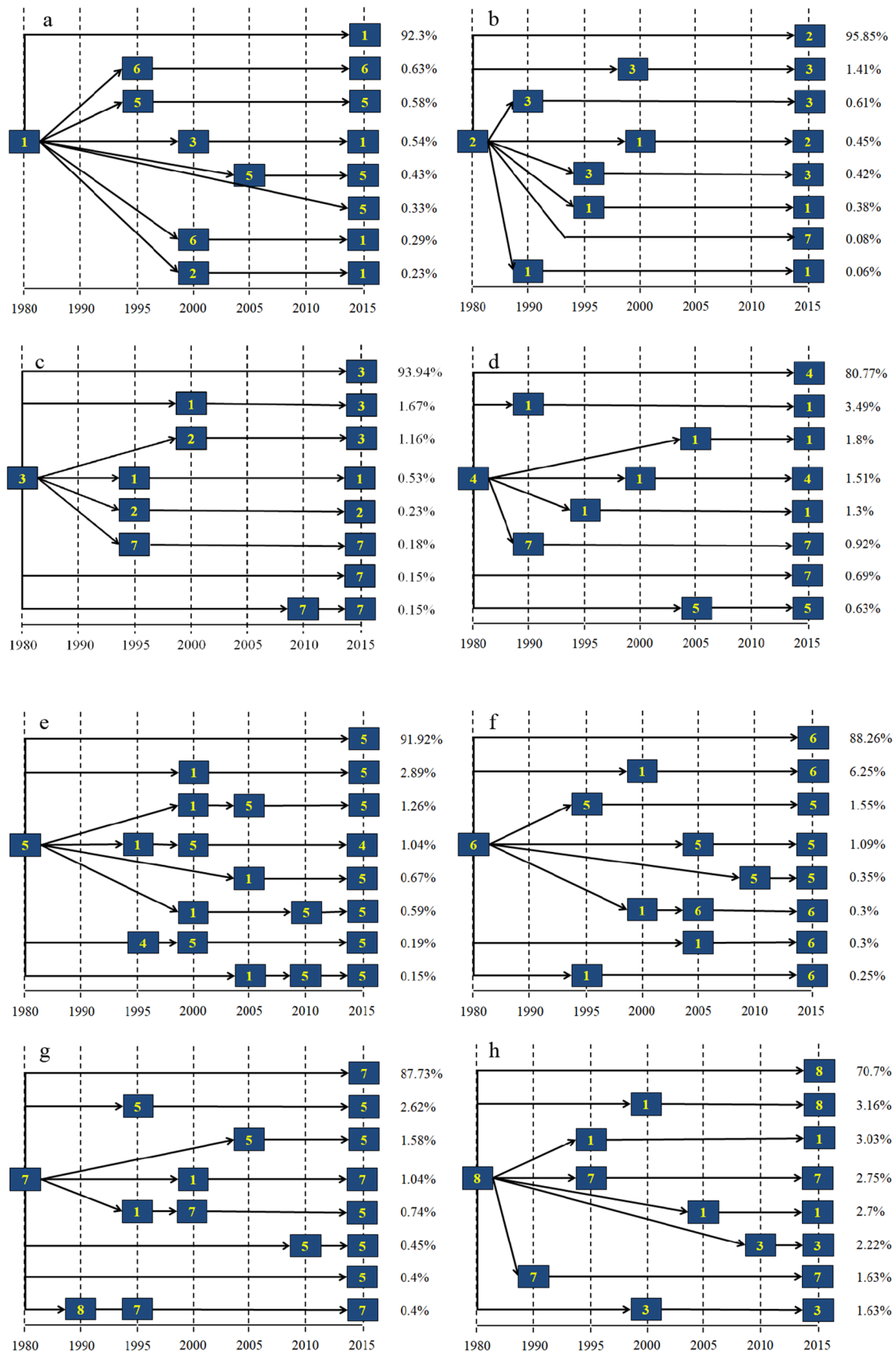


Fig. 3 The eight most common transitional pathways for each LUC class from 1980 to 2015 from the origin. Percentages of all multiple transitions combined are given on the right of each plot. 1—crop land; 2—forest; 3—grass; 4—water; 5—urban and townland; 6—rural residential land; 7—other built-up land; 8—unused land

For urban and townlands, most of the original area remained or transitioned to urban and townlands via a multistep pathway (Fig. 3e). In contrast, only 31.15% of the urban and townlands in 2015 came from the original area in 1980, and most of the gained area came from croplands and rural residential lands (Fig. 4e) in all periods except for 2000, indicating that the process of urbanization invaded a large amount of cropland and merged with a small amount of rural residential lands. Similarly, most of the original rural residential area remained unchanged from 1980 to 2015 (Fig. 3f), and most of its increased rural residential area came from croplands in all periods except for 2000 (Fig. 4f). Figure 3f also shows that a small amount of rural residential land transitioned to urban and town lands in 1995, 2005, and 2010. Figure 3g shows that most of the original other built-up lands that were lost were converted into urban and town lands, with single, double, or triple transition pathways, while 87.73% of its area remained unchanged from 1980 to 2015. Table 2 shows that other built-up lands increased by 107.33%, and most of these areas came from croplands, grasslands, and unused lands (Fig. 4g). As shown in Fig. 3h, more than 20% of the unused lands were developed into other land use/cover classes, such as cropland, other built-up land, and grassland. However, 70.7% of the original unused lands were still unused from 1980 to 2015, and > 10% of the unused land in 2015 was derived from grasslands, croplands, or water areas (Fig. 4h).

Dynamic mechanism results

There were a total of eight land use/cover classes, and consequently, there were 56 types of land use/cover transitions (i.e., $8 \times 8 - 8 = 56$) in theory. However, the probabilities of most types of land use/cover transitions were very low. Thus, the five most common transitions within all time intervals, including cropland to rural residential land (4403 km²), urban and town land (3864 km²), grassland to cropland (2815 km²), cropland to grassland (2516 km²), and forestland to grassland (2376 km²), were further studied. The spatial distributions of these transitions in the six neighboring time intervals from 1980 to 2015 are shown in Fig. 5.

Based on the methods introduced in “[Relationship between land use/cover transition and driving factors](#)”, all transition probabilities, P_k^{ij} , for each explanatory variable, X_k , and the five most common land use/cover transitions were calculated. Tables S2–S6 in the “Supplementary Material” show the transition probabilities for each driving

factor in detail. Based on the data shown in Tables S2–S6, the Spearman correlation coefficients between the transition probabilities and the driving factors are calculated, and the results are shown in Table 4. For example, in the Table 4, the first result (−0.87**) is the Spearman correlation coefficient between land use/cover transition type “1–6” and the explanatory variable X_1 (elevation). It was calculated by using the data shown in column 2 (1, 2, 3, 4, 5, 6, 7, 8, 9, 10) and 3 (0.47, 0.62, 0.74, 0.75, 0.26, 0.14, 0.15, 0.11, 0.10, 0.03) of the Table S2 in the “Supplementary Material” file.

Croplands that were converted to construction lands, including rural residential lands (class 1–6) and urban and town lands (1–5), were widely distributed throughout the HRB. The transition from cropland to construction land was significantly and negatively correlated with elevation, slope, distance to the main river, distance to the municipal-level administrative center, and distance to the main road at the 0.01 or 0.05 alpha levels, with the changes in GDP and population positively and significantly correlated at the 0.01 or 0.05 level. Among the seven driving factors, distance to the municipal-level administrative center, distance to the main road, distance to the main river, elevation, and slope had the most significant negative impacts on the transformation of cropland to construction land. However, the changes in GDP and population had significant and positive impacts on the conversion of cropland to construction land.

Grasslands that were transformed into croplands (class 3–1) were mainly distributed in the western part of the HRB. This type of transition was significantly and negatively correlated with slope and the change in annual rainfall at the 0.01 level, and with elevation and the distance to the municipal-level administrative center at the 0.05 level. Among these four driving factors, elevation and slope had extremely significant negative impacts on the probability that grasslands would be transformed into croplands.

The transition from cropland to grassland was significantly and positively correlated with elevation, slope, distance to the main river, distance to the municipal-level administrative center, and distance to the main road at the 0.01 or 0.05 levels. However, it was significantly negatively correlated with the changes in GDP and population at the 0.05 level. Meanwhile, the transition from forestland to grassland was significantly and positively correlated with elevation and slope at the 0.01 level, and with distance to the main river at the 0.05 level.

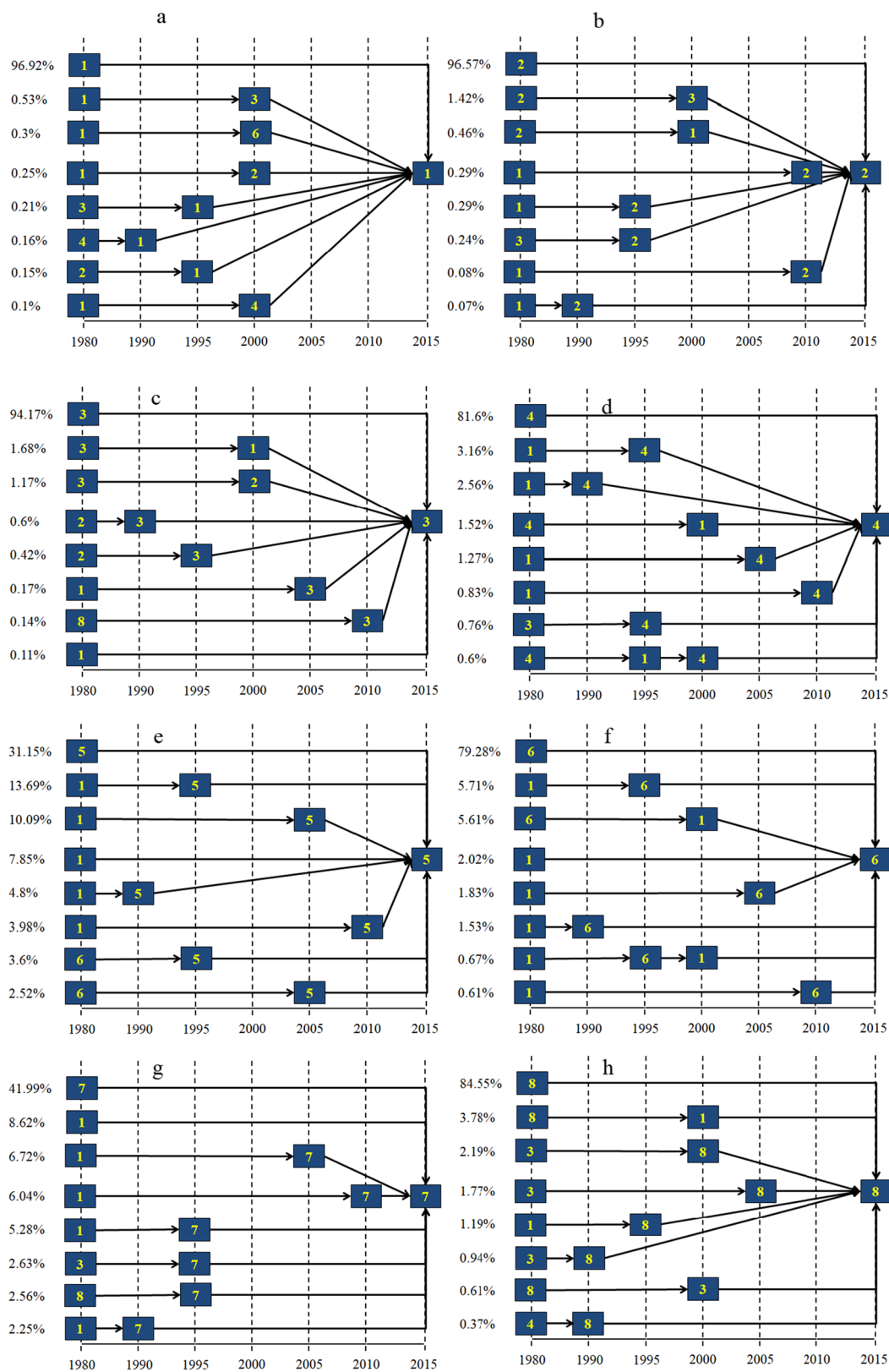


Fig. 4 The eight most common transitional pathways for each LUC class from 1980 to 2015 toward the next LUC class. The percentages of all multiple transitions combined are given on the left of each plot.

1—crop land; 2—forest; 3—grass; 4—water; 5—urban and town-land; 6—rural residential land; 7—other built-up land; 8—unused land

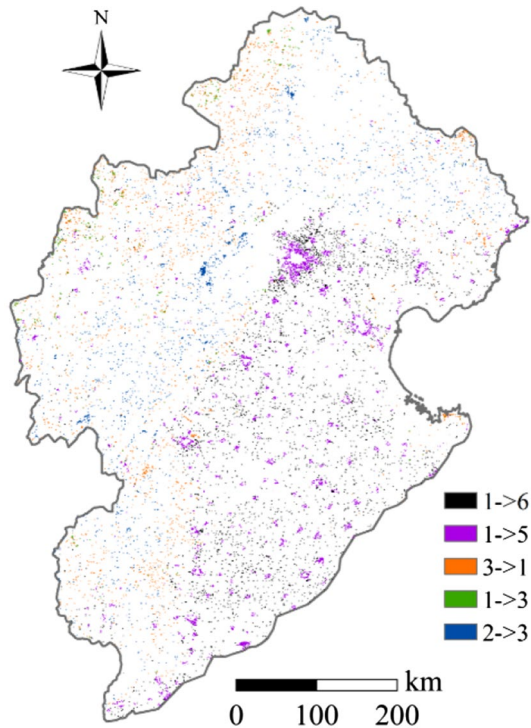


Fig. 5 The 5 most common transitions from 1980–2015. 1—crop land; 2—forest; 3—grass; 4—water; 5—urban and town land; 6—rural residential land; 7—other built-up land; 8—unused land

Discussions

Main characteristic of land use/cover transitions of HRB in different periods

From 1980 to 2015, the most prominent characteristic of land use/cover transitions in HRB was the occupation of cropland by construction land. The area of construction

lands, including rural residential lands, urban and town lands, and other built-up lands, exhibited continuous growth during the study period. Among them, the area of urban and town lands increased by more than 150% from 1980 to 2015. Since the late 1970s, owing to reformation policies, the economy and population of the study area increased rapidly (Fig. S2a–k). Thus, the increases economic and population growth required more land to accommodate the needs of industry, commerce, and housing. Additionally, in the HRB, the higher population density, better infrastructure, and relatively flat terrain, provided a good basis for regional urban development. Meanwhile, the growth of construction land presents different characteristics in different periods. For example, according to the results of Table 2, for urban and town land, the average annual growth rates are 1.53%, 8.98%, 0.14%, 5.59%, 1.64% and 1.92% in the periods of 1980–1990, 1990–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015, respectively, indicating different characteristics of the times. The period of 1990 to 1995 is the period with the largest urban growth rate, because of the rise of foreign investment, economic and technological development, and real estate development in this period. However, the area of construction land increased slowly from 1995 to 2000, and might reflecting the impact of the 1997 Asian financial crisis. Meanwhile, in this period, under the influence of national macro-control policies, especially the implementation of western developmental strategies, urbanization in eastern China, including in the study area, slowed. Then, in the period of 2000–2005, the social and economy of China was developing fast and continuously. Double GDP and increasing proportion of urban population lead to the average annual growth rate of urban and town land rising from 0.14 to 5.59% in this period.

The expansion of construction land was mainly at the cost of cropland. According to the results shown in Fig. 4e–g,

Table 4 Spearman correlation coefficients between the probabilities of transition for the five most common LUC transitions and the explanatory variables in Haihe River Basin from 1980 to 2015

| Transition type | X_1 | X_2 | X_3 | X_4 | X_5 | X_6 | X_7 | X_8 | X_9 |
|-----------------|---------|---------|---------|---------|-------|--------|--------|---------|---------|
| 1 to 6 | -0.87** | -0.95** | -0.94** | -0.71* | 0.41 | 0.72* | 0.68* | -0.99** | -0.95** |
| 1 to 5 | -0.86** | -0.96** | -0.89** | -0.4 | -0.19 | 0.88** | 0.74* | -0.86* | -0.63* |
| 3 to 1 | -0.69* | -0.99** | 0.18 | -0.88** | 0.29 | -0.26 | -0.47 | -0.7* | -0.48 |
| 1 to 3 | 0.92** | 0.71* | 0.99** | -0.65* | 0.19 | -0.69* | -0.68* | 1** | 0.95** |
| 2 to 3 | 0.83** | 0.96** | 0.55* | -0.61 | 0.4 | -0.46 | -0.34 | 0.59 | 0.01 |

1—crop land; 2—forest; 3—grass; 4—water; 5—urban and town land; 6—rural residential land; 7—other built-up land; 8—unused land

X_1 elevation, X_2 slope, X_3 distance to the main river, X_4 change in annual rainfall, X_5 change in mean annual temperature, X_6 change in GDP, X_7 change in population, X_8 distance to the municipal-level administrative center, X_9 distance to the main road

*Correlation is significant at the 0.05 level (two-tailed)

**Correlation is significant at the 0.01 level (two-tailed)

58.3% of new urban and town lands, 59.7% of new rural residential lands, and 49.8% of new other built-up lands in 2015 came from the occupation of croplands, leading to a decrease of more than 6500 km² of cropland in the HRB. In terms of temporal variation, the rates of cropland reduction were 0.39%, 1.36%, -0.29%, 0.94%, 0.43%, and 1.25%, during the periods of 1980–1990, 1990–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015, respectively. It is noteworthy that the area of cropland increased slightly from 1995 to 2000. This was due to the promulgation and implementation of a series of land management policies and regulations, such as the “Regulations on the Protection of Basic Farmland” and the Land Management Law, which played an important role in protecting cropland resources. Moreover, the new grain croplands were mainly derived from grasslands. According to the daily temperature data from 250 meteorological stations, the mean annual temperature in the HRB increased by 1.65 °C over this period. In the northern region of the study area, due to climatic warming, it has been possible for traditional pastures to be converted into croplands, which has, to some extent, led to the reclamation of pasture resources (Liu et al. 2003).

Analysis of the dynamic mechanisms

Natural geographic factors and socioeconomic development have jointly affected land use/cover transitions in the HRB. According to our dynamic mechanism analyses (Table 4), croplands in better locations (close to a city), with better traffic (near roads), and topographic (low altitude and flat terrain) and hydrological (close to the river) conditions, as well as rapid economic and population growth, were more likely to be changed into construction land. Similarly, grasslands at low altitudes and on flat terrain are easily converted into cropland because such grasslands are readily cultivated. For example, as shown in Table S4, 1.98% and 2.21% of the grasslands with slopes of 0–0.64 and 0.66–1.97, respectively, were transformed into croplands during the study period. However, only 0.19% of the grasslands with slopes ranging from 15.32 to 23.95 were thus transformed. Meanwhile, the distance to the municipal-level administrative center had a significant negative impact on the transformation of grasslands into croplands, indicating that the population and food pressures near the city were among the major reasons for grasslands to be transformed into croplands. In particular, the change in annual rainfall significantly affected the transformation of grasslands into croplands but had no significant impact on the other four land use/cover transition types. Thus, with the decrease in rainfall, grasslands were rapidly transformed into croplands, especially if the grasslands had favorable topographic and hydrological conditions, and were conveniently located.

The elevation, slope, and distance to the main river had significant positive impacts on the cropland and forestland areas that were transformed into grasslands, indicating that croplands and forestlands with poor topographic (high altitude and uneven terrain) and hydrological (far from a river) conditions were more likely to be changed into grasslands. Meanwhile, the distance to the municipal-level administrative center and to the main road also had significant positive impacts on the transformation of croplands into grasslands, indicating that cropland areas far from cities and roads were more likely to be transformed into construction land than those areas close to cities and roads. However, the changes in GDP and population also had significant negative effects on the transformation of croplands into grasslands, indicating that croplands in areas with slow economic and population growth were more likely to be transformed into grasslands than that in the areas with rapid economic and population growth.

Conclusions

The transitional patterns of land use/cover in the HRB changed significantly from 1980 to 2015 and were characterized by an increase in rural–urban industrial lands and decreases in the other land use/cover classes, including croplands, forestlands, grasslands, water areas, and unused lands. Among the decreasing classes, croplands exhibited the largest decrease, 6507 km² from 1980 to 2015, accounting for 4.02% of its original area in 1980. The results of persistence analyses indicated that 93% of the area in the HRB remained unchanged in land use/cover during the study period. The details of these transitions were clearly displayed by the multi-temporal transition pathways from the original class and toward the new class. For example, most of the original cropland in 1980 that was lost was ultimately transformed into rural–urban industrial land in 2015; however, most of the cropland that was gained in 2015 was derived from grasslands, water areas, and forestlands.

The results of dynamic mechanism analyses indicated that the topographic factors, including elevation, slope, and distance to the main river, had significant impacts on all five of the most common types of land use/cover transitions, except for the impact of distance to the main river on grasslands transformed into croplands. Meanwhile, climatic factors had no significant impact on the five most common types of land use/cover transition, except for the impact of change in annual rainfall on grasslands that were transformed into croplands. Economic factors, including changes in GDP and population, location factors (i.e., distance to the municipal-level administrative center), and traffic factors (i.e., distance to the main road) had significant effects on three types of

land use/cover transitions, including those from cropland to rural–urban industrial land and from grassland to cropland.

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