Habitat International 94 (2019) 102069

Contents lists available at ScienceDirect

Habitat International

journal homepage: http://www.elsevier.com/locate/habitatint

Mapping settlement systems in China and their change trajectories between 1990 and 2010

Mengmeng Li[a,*], Jasper van Vliet[a], Xinli Ke[b], Peter H. Verburg[a,c]

[a] Institute for Environmental Studies, VU University Amsterdam, De Boelelaan 1085, 1081 HV, Amsterdam, the Netherlands
[b] College of Land Administration, Huazhong Agricultural University, Shizishan Street, 430070, Wuhan, PR China
[c] Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903, Birmensdorf, Switzerland

ARTICLE INFO

Keywords:
Land use change
Urban expansion
Human settlements
Land systems
Villages
Spatial patterns

ABSTRACT

A wide variety of settlement systems exist, ranging from small villages to large metropolises. However, spatial analyses are typically confined to the mere presence or absence of built-up land and the changes therein, while more subtle differences between various settlement systems are ignored. In this paper we study the spatial distribution of Chinese settlements in terms of their built-up land, cluster density and cluster size, as well as their changes between 1990 and 2010. Subsequently, we use these three properties to delineate settlement systems, and analyze the observed change trajectories between 1990 and 2010. We find that roughly 70% of all built-up land and more than 50% of all new built-up land added between 1990 and 2010 is included in village landscapes, which challenges the current focus on studying mega-cities. We also find that settlement changes mostly follow small and incremental steps towards more dense urban systems, following multiple different development trajectories. Specifically, rural villages seldom convert into urban systems directly, but typically increase gradually to towns and sub-urban landscapes. Settlement systems provide a first step towards a comprehensive understanding of human settlements and their change trajectories, which can inform targeted land use planning and the development of policies that more explicitly accounts for diversity in settlement types.

1. Introduction

The vast majority of the global alterations in land cover relate to the conversion of natural ecosystems into agricultural land. Human settlements initially emerged as an integral part of these agricultural systems. However, as settlements developed, they became increasingly disconnected from their resource base (Cumming et al., 2014). Due to population growth, migration, and economic development, settlements have been growing across the globe, especially in recent decades (Angel, Parent, Civco, Blei, & Potere, 2011), to the point that built-up land is now competing for land with food production and other land demands (Bren d'Amour et al., 2017; Lambin & Meyfroidt, 2011; van Vliet, 2019). As the world population is expected to continue growing for at least the next few decades, there is a need for a nuanced understanding of the different forms of human settlements and their change processes over time, in order to inform land use policies and allow landscape planning to fully account for the diversity in forms of human settlement.

Urban growth has been studied extensively in recent years, mostly in terms of the expansion of built-up land and its spatial patterns. In these studies, the characterization of land is typically divided into urban and non-urban land, and as a result many studies are based on the conversion of non-built-up land to built-up land (Long, Liu, Hou, Li, & Li, 2014; Yue, Liu, & Fan, 2013), and the environmental impacts of these conversions (Angel et al., 2011; Seto, Guneralp, & Hutyra, 2012). In particular, the spectacular growth of large metropolises has received a considerable amount of attention (Ianoș & Jones, 2019; Schneider & Mertes, 2014; Xu, Huang, Ding, Mei, & Qin, 2018a). Furthermore, several studies also use derivatives of built-up land, especially landscape metrics, to further characterize the environmental impacts of human settlements (Alberti et al., 2007; Ramachandra, Bharath, & Sowmyashree, 2015). China is currently the most populated country in the world and it has developed quickly from a relatively rural to a relatively urban society in recent decades. As a result of this societal transition, it has experienced unprecedented urban growth, fueled by a large-scale migration from rural to urban areas (Shi, Taubenböck, Zhang, Liu, & Wurm, 2017). This urbanization process has led to large-scale urban expansion, which has been analyzed mainly in terms of the expansion of impervious land surface or built-up land (Gong, Li, & Zhang, 2019; Wang et al., 2012).

* Corresponding author.
E-mail address: mengmeng.li@vu.nl (M. Li).

https://doi.org/10.1016/j.habitatint.2019.102069
Received 7 August 2019; Received in revised form 11 September 2019; Accepted 17 October 2019
Available online 25 October 2019
0197-3975/© 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

This expansion has been well-studied for some of the larger metropolitan areas in China, including Beijing-Tianjin-Hebei region, Yangtze River Delta, Pearl River Delta, and some other areas (Tian, Jiang, Yang, & Zhang, 2011; Wu, Zhao, Zhu, & Jiang, 2015; Yue, Zhang, & Liu, 2016).

Yet, the analysis of changes in built-up land are mostly confined to the analysis of pixels that change from non-built-up to built-up land (Liu et al., 2015; Xu, Huang, Ding, Mei, & Qin, 2018; Yue et al., 2013). Changes at the landscape level, as reflected in the spatial pattern of built-up land and covering the full spectrum from urban to rural settlements have remained largely unexplored. The focus on large urban areas that is dominant in the literature obscures other changes in built-up land affecting smaller settlements but affecting large areas of land.

Increasingly, land use typologies are used to characterize typical combinations of land use or land cover and to study the changes therein, aiming to provide actionable solutions to sustainability challenges (Loures & Vaz, 2018; Rounsevell et al., 2012). Notably, Václavík, Lautenbach, Kuemmerle, and Seppelt (2013) identified 12 land system archetypes globally, based on a variety of variables, pointing out that land systems resemble across the globe but spatial pattern differs at subnational scales. At a national scale Ornetsmüller, Heinimann, and Verburg (2018) identified land systems in Lao PDR based amongst others on the typical combination of agricultural land and forested land, in order to analyze gradual shifts from swidden-forest mosaics to permanently managed agricultural land. However, these studies do not normally represent different settlement systems, as they are mostly focused on agricultural landscapes. At the scale of a single city, several studies have developed typologies for urban land. For example, focusing on vacant land within urban landscape, Kim, Miller, and Nowak (2018) developed a vacant land typology for Roanoke in Virginia, which could potentially be used for optimizing vacant parcel configurations at city scale. Krehl and Siedentop (2018) theoretically developed a classification scheme for urban land based on land use, built environment and other characteristics, which was subsequently applied in four German urban regions. However, such characterization have not been applied at landscape and national scales, while these are the scales at which land use policies are primarily targeted (Cullum, Brierley, Perry, & Witkowski, 2016; Levers et al., 2015).

The objective of this study is to identify settlement systems at a national scale, specifically for China, and analyze their recent change trajectories. To that effect, we first analyze three properties of settlements: the distribution of built-up land, the size of the largest cluster of built-up land, and density of clusters of built-up land, in order to provide a comprehensive picture of settlement changes. Subsequently, we use these characteristics to develop a characterization of settlement systems, and analyze the different change trajectories between 1990 and 2010. With the characterization and analysis of settlement systems, this study provides a more comprehensive view of settlement changes in China by also explicitly addressing the dynamics outside large metropolitan areas.

2. Materials and methods

2.1. Data sets

Our analyses are primarily based on China's Land-Use/Cover Datasets (CLUDs) for 1990, 2000 and 2010, complemented with elevation data and a map of administrative boundaries (see Table 1). All data are projected in an Albers equal area projection, with standard parallels of 25°N and 47°N. While CLUD is also available for 2015, this data is not used in this study, because our exploratory data analysis reveals that it is not consistent with data from other years.

The CLUDs data represent land use in China in six classes with 25 subclasses. We characterize and analyze settlement systems based on urban land (subclass-51) and rural residential land (subclass-52) only. These two subclasses mainly differ in administrative properties, but since we are interested in land cover rather than administrative classifications, they are combined in this study and henceforth referred to as *built-up area*. Both classes represent built-up area following the classification of Liu, He, Zhou, & Wu (2014b), as they predominantly consist of impervious surface, complemented with vegetated area, barren land, and water surface in built environment. These classes exclude land that is used for industrial purposes such as quarries, factories, mining, as well as transportation infrastructure outside cities (Kuang, Liu, Dong, Chi, & Zhang, 2016), which might otherwise obfuscate the delineation of human settlements. In addition, we used data about water bodies from CLUDs, including water as well as permanent snow cover. Next to land cover data we included a DEM and administrative boundaries for calculating built-up density and constraining the study area to continuous China. Specifically, continuous China excludes Taiwan, the islands in South China Sea and some other small islands around the continent, but includes Hong Kong and Macao.

2.2. Analyzing settlement patterns and their changes over time

We use three properties to characterize settlement systems: the density of built-up land, the density of built-up clusters, and the size of the largest cluster (Fig. 1a). These three properties are selected because they represent different characteristics of settlement systems. In particular, the density of built-up land resembles the traditional focus on the distribution of built-up and non-built-up land, the density of built-up clusters characterizes the extent to which built-up land is dispersed or concentrated within a landscape, and the size of the largest cluster is important to identify the hierarchy in human settlements as determined by their size and their influence on neighboring settlements. The exact spatial resolution of output data is 2010 m, as this is an exact multiple of the 30-m input data, to which we refer as 2 km cells hereafter. This resolution is chosen because it reflects the landscape level at which settlement systems exist, as is suggested in other analyses of landscape

Table 1
Data sets used in this study.

Dataset	Selection/process	Spatial resolution	Temporal resolution	Source	Reference
Built-up area (from China's land-use/Cover datasets (CLUDs))	Classes 51 (urban land) and 52 (rural residential land)	30 m	1990, 2000, 2010	Institute of Geographical Sciences and Natural Resources Research	Liu, Liu, Zhuang, Zhang, and Deng (2003)
Water/permanent snow cover (from China's land-use/Cover datasets (CLUDs))	Classes 41-46	30 m	1990, 2000, 2010	Institute of Geographical Sciences and Natural Resources Research	Liu et al. (2003)
DEM	Derive slope	30 m	/	Aster GDEM v2, USGS Earth Explorer	Tachikawa et al. (2011)
Administrative boundaries	/	Vector	/	Resource and Environment Data Cloud Platform	http://www.resdc.cn/

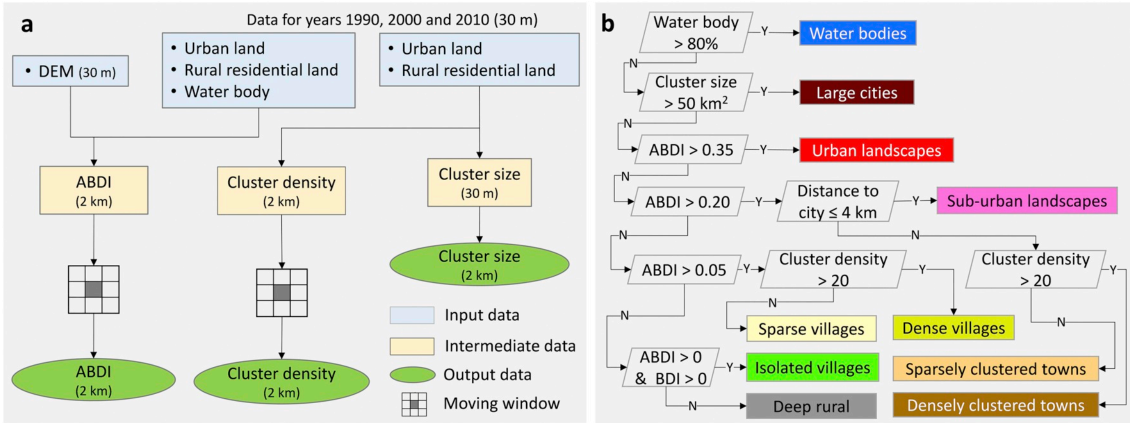

Fig. 1. a) Flowchart of characterizing settlement patterns; b) Expert-based classification scheme used to categorize settlement systems. "City" refers to the combination of large cities and urban landscapes. BDI is the ratio of built-up area to the total area of a 2 km cell, as such, BDI >0 excludes cells that no built-up land exists within. To enhance visual interpretation of settlement systems distribution in the resulted maps, deep rural and water bodies are also presented as two separated categories.

patterns (Jha & Kremen, 2013; Malek & Verburg, 2017; Ornetsmüller et al., 2018).

To calculate built-up density, we define the Adjusted Built-up Density Index (ABDI) as the built-up area within a 3*3 moving window around a 2 km cell, divided by the total area that is suitable for built-up land therein. Suitable land here refers to all areas that are not water or permanent snow, and that have a slope that does not exceed 25%. The 25% threshold is based on the *Code for Vertical Planning on Urban and Rural Development Land of China* (CJJ 83–2016), which indicates that areas with a slope greater than 25% are not suitable for construction. A moving window approach is applied because settlement systems relate to the scale at which the system or process exists or responds (McGarigal & Cushman, 2005), which we interpret to be larger than the 2 km cells on which we define settlement systems.

Cluster density indicates the number of clusters of built-up land within a 3*3 moving window around each 2 km cell. To compute cluster density, we firstly convert original 30-m CLUDs data into simplified polygons, effectively generating patches of built-up area, and subsequently generate feature points within these polygons that represent these patches. Patches are defined by direct as well as diagonal neighbors in this procedure. Then, we calculate the number of points within each 2 km cell and sum these results using a moving window method. These processes are successively conducted using conversion tools (Raster to Polygon), data management tools (Feature to Point), and spatial analysis tools (Point Density and Focal Statistics), all provided in the ArcToolbox of ArcGIS 10.4. The representation of clusters as points avoids double-counting patches that are spread over multiple 2 km cells.

Cluster size is calculated as the size of the largest patch of built-up area that has at least some area in a 2 km cell. Similar to the analysis of cluster density, patches are identified based on direct as well as diagonal neighbors, using the algorithm settings of Map Comparison Kit (Visser & de Nijs, 2006).

We calculate ABDI, cluster density, and cluster size for the years 1990, 2000, and 2010, and analyze changes in each of the three properties, as well as the relation between different types of changes. First, we analyze how changes in ABDI, cluster density, and cluster size relate to the starting situation, e.g. in order to analyze whether new built-up area appears in already built-up areas, or instead in more sparse areas. Then, we compare results for different years to explore changes in these properties over time. To explore the relation between changes in these properties, we categorize changes in each of the properties on a 2 km cell level as decrease, stable or increase. Subsequently, for each pair of properties, we analyze how changes in one property relate to changes in another property, in order to characterize spatial patterns of change. The thresholds for ABDI, cluster density, and cluster size are selected using a histogram-based method (see for example Yu, Hu, van Vliet, Verburg, and Wu (2018)). Specifically, we create histograms showing the distribution of changes, and identify the boundary between change and no change based on the absolute amount of change, so that at least 2% of all cells were identified as changes. This value of 2% is chosen for all classes to make their changes comparable, while at the same time accounting for the relatively static nature of built-up area. Associated threshold values for each change category are presented in Table 2.

The accuracy of spatial analyses is highly dependent on the accuracy of the input data. The CLUDs maps have been validated, yielding an overall accuracy of more than 90% (Liu et al., 2014c). Yet, due to our aggregation into tiles of 2 km, we expect that the accuracy at this resolution is effectively higher, and hence CLUDs are sufficient for the purpose of this study.

2.3. Mapping settlement systems and their changes over time

We use a decision tree (Fig. 1b) to map settlement systems based on the three characteristics that are also used for the analysis of settlement patterns: ABDI, cluster density and cluster size. In addition, we use the relation between clusters in the neighborhood (i.e. proximity). Decision trees are expert-systems, which are preferred over statistical clustering methods as the latter are found sensitive to the selected distance metric and criteria for determining the order of clustering (van der Zanden, Levers, Verburg, & Kuemmerle, 2016). We identify archetypical settlement systems in cells with a 2 km resolution, similar to the analysis of settlement patterns described above. For all cells that are not water, we first identify those that contain *large cities*, i.e. clusters of built-up area larger than 50 km^2 (Fang, Yu, Mao, Bao, & Huang, 2018). Subsequently, *urban landscapes* are defined as cells with an ABDI above 0.35, indicating landscapes with a predominantly urban character (Jiao, 2015; Xu et al., 2019). *Large cities* and *urban landscapes* together, are used to generate a proximity layer for detecting *sub-urban landscapes*. The remaining areas where categorized as clustered towns and clustered villages, based on their ABDI and cluster density (Tan & Li, 2013). *Isolated villages* are characterized by their small fraction (<0.05) of built-up area as

Table 2
Thresholds used to classify changes in ABDI, cluster density and cluster size.

Property	Threshold	Proportion of the study area that is stable	
		1990–2000	2000–2010
ABDI	±0.02	97.59%	97.91%
Cluster density	±1	97.78%	97.72%
Cluster size	±0.09 km^2	97.53%	97.78%

indicated by lower threshold of ABDI, while cells with no built-up area at the 2 km resolution are represented as *deep rural*. We tested a range of threshold values for identifying settlement systems and found that minor changes in threshold values did not yield drastically different patterns, but only a marginal displacement of class boundaries, suggesting a robust classification method.

To analyze changes between settlement systems, we calculated two change matrices, for the periods 1990–2000 and 2000–2010, respectively, and identified the major conversions relative to each settlement system. These change matrices are subsequently used to identify settlement change trajectories, based on the relative occurrence of changes from one settlement system to another.

3. Results

3.1. Spatial pattern of built-up area and its changes in China

ABDI, cluster density and cluster size for year 2010 are presented in Fig. 2 (see Fig. S1 for years 1990 and 2000). High values for ABDI are, expectedly, concentrated around the larger urban areas, such as Beijing, Shanghai, Guangzhou, and Hong Kong. Yet, Fig. 2a also shows that there is a large part of China that has at least some built-up land outside these large urban areas, albeit mostly with an ABDI lower than 0.20. Cluster density, on the other hand, shows the highest values not in the urban areas, but in the intensive agricultural areas, such as the North China Plain, Northeast China Plain, and the Chengdu Plain (Fig. 2b). The distribution of cluster sizes reflects the location of large urban areas, as these are reflected in the largest cluster sizes, while the cluster size quickly reduces farther away from these large urban areas (Fig. 2c).

The combined changes in ABDI, cluster density and cluster size reflect a spatial restructuring process of settlement systems. As is illustrated in Fig. 3, most non-stable areas show an increase in both ABDI and cluster size, while patterns in terms of cluster density are spatially heterogeneous. Two typical combinations of ABDI and cluster density changes were found (Fig. 3a). The combination of increased ABDI and decreased cluster density reflects urban areas growing connected, while a higher cluster density in combination with a higher ABDI indicates the appearance of new urban clusters (with or without edge-growth). Fig. 3b indicates that an increase in ABDI mostly coincides with an increase in cluster size, which is typically the result of edge growth of existing urban areas, affecting both in the same direction. The relation between cluster density and cluster size varies mostly between two typical combinations. A combination of lower cluster density and larger cluster size typically reflects consolidation, i.e. formerly isolated clusters growing together. The opposite, a higher cluster density in combination with a larger cluster size, indicates a combination of different processes, such as edge growth and the appearance of new scattered clusters. There is little difference between the changes in the both periods.

Analyses of changes in ABDI, cluster density, and cluster size as a function of their original values for these indicators reveal some typical patterns. The average increase in ABDI is largest for cells that are already have an ABDI between 0.5 and 0.8, while the average increases in cells with a lower ABDI is much smaller (Fig. 4a). It should be noted however that the number of cells with a low ABDI at the start of the period is much larger, and that therefore these cells still accommodate the majority of new built-up area (see Fig. S3). Cluster density can increase over time due to the appearance of new clusters but also decrease as a result of clusters growing together. The net effect is that for most cluster densities, the average change is near zero, except for cells that start without any built-up area, as the cluster density can only increase here (Fig. 4b). Changes in cluster size show that large clusters often also experience large changes in size, while small clusters typically experience only smaller changes (Fig. 4c, also see Fig. S4). Additionally, some other small clusters witness a considerable increase in size, especially between 2000 and 2010, which indicates the consolidation process as mentioned that small clusters in close proximity to large ones get connected to each other, resulting in a large increase in the size of the largest clusters as well as a decrease in cluster density.

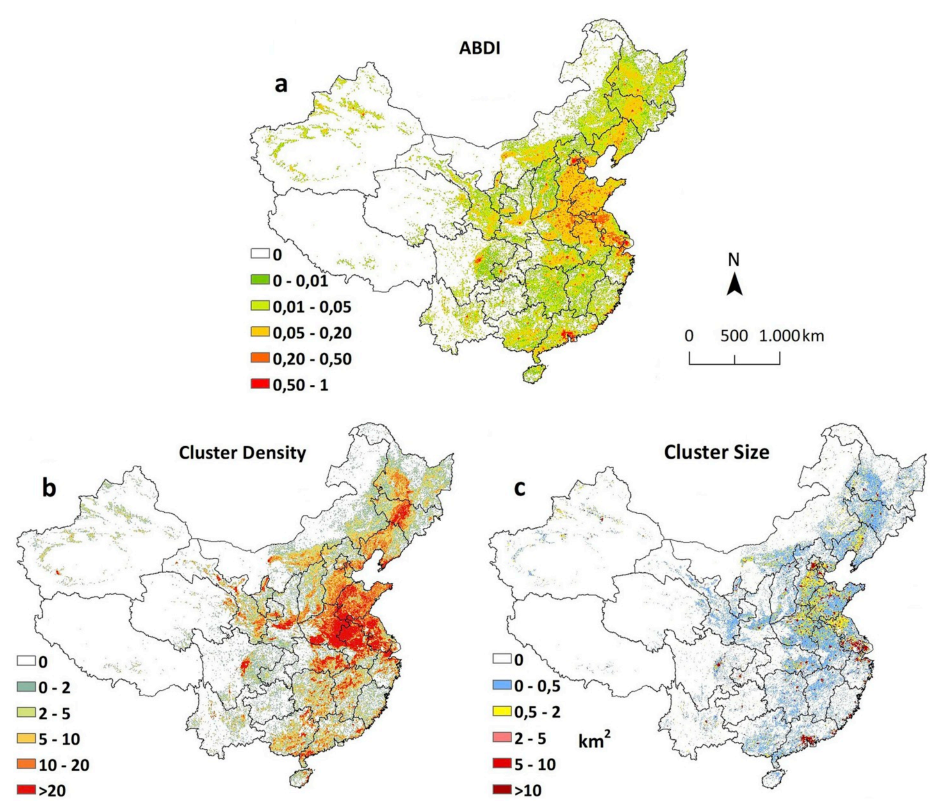

Fig. 2. ABDI, cluster density and cluster size for year 2010 (a–c). Comparable figures for 1990 and 2000 are provided in the supplementary material.

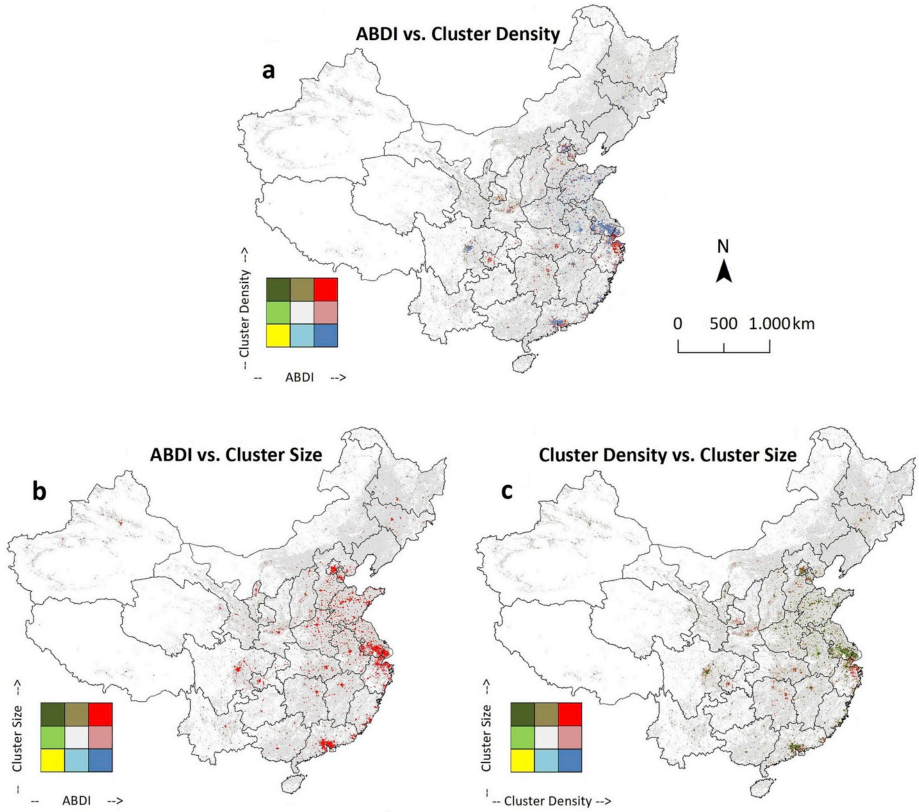

Fig. 3. Relations between changes in ABDI, cluster density, and cluster size during 2000–2010. Similar figures for changes between 1990 and 200 are provided in the supplementary material.

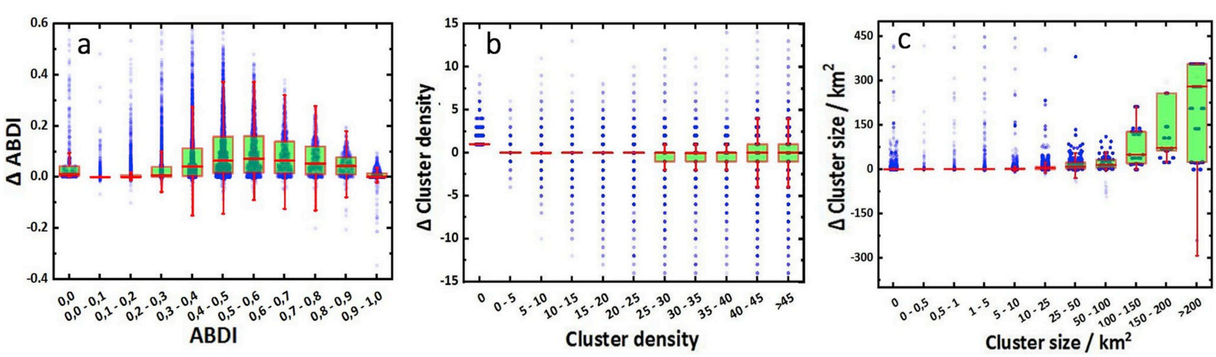

Fig. 4. Changes in ABDI, cluster density and cluster size as a function of their initial value during 2000–2010. The horizontal bars in each boxplot correspond to the 25th, 50th, and 75th percentiles. The whiskers extend to 1.5 times the interquartile ranges. Figs. S4 and S5 provide results for the period 1990–2000 and a more detailed view on the results shown in Fig. 4c, respectively.

3.2. Settlement systems and their changes over time

Combining the characteristics of built-up area allows the categorization of different settlement systems in China. About 20% of all land in China can be characterized as a settlement system, mostly concentrated in the Eastern part of the country (Fig. 5). Conversely, *Deep rural*, including both wild land and agricultural areas without any built-up land, accounts for almost 80% of the total area, which is mostly located in the western part of the country. The distribution of settlement systems as well as built-up area within each system is presented in Fig. 6. In 1990, 8.50% of all land in China is characterized as *isolated villages*, comprising 17.58% of all built-up surfaces. *Sparse villages* take up 6.89% of all land, yet incorporate 35.38% of built-up area, the largest share among all settlement systems. *Dense villages* occupy 3.46% of all land, while its proportion of built-up area is 25.83%. Other settlement systems including *sparsely clustered towns*, *densely clustered towns, sub-urban landscapes*, *urban landscapes*, and *large cities* together take up only 1.08% of the land area, but account for 21.23% of all built-up land. In 2010, village landscapes (*isolated villages*, *sparse villages*, and *dense villages*) accounted for 18.46% of the land, which is only slightly less than in 1990. The share of built-up land included in these three settlement systems has decreased from 78.80% in 1990 to 63.75% in 2010. *Sparsely clustered towns* and *densely clustered towns* combined account for 0.62% of the land in 2010, which is slightly more than the 0.55% they occupy in 1990. Conversely, the proportion of built-up area in these two types of towns shows a slight decrease from 8.83% to 8.27%. The proportion of China's built-up area that is found in in *large cities*, *urban landscapes*, and *sub-urban landscapes* more than doubled, from 12.29% in 1990 to 27.91% in 2010.

Changes in settlement systems between 1990 and 2000, as well as

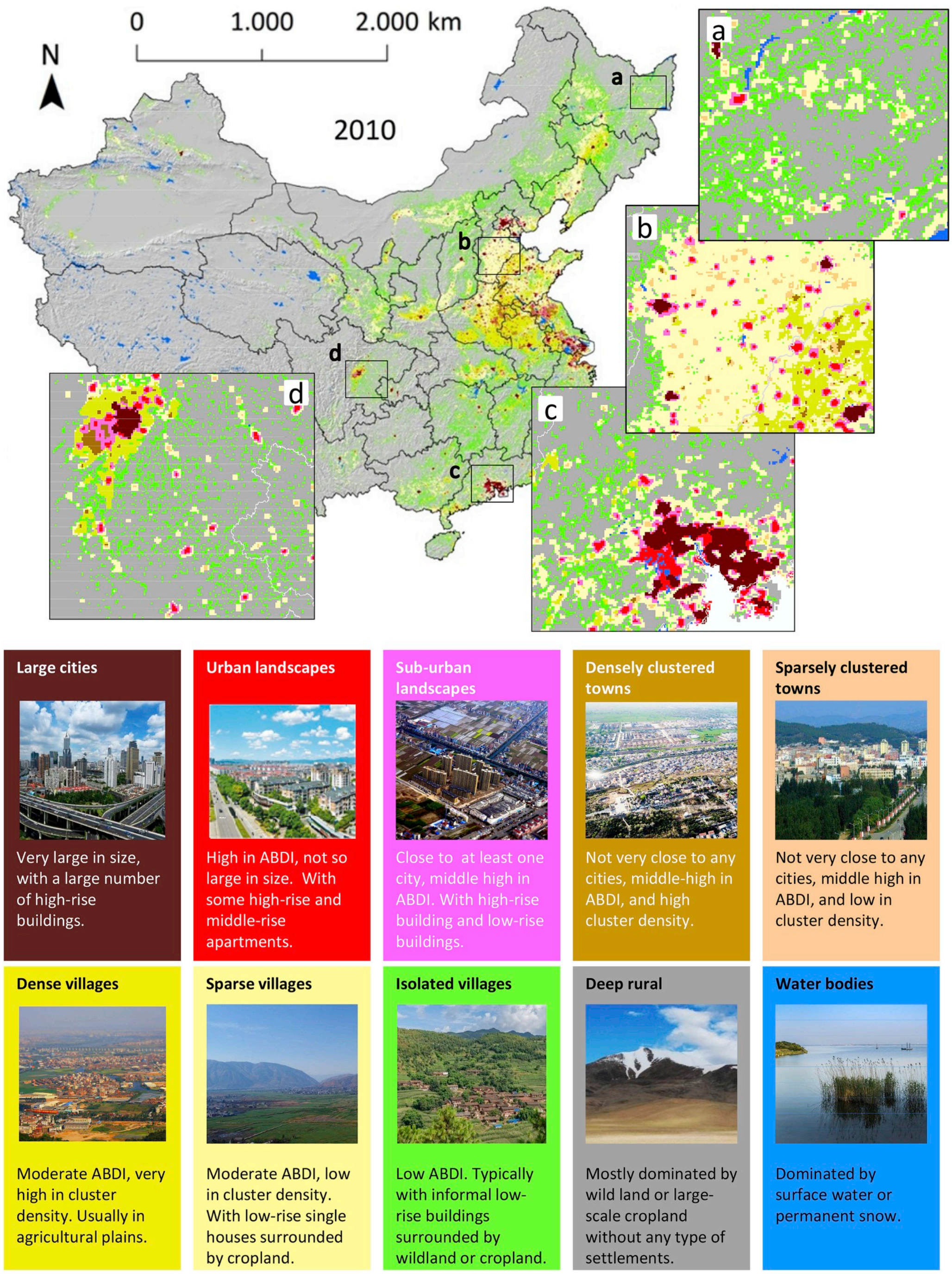

Fig. 5. Settlement systems in 2010. Comparable settlement system maps for 1990 and 2000 are provided in Fig. S6. As a holistic map, deep rural and water bodies are also presented to enhance visual interpretation of settlement systems distribution.

between 2000 and 2010 show a development towards denser settlement systems, although this development mostly comes in small incremental steps, rather than sudden large-scale changes. Fig. 7 shows the transformation matrices of settlement systems. Between 1990 and 2000, nearly all *densely clustered towns* developed into *sub-urban landscapes* which is mainly a result of the fast increase of *large cities* and *urban landscapes* in the surroundings. Another prominent change trajectory is from village landscapes into *sub-urban landscapes,* also reflecting a process of urban sprawl in which the former villages are embedded in the urban landscape of growing cities nearby. At the same time, a large share of the *sub-urban landscapes* developed into *large cities* or *urban landscapes,* especially in the period 2000–2010. Consistently, *large cities* and *urban landscapes* basically gain from *sub-urban landscapes*, indicating a continuous process of urban expansion. In addition to this typical pattern of urban growth, this transition matrix reveals the important dynamics in the more rural parts of the spectrum. Large portions of *deep rural* change into village landscapes as well as the conversion of *isolated villages* to *sparse villages*, and *sparse villages* into *dense villages*, all indicating the appearance of new villages over time in these areas. This variety of observed changes indicates that settlement change is not only taking place near *large cities*, but also in more remote areas with very small fractions of build-up land to start with.

Selecting from the transformation matrices the most important changes per settlement system reveals typical change trajectories. Fig. 8 shows these change trajectories for the period 2000–2010. Settlement changes mainly follow small incremental changes towards increasingly

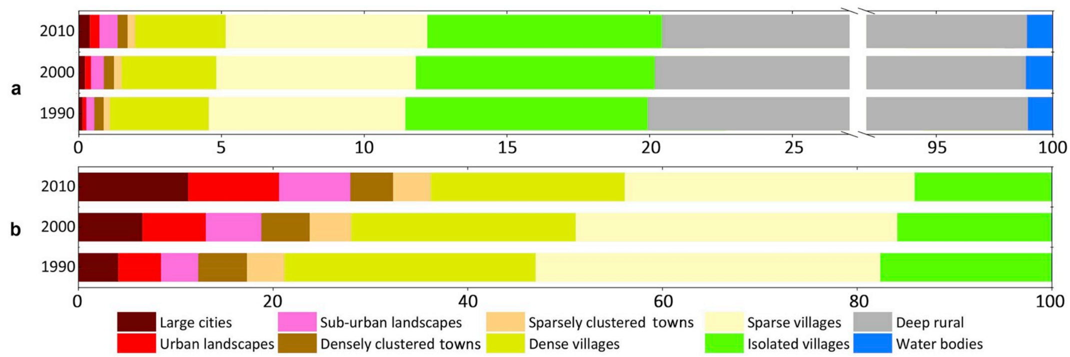

Fig. 6. a) Percentage of all land occupied by each settlement system. b) Percentage of built-up area included in each settlement system. No built-up area is found in deep rural area which is consistent with its definition in part 2.2.

1990-2000

	LC	UL	SU	DT	ST	DV	SV	IV	DR	WB
LC	11.26	0.01	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.02
UL	1.98	10.64	0.04	0.00	0.02	0.00	0.01	0.00	0.00	0.10
SU	2.54	4.49	18.79	0.01	0.07	0.02	0.13	0.00	0.01	0.11
DT	1.26	4.14	24.52	0.59	0.66	0.03	0.00	0.00	0.00	0.08
ST	0.21	2.31	3.46	0.21	14.31	0.00	0.23	0.02	0.02	0.08
DV	0.90	0.29	6.34	8.48	0.90	302.32	8.03	1.11	0.32	0.03
SV	2.07	1.30	9.03	0.55	9.41	6.36	615.89	4.30	3.13	1.07
IV	0.08	0.04	0.15	0.05	0.03	4.65	23.37	768.92	8.81	0.19
DR	0.14	0.07	0.26	0.03	0.10	0.71	15.36	20.35	7446.47	10.39
WB	0.03	0.08	0.02	0.00	0.01	0.01	0.29	0.13	4.38	96.91

2000-2010

	LC	UL	SU	DT	ST	DV	SV	IV	DR	WB
LC	19.22	0.01	0.01	0.00	0.00	0.00	0.03	0.00	0.01	0.00
UL	3.55	16.94	0.06	0.00	0.02	0.00	0.00	0.00	0.00	0.01
SU	5.34	8.35	28.33	0.00	0.07	0.04	0.13	0.00	0.00	0.03
DT	0.21	1.45	4.08	27.63	0.36	0.12	0.00	0.00	0.00	0.00
ST	0.29	2.30	4.27	0.43	17.91	0.00	0.27	0.00	0.00	0.01
DV	2.30	1.31	10.29	5.10	0.56	289.28	5.56	0.28	0.01	0.03
SV	3.69	1.68	12.11	0.11	6.00	8.65	625.70	3.58	1.47	0.46
IV	0.22	0.13	0.36	0.00	0.11	2.51	21.74	764.52	5.08	0.18
DR	0.32	0.17	0.43	0.00	0.11	0.19	15.75	12.30	7431.34	3.35
WB	0.13	0.35	0.13	0.00	0.08	0.02	0.86	0.10	6.52	100.63

Fig. 7. Settlement change matrices for 1990–2000 and 2000–2010, with values in 1000 km^2 of land area. The shades of red correspond with the size of the observed changes. A darker pane highlights a larger area that is transformed. Legend: LC = large cities, UL = urban landscapes, SU = sub-urban landscapes, DT = densely clustered towns, ST = sparsely clustered towns, DV = dense villages, SV = sparse villages, IV = isolated villages, DR = deep rural, WB = water bodies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

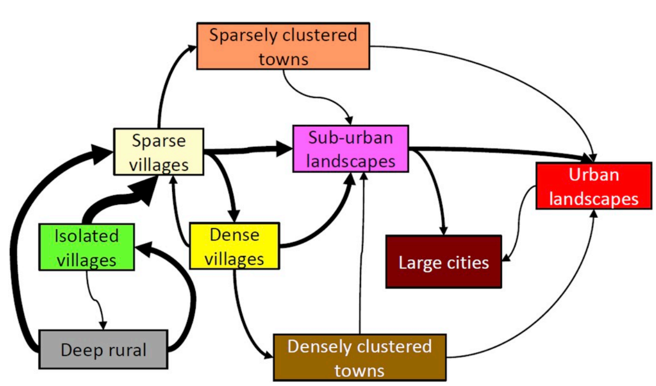

Fig. 8. Main transitions between settlement systems observed in China between 2000 and 2010. Depicted transitions are selected to show at least 70% of all observed changes from any particular land system starting from the largest transition category, and to have at least one arrow feed into each class. The width of the arrows is proportional to the land area of the corresponding settlement system change.

urban landscapes, rather than sudden transformation from rural to urban landscapes. Moreover, this figure also shows that multiple settlement change trajectories occur at the same time. For example, *sparse villages* changed into *sparsely clustered towns*, *dense villages* and *sub-urban landscapes*, reflecting respectively an increase in ABDI, an increase in cluster density, and an increase in large urban areas in the neighborhood.

4. Discussion

4.1. Settlement systems and their change trajectories in China

The map of settlement systems in China shows a distribution ranging from completely built-up to completely non-built-up, with the vast majority of built-up area distributed as small fractions in otherwise rural landscapes. Overall, more than 20% of all land in China is classified as one of the settlement systems in 2010. Changes in built-up area are found throughout this area, but the majority of new built-up land is added to areas that initially have a low fraction of urban land (i.e. village growth). For instance, between 1990 and 2000 more than 65% of all new built-up area emerged in village landscapes and *deep rural* areas. This percentage drops for the period 2000–2010, but still remains above

50% of all new built-up land. Hence, while locally the changes in metropolises can be dramatic, the aggregated effect of increases in smaller settlements is at least as large. These findings resemble those found for Europe (van Vliet, Verburg, Grădinaru, & Hersperger, 2019). This result suggests that analyses of urban growth in large metropolitan areas that have received much attention in recent years (Gong, Hu, Chen, Liu, & Wang, 2018; Xu et al., 2007; You & Yang, 2017) are not necessarily representative for built-up area expansion in China. Instead, it suggests that there is a need to analyze settlement systems more comprehensively by also including more subtle change processes in village landscapes, towns, and peri-urban areas.

Large metropolitan areas, particularly Beijing-Tianjin-Hebei region, Yangtze River Delta, and Pearl River Delta, are identified as *large cities*, *urban landscapes*, and *sub-urban landscapes*. Between 1990 and 2010 each of these three regions is characterized by typical urban growth processes, as reflected through an increase in built-up area, and an increase in cluster size in many cells (also see Xu et al. (2007), You and Yang (2017), and Gong et al. (2018)). As a result of their rapid growth, many *large cities* in these areas are facing a scarcity in land and a pressure on existing infrastructure. In order to deal with these constraints, the Beijing municipal government is gradually moved to Tongzhou district, which is quite distant from central Beijing (CGTN, 2017). At the same time, Tongzhou is now connected to downtown Beijing, leading to an continuous area characterized as *large cities*. The development in the more densely populated areas elsewhere in China are also fueled by national level policies. For example in Xiong'an New District in northern China, which was initiated by the Central Committee of the Communist Party of China and the State Council in 2017 with a long-term control area of about 2000 km^2 (Kuang, Yang, & Yan, 2017; Xu, Shi, Wang, Fang, & Lin, 2018b).

The most productive agricultural areas of China, notably the North China Plain, Northeast China Plain, and Guanzhong Plain, are characterized by sparse and dense village landscapes. These settlement systems reflect the patterns that emerged exactly because of the agricultural character of the region, as they are relatively densely clustered, but the clusters themselves are smaller. However, due to the economic development in all of eastern China, as well as population growth and migration from more remote parts of the country (Cao, Zheng, Liu, Li, & Chen, 2018; Li, Sun, & Fang, 2018), there is an increase in urban and sub-urban landscapes in these prime agricultural regions. For example, Jiangsu, a typical developed coastal province, experienced a dramatic development towards the more urban settlement systems, especially for regions closer to the economic hub of Shanghai. The growth of urban areas is often attributed to migration from rural areas (Henderson, Quigley, & Lim, 2009). At the same time, our results show that there is no decrease in built-up land in the agricultural areas between these cities, nor in the more remote areas elsewhere in China. The southeastern part of China, for example, is characterized by a rugged landscape, providing a natural constraint for both agricultural activities underlying the development of villages elsewhere as well as the emergence of large metropolitan areas. These mountain valleys are mainly filled with isolated villages, but these villages did not change much in recent decades or even showed small increases in ABDI.

The development of settlements in rural areas mostly consists of low-density developments, thus leading to relatively large amounts of land take and soil sealing for the benefit of few people. As these developments often come at a cost of agricultural lands, it further contributes to competition for land, thus affecting food security and biodiversity habitat (van Vliet, Eitelberg, & Verburg, 2017). This problem is not unique to China, as similar challenges have been observed elsewhere (Tóth, 2012; van Vliet, 2019). There is a window of opportunity for land use planning and national policies to reduce such conflicts by restricting built-up expansion and fostering more compact settlement types. In China, there is a long history of compensation policies and densification incentives (Liu, Fang, & Li, 2014a; Long, Li, Liu, Woods, & Zou, 2012). For example, the lost villages in Shandong Province are likely a policy effect ((Li, Wu, & Liu, 2018b), to cater for the national policy termed "increasing vs. decreasing balance of urban-rural construction land", which aims to balance the total construction land and hence compensate for urban development elsewhere (Cheng, Liu, Brown, & Searle, 2018). Yet, our results show that these initiatives have not effectively controlled the process of increasing built-up area in these regions. On top of that, such policies can have tradeoffs on social conditions (Howley, 2009; Schindler & Caruso, 2014) and may challenge rural cultural heritage (Yu, Verburg, Liu, & Eitelberg, 2016), indicating that plans need to carefully consider local conditions and impacts.

The need for a more nuanced understanding of settlements and settlement changes is relevant beyond Chinese territory. As in China, analyses of settlement changes elsewhere have focused mainly on few large urban areas (Bagan & Yamagata, 2012; Georg, Blaschke, & Taubenböck, 2018; Taubenböck et al., 2012). Meanwhile, a large part of the built-up land in the US was found outside urban and sub-urban areas (Theobald, 2001), suggesting the necessity of land use analysis through the whole urban-to-rural continuum. Consistently, most built-up expansion in South America occurs in small cities and rural areas, not only concentrated around major cities (Andrade-Núñez & Aide, 2018). A study on selected European countries has also shown that most built-up land is embedded in predominantly rural landscapes (van Vliet et al., 2019). As a result of the typical mosaics of settlements and other land uses, large parts of Europe have been characterized as peri-urban, or "territories-in-between" (Alexander Wandl, Nadin, Zonneveld, & Rooij, 2014). Global simulations of future land use show that such peri-urban and densified village landscapes will cover increasingly large parts of the earth and therefore need more attention (van Vliet et al., 2017).

4.2. *From built-up area to settlement systems*

Urban growth is often analyzed or simulated based on the conversion of non-built-up to built-up land, without further consideration of the structure of the landscape within which this conversion takes place (Huang et al., 2019; Yue et al., 2013). Otherwise, human settlements in China are usually indicated as cities, towns, and villages (Tian, Yang, & Zhang, 2007). However, these classes reflect an administrative classification, rather than a landscape description. In addition, a breath of spatial indices have been used to investigate patterns of urban land cover (Liu & Yang, 2015). This study, in contrast, uses spatial pattern indices for the characterization of settlement systems, a typology within which specific settlement change trajectories can be studied in their specific contexts. These processes include processes such as village growth, urban expansion, and sub-urbanization. Such in-depth understanding of settlement change trajectories is an essential prerequisite for designing policies dedicated to a more efficient land use (Hersperger et al., 2018; Mustafa, Van Rompaey, Cools, Saadi, & Teller, 2018; Wang, van Vliet, Pu, & Verburg, 2019).

The identification of settlement systems resembles recent developments in land use science leading to the identification of anthromes (Ellis & Ramankutty, 2008), land systems (van Asselen & Verburg, 2012) and land system archetypes (Václavík et al., 2013). These classification approaches move beyond the characterization of the terrestrial biosphere based on the predominant land cover or its related land use, and instead acknowledge the spatial distribution and spatial patterns that characterize landscapes. While urban areas are included in these approaches, their focus is essentially on the agricultural and natural parts of the landscape, leading to relatively little differentiation in settlement systems (Ornetsmüller et al., 2018; van Vliet et al., 2019). Settlement systems, therefore, complement these approaches and allow for a more in-depth investigation of settlement change processes and a more nuanced view on urban systems for land use policies and planning.

Settlement systems could also provide a starting point for a more nuanced representation of settlement change processes in land-use models. As of yet, many models are limited to the simulation of land cover conversions including a conversion from non-urban to urban land (van Vliet et al., 2019). For a large number of urban growth models, this is even the only type of change that is simulated (Kamusoko & Gamba, 2015; Mahiny & Clarke, 2012). The results of this study show the wide variety in settlement systems, as well as the different change trajectories that take place in parallel. Hence the representation of built-up land constraints the extent to which we can learn from such models or use them to explore solutions for sustainability challenges. To facilitate further research in this direction, we make the dataset produced in this study freely available from the website (https://cscproject.github.io).

5. Conclusion

Settlement systems exist in a wide variety ranging from isolated villages to larger metropolitan areas. This study analyses changes in settlements beyond merely assessing the conversion of non-built-up land into built-up land. Results show that settlement systems typically change gradually and incrementally, from villages to towns to peri-urban and urban areas. Moreover, results of this study also show that the combined increase in built-up land in smaller cities, towns and villages exceeds that of large urban areas. This suggests that there is a need to analyze settlement systems more comprehensively, and beyond the increase of a few mega-cities only.

Declaration of competing interest

None.

Acknowledgments

M. Li would like to acknowledge funding from China Scholarship Council (Grant No. 201706510011). This research contributes to the Global Land Programme (www.glp.earth).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.habitatint.2019.102069.

References

Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S., et al. (2007). The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. *Landscape and Urban Planning, 80*, 345–361.

Alexander Wandl, D. I., Nadin, V., Zonneveld, W., & Rooij, R. (2014). Beyond urban–rural classifications: Characterising and mapping territories-in-between across Europe. *Landscape and Urban Planning, 130*, 50–63.

Andrade-Núñez, M. J., & Aide, T. M. (2018). Built-up expansion between 2001 and 2011 in South America continues well beyond the cities. *Environmental Research Letters, 13*.

Angel, S., Parent, J., Civco, D. L., Blei, A., & Potere, D. (2011). The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. *Progress in Planning, 75*, 53–107.

Bagan, H., & Yamagata, Y. (2012). Landsat analysis of urban growth: How Tokyo became the world's largest megacity during the last 40 years. *Remote Sensing of Environment, 127*, 210–222.

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Guneralp, B., Erb, K. H., et al. (2017). Future urban land expansion and implications for global croplands. *Proceedings of the National Academy of Sciences of the United States of America, 114*, 8939–8944.

Cao, Z., Zheng, X., Liu, Y., Li, Y., & Chen, Y. (2018). Exploring the changing patterns of China's migration and its determinants using census data of 2000 and 2010. *Habitat International, 82*, 72–82.

CGTN. (2017). *Beijing city gov't begins move to Tongzhou.* https://news.cgtn.com/news/3141544d33637a6333566d54/share_p.html.

Cheng, L., Liu, Y., Brown, G., & Searle, G. (2018). Factors affecting farmers' satisfaction with contemporary China's land allocation policy – the Link Policy: Based on the empirical research of Ezhou. *Habitat International, 75*, 38–49.

Cullum, C., Brierley, G., Perry, G. L. W., & Witkowski, E. T. F. (2016). Landscape archetypes for ecological classification and mapping. *Progress in Physical Geography: Earth and Environment, 41*, 95–123.

Cumming, G. S., Buerkert, A., Hoffmann, E. M., Schlecht, E., von Cramon-Taubadel, S., & Tscharntke, T. (2014). Implications of agricultural transitions and urbanization for ecosystem services. *Nature, 515*, 50–57.

Ellis, E. C., & Ramankutty, N. (2008). Putting people in the map: Anthropogenic biomes of the world. *Frontiers in Ecology and the Environment, 6*, 439–447.

Fang, C., Yu, D., Mao, H., Bao, C., & Huang, J. (2018). *The dynamic evolution and moving tracks of the center of gravity for the spatial pattern of China's urban development. China's Urban Pattern* (pp. 37–81). Singapore: Springer.

Georg, I., Blaschke, T., & Taubenböck, H. (2018). Are we in boswash yet? A multi-source geodata approach to spatially delimit urban corridors. *ISPRS International Journal of Geo-Information, 7*, 15.

Gong, J., Hu, Z., Chen, W., Liu, Y., & Wang, J. (2018). Urban expansion dynamics and modes in metropolitan Guangzhou, China. *Land Use Policy, 72*, 100–109.

Gong, P., Li, X., & Zhang, W. (2019). 40-Year (1978–2017) human settlement changes in China reflected by impervious surfaces from satellite remote sensing. *Science Bulletin, 64*, 756–763.

Henderson, J. V., Quigley, J., & Lim, E. (2009). *Urbanization in China: Policy issues and options*. Brown University. Unpublished manuscript.

Hersperger, A. M., Oliveira, E., Pagliarin, S., Palka, G., Verburg, P., Bolliger, J., et al. (2018). Urban land-use change: The role of strategic spatial planning. *Global Environmental Change, 51*, 32–42.

Howley, P. (2009). Attitudes towards compact city living: Towards a greater understanding of residential behaviour. *Land Use Policy, 26*, 792–798.

Huang, A., Xu, Y., Liu, C., Lu, L., Zhang, Y., Sun, P., et al. (2019). Simulated town expansion under ecological constraints: A case study of zhangbei county, Heibei province, China. *Habitat International, 91*.

Ianoș, I., & Jones, R. (2019). Local aspects of change in the rural-urban fringe of a metropolitan area: A study of bucharest, Romania. *Habitat International, 91*.

Jha, S., & Kremen, C. (2013). Resource diversity and landscape-level homogeneity drive native bee foraging. *Proceedings of the National Academy of Sciences of the United States of America, 110*, 555–558.

Jiao, L. (2015). Urban land density function: A new method to characterize urban expansion. *Landscape and Urban Planning, 139*, 26–39.

Kamusoko, C., & Gamba, J. (2015). Simulating urban growth using a random forest-cellular automata (RF-CA) model. *ISPRS International Journal of Geo-Information, 4*, 447–470.

Kim, G., Miller, P. A., & Nowak, D. J. (2018). Urban vacant land typology: A tool for managing urban vacant land. *Sustainable Cities and Society, 36*, 144–156.

Krehl, A., & Siedentop, S. (2018). Towards a typology of urban centers and subcenters – evidence from German city regions. *Urban Geography, 40*, 58–82.

Kuang, W., Liu, J., Dong, J., Chi, W., & Zhang, C. (2016). The rapid and massive urban and industrial land expansions in China between 1990 and 2010: A CLUD-based analysis of their trajectories, patterns, and drivers. *Landscape and Urban Planning, 145*, 21–33.

Kuang, W., Yang, T., & Yan, F. (2017). Examining urban land-cover characteristics and ecological regulation during the construction of Xiong'an New District, Hebei Province, China. *Journal of Geographical Sciences, 28*, 109–123.

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences, 108*, 3465–3472.

Levers, C., Müller, D., Erb, K., Haberl, H., Jepsen, M. R., Metzger, M. J., et al. (2015). Archetypical patterns and trajectories of land systems in Europe. *Regional Environmental Change, 18*, 715–732.

Liu, J., Kuang, W., Zhang, Z., Xu, X., Qin, Y., Ning, J., et al. (2014). Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s. *Journal of Geographical Sciences, 24*, 195–210.

Liu, J., Liu, M., Zhuang, D., Zhang, Z., & Deng, X. (2003). Study on spatial pattern of land-use change in China during 1995–2000. *Science in China - Series D: Earth Sciences, 46*, 373–384.

Liu, Y., Fang, F., & Li, Y. (2014). Key issues of land use in China and implications for policy making. *Land Use Policy, 40*, 6–12.

Liu, Y., Luo, T., Liu, Z., Kong, X., Li, J., & Tan, R. (2015). A comparative analysis of urban and rural construction land use change and driving forces: Implications for urban–rural coordination development in Wuhan, Central China. *Habitat International, 47*, 113–125.

Liu, T., & Yang, X. (2015). Monitoring land changes in an urban area using satellite imagery, GIS and landscape metrics. *Applied Geography, 56*, 42–54.

Li, G., Sun, S., & Fang, C. (2018). The varying driving forces of urban expansion in China: Insights from a spatial-temporal analysis. *Landscape and Urban Planning, 174*, 63–77.

Li, Y., Wu, W., & Liu, Y. (2018). Land consolidation for rural sustainability in China: Practical reflections and policy implications. *Land use policy, 74*, 137–141.

Liu, Z., He, C., Zhou, Y., & Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landscape Ecology, 29*, 763–771.

Long, H., Li, Y., Liu, Y., Woods, M., & Zou, J. (2012). Accelerated restructuring in rural China fueled by 'increasing vs. decreasing balance' land-use policy for dealing with hollowed villages. *Land Use Policy, 29*, 11–22.

Long, H., Liu, Y., Hou, X., Li, T., & Li, Y. (2014). Effects of land use transitions due to rapid urbanization on ecosystem services: Implications for urban planning in the new developing area of China. *Habitat International, 44*, 536–544.

Loures, L., & Vaz, E. (2018). Exploring expert perception towards brownfield redevelopment benefits according to their typology. *Habitat International, 72*, 66–76.

Mahiny, A. S., & Clarke, K. C. (2012). Guiding SLEUTH land-use/land-cover change modeling using multicriteria evaluation: Towards dynamic sustainable land-use planning. *Environment and Planning B: Planning and Design, 39*, 925–944.

Malek, Ž., & Verburg, P. (2017). Mediterranean land systems: Representing diversity and intensity of complex land systems in a dynamic region. *Landscape and Urban Planning, 165*, 102–116.

McGarigal, K., & Cushman, S. (2005). The gradient concept of landscape structure [Chapter 12]. In J. A. Wiens, & M. R. Moss (Eds.), *Issues and perspectives in landscape ecology* (pp. 112–119). Cambridge University Press, 112-119.

Mustafa, A., Van Rompaey, A., Cools, M., Saadi, I., & Teller, J. (2018). *Addressing the determinants of built-up expansion and densification processes at the regional scale*. Urban Studies.

Ornetsmüller, C., Heinimann, A., & Verburg, P. H. (2018). Operationalizing a land systems classification for Laos. *Landscape and Urban Planning, 169*, 229–240.

Ramachandra, T. V., Bharath, A. H., & Sowmyashree, M. V. (2015). Monitoring urbanization and its implications in a mega city from space: Spatiotemporal patterns and its indicators. *Journal of Environmental Management, 148*, 67–81.

Rounsevell, M. D. A., Pedroli, B., Erb, K.-H., Gramberger, M., Busck, A. G., Haberl, H., et al. (2012). Challenges for land system science. *Land Use Policy, 29*, 899–910.

Schindler, M., & Caruso, G. (2014). Urban compactness and the trade-off between air pollution emission and exposure: Lessons from a spatially explicit theoretical model. *Computers, Environment and Urban Systems, 45*, 13–23.

Schneider, A., & Mertes, C. M. (2014). Expansion and growth in Chinese cities, 1978–2010. *Environmental Research Letters, 9*.

Seto, K. C., Guneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of the United States of America, 109*, 16083–16088.

Shi, L., Taubenböck, H., Zhang, Z., Liu, F., & Wurm, M. (2017). Urbanization in China from the end of 1980s until 2010 – spatial dynamics and patterns of growth using EO-data. *International Journal of Digital Earth*, 1–17.

Tachikawa, T., Kaku, M., Iwasaki, A., Gesch, D., Oimoen, M., Zhang, Z., et al. (2011). *ASTER global digital elevation model version 2–summary of validation results*. August 31, 2011.

Tan, M., & Li, X. (2013). The changing settlements in rural areas under urban pressure in China: Patterns, driving forces and policy implications. *Landscape and Urban Planning, 120*, 170–177.

Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A., & Dech, S. (2012). Monitoring urbanization in mega cities from space. *Remote Sensing of Environment, 117*, 162–176.

Theobald, D. M. (2001). Land-use dynamics beyond the American urban fringe. *Geographical Review, 91*, 544–564.

Tian, G., Jiang, J., Yang, Z., & Zhang, Y. (2011). The urban growth, size distribution and spatio-temporal dynamic pattern of the Yangtze River Delta megalopolitan region, China. *Ecological Modelling, 222*, 865–878.

Tian, G., Yang, Z., & Zhang, Y. (2007). The spatio-temporal dynamic pattern of rural residential land in China in the 1990s using Landsat TM images and GIS. *Environmental Management, 40*, 803–813.

Tóth, G. (2012). Impact of land-take on the land resource base for crop production in the European Union. *The Science of the Total Environment, 435*, 202–214.

Václavík, T., Lautenbach, S., Kuemmerle, T., & Seppelt, R. (2013). Mapping global land system archetypes. *Global Environmental Change, 23*, 1637–1647.

Visser, H., & de Nijs, T. (2006). The map Comparison Kit. *Environmental Modelling & Software, 21*, 346–358.

van Asselen, S., & Verburg, P. H. (2012). A Land System representation for global assessments and land-use modeling. *Global Change Biology, 18*, 3125–3148.

van der Zanden, E. H., Levers, C., Verburg, P. H., & Kuemmerle, T. (2016). Representing composition, spatial structure and management intensity of European agricultural landscapes: A new typology. *Landscape and Urban Planning, 150*, 36–49.

van Vliet, J. (2019). Direct and indirect loss of natural area from urban expansion. *Nature Sustainability, 2*(8), 755–763.

van Vliet, J., Eitelberg, D. A., & Verburg, P. H. (2017). A global analysis of land take in cropland areas and production displacement from urbanization. *Global Environmental Change, 43*, 107–115.

van Vliet, J., Verburg, P. H., Grădinaru, S. R., & Hersperger, A. M. (2019). Beyond the urban-rural dichotomy: Towards a more nuanced analysis of changes in built-up land. *Computers, Environment and Urban Systems, 74*, 41–49.

Wang, L., Li, C., Ying, Q., Cheng, X., Wang, X., Li, X., et al. (2012). China's urban expansion from 1990 to 2010 determined with satellite remote sensing. *Chinese Science Bulletin, 57*, 2802–2812.

Wang, Y., van Vliet, J., Pu, L., & Verburg, P. H. (2019). Modeling different urban change trajectories and their trade-offs with food production in Jiangsu Province, China. *Computers, Environment and Urban Systems, 77*(101355).

Wu, W., Zhao, S., Zhu, C., & Jiang, J. (2015). A comparative study of urban expansion in Beijing, Tianjin and Shijiazhuang over the past three decades. *Landscape and Urban Planning, 134*, 93–106.

Xu, G., Dong, T., Cobbinah, P. B., Jiao, L., Sumari, N. S., Chai, B., et al. (2019). Urban expansion and form changes across African cities with a global outlook: Spatiotemporal analysis of urban land densities. *Journal of Cleaner Production, 224*, 802–810.

Xu, C., Liu, M., Zhang, C., An, S., Yu, W., & Chen, J. M. (2007). The spatiotemporal dynamics of rapid urban growth in the Nanjing metropolitan region of China. *Landscape Ecology, 22*, 925–937.

Xu, H., Shi, T., Wang, M., Fang, C., & Lin, Z. (2018). Predicting effect of forthcoming population growth–induced impervious surface increase on regional thermal environment: Xiong'an New Area, North China. *Building and Environment, 136*, 98–106.

Xu, L., Huang, Q., Ding, D., Mei, M., & Qin, H. (2018). Modelling urban expansion guided by land ecological suitability: A case study of changzhou city, China. *Habitat International, 75*, 12–24.

You, H., & Yang, X. (2017). Urban expansion in 30 megacities of China: Categorizing the driving force profiles to inform the urbanization policy. *Land Use Policy, 68*, 531–551.

Yue, W., Zhang, L., & Liu, Y. (2016). Measuring sprawl in large Chinese cities along the Yangtze River via combined single and multidimensional metrics. *Habitat International, 57*, 43–52.

Yue, W., Liu, Y., & Fan, P. (2013). Measuring urban sprawl and its drivers in large Chinese cities: The case of Hangzhou. *Land Use Policy, 31*, 358–370.

Yu, Q., Hu, Q., van Vliet, J., Verburg, P. H., & Wu, W. (2018). GlobeLand30 shows little cropland area loss but greater fragmentation in China. *International Journal of Applied Earth Observation and Geoinformation, 66*, 37–45.

Yu, H., Verburg, P. H., Liu, L., & Eitelberg, D. A. (2016). Spatial analysis of cultural heritage landscapes in rural China: Land use change and its risks for conservation. *Environmental Management, 57*, 1304–1318.