Research Paper

Settlement changes after peak population: Land system projections for China until 2050

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HIGHLIGHTS

- We simulate settlement system changes in China until 2050.
- Our model includes multiple settlement systems, allowing for different urbanization trajectories.
- Future changes include both urban development and a development of village landscapes.
- Increase in built-up land mostly leads to a decline in natural areas via cropland displacement.
- Maintaining current population densities can avoid a loss of 57–73 × 10^3 km^2 of natural land.

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ABSTRACT

China has experienced unprecedented urbanization in the past few decades, fueled by population growth, economic development, and rural to urban migration. In the future, economic growth as well as rural to urban migration is expected to continue, but demographic scenarios indicate that the population of China will peak and subsequently decline. As a result, it is unsure how urban areas will develop after peak population. In this study we further develop the CLUMondo land system model to simulate land system changes in China until 2050. Our application represents a range of settlement systems, from dense urban areas to village landscapes, differing in their built-up area as well as their population density to enable the simulation of different settlement change trajectories. Our results show that a UN high population scenario in combination with a continued decline in population density leads to an increase of built-up land of about 48%. Conversely, the UN low population scenario in combination with a constant population density could be accommodated within the current amount of built-up land in China. Due to prevailing cropland protection policies, increase in built-up land will mostly lead to a loss of natural areas, hence our scenarios highlight the opportunity space for limiting land take and saving natural areas. This study also demonstrates the need for more nuanced representation of settlement systems for the assessment of land change trajectories.

1. Introduction

Population change is one of the main drivers underlying the trend in urban land expansion that has been observed in recent years (Angel et al., 2011; Colsaet et al., 2018). This relationship is moderated by economic development, prevailing policies, and other local conditions leading to differences both within and across countries (Colsaet et al., 2018). Changes in built-up land can thus be conceptualized as the result of changes in the population and changes in the urban area used per person, where a small area per person is similar to a high residential density. Generally, residential densities are higher in large cities than in rural villages, and therefore urbanization can decrease or reduce land take (Fernandez Milan and Creutzig, 2016; Guastella et al., 2017; Howell-Moroney, 2007). At the same time, built-up land expansion has

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exceeded population growth in recent years. In other words, the area of built-up land per person has increased, globally, which suggests that urban growth is becoming more dispersed than compact (Decouville and Schneider, 2016). This trend has for example been observed in many European countries, such as Switzerland and southern France (Chanel et al., 2014; van Vliet et al., 2019; Wellemann et al., 2017).

The growth of cities is often, at least partly, fueled by migration from rural to urban areas, which at the same time leads to a population decline in rural areas in many countries (Alami-Sabater et al., 2019; Liu and Li, 2017). Since the late 19th century, rural population decline and village abandonment have been widely reported in industrial countries, such as the United States, the United Kingdom, France, Italy, Spain, Portugal, and Japan (Wang, Zhang, et al., 2019; Watanabe, 2014). Yet, this population decline has not necessarily led to a reduction in built-up land in rural areas, because this development was accompanied by a decrease in family size, leading to lower densities (Haase et al., 2013; Liu et al., 2003). Irrespective of population dynamics, Angel et al. (2010) found that urban population densities have been declining for at least a century, globally. In India, Europe, Unites States, and Sub-Saharan Africa, the average annual decline rate of residential densities between 2000 and 2014 were 2.35%, 1.50%, 0.78% and 0.82%, respectively (Xu et al., 2019).

China has experienced unprecedented urbanization during the past decades, as the urbanization rate increased from 17.9% in 1978 to 57.4% in 2016. As a result, towns and cities of various sizes have grown in population as well as built-up area (Li et al., 2019; Li, Jia, & et al., 2018). Urban growth in China was also accompanied by a decline in residential density, as urban area has expanded much faster than urban population (Deng et al., 2009). Average residential density in urban areas in China dropped from 8500 persons/km² in 2000 to 7300 persons/km² in 2010 (Guan et al., 2018). Apart from Beijing and Shanghai, the average decline in residential density in 33 Chinese cities varied from 1% to 9%, with an average of 4.65% between 2001 and 2015 (Xu et al., 2019). Similar to many industrialized countries, urban growth in China is partly caused by rural-to-urban migration. This has led to cropland abandonment as well as the phenomenon known as "hollow villages", i.e. villages of which most residents have moved, especially in mountainous areas (Wang et al., 2019; Li, Wu, & Liu, 2018; Zhang, Jiang, & Zhang, 2019) but more recently also in Jiangsu province (Shen et al., 2020). Despite rural depopulation, the built-up land in rural areas nearly tripled between 1967 and 2008 (Liu, Yang, & et al., 2014). Consistently, Li et al. (2019), found that the majority of all new built-up area added between 1990 and 2010 was added to rural areas in China. The total fertility rate in China has remained stable between 1995 and 2015, at a value of about 1.62–1.64, which has contributed to a slow-down of the population growth in this period (United Nations, 2019). As it is expected that the fertility in China will remain well below the replacement rate, studies project that the population will peak around the year 2030, and decrease afterwards (Cheng and Duan, 2016; United Nations, 2019). Depending on the projections, this decline can be as large as 153 million people until 2050 in China. As these projections affect the entire country, it raises the questions of how this will affect urban development. Many land-use models have simulated built-up land expansion, often driven by population increase (Decouville and Schneider, 2016; Kroll and Haase, 2010), but projections of settlement change as a result of population decline are scarce. In this paper, we assess how different settlement systems in China can develop under various scenarios of population decline. To this effect, we first characterize land systems, so they represent a gradient from rural to urban area, including for example village landscapes, towns, and dense urban areas. Subsequently, we model future land system changes under different population scenarios and development densities, and analyze results in terms of settlement change trajectories as well as associated land cover changes. Simulated land change scenarios can reveal the potential for future-proof urbanization trajectories that limit impact through urban sprawl and cropland displacement.

2. Methodology

2.1. Land system classification

We developed a land system map for China for the year 2000 and the year 2015 using an expert-based classification. This classification is designed to represent multiple different settlement systems, which are normally not distinguished in land cover maps. The classification contains four major groups: urban systems, village systems, agricultural systems, and natural systems. Urban systems and village systems are together referred to as settlement systems in this paper and reflect the various stages along the rural–urban gradient. As a result, settlement change trajectories can be simulated as a series of small and incremental steps along this gradient (Wang, van Vliet et al., 2019).

We identified 18 land system classes, each of which is defined by the combination of its land cover composition, population density, and agricultural productivity. As a first step, all data was aggregated to a 2 × 2 km resolution, and subsequently combined following the decision tree in Fig. 1. Urban systems include High-dense urban area, Low dense urban area, Peri-urban area, and Sub-urban area, and differ both in the amount of built-up land as well as the population density within this built-up land. As a result, we can analyze urban expansion and urban intensification separately. The threshold between high and low population density corresponds with the threshold between areas with mainly single and detached houses, and areas with mainly apartment blocks. A threshold value of 5000 persons per km² was determined by assessing the population density of 112 randomly selected locations in Google Earth and classifying them as high- or low-density. This threshold yielded an accuracy of 81.5% and 91.8% for low and high density, respectively. We used the share of built-up land, in combination with the number of clusters of built-up land to identify various village systems. Clustered landscapes and spread landscapes are characterized by larger and smaller settlements, respectively. Three types of hinterland villages are classified according to the predominant land cover type these villages are placed in. Agricultural systems consist mostly of cropland and differ in their agricultural land productivity, which was derived from crop production data at the county level in combination with cropland area and multi-cropping frequencies. Natural systems are divided into grassland system, forest system, forest-grass mix system, wetland, water and other land, based on the share of land cover in a pixel. The data sources used for this classification are listed in Table 1.

2.2. Modelling land system changes

The CLUMondo model was used to simulate changes in land systems until 2050 under different scenarios. Contrary to other land change models, CLUMondo simulates land system changes, rather than land cover conversions (van Asselen and Verburg, 2013; Verburg et al., 2019). This allows to model urban development as a gradual process and also to model both urban expansion and urban intensification as two separate processes (Wang, van Vliet et al., 2019).

CLUMondo simulates land system changes in response to various types of exogenously defined demands, and allocates these changes in an iterative procedure using conversion rules and empirically derived suitability values (van Asselen and Verburg, 2013). Specifically, in each time step, the model allocates to each pixel the land system for which they have the highest potential, where the potential is a function of the suitability of a location, land system characteristics, the influence of neighboring pixels, and the competitive advantage for each specific land system. Suitability values of locations are quantified empirically, based on a logistic regression analysis using socio-economic and biophysical factors as explanatory variables. Land system characteristics indicate whether or not a specific land system can convert into another land system, and if so how much resistance there is for such conversion. These parameters reflect both physical constraints, for example by assuming that water will not change into other classes, and economic effects, for
example indicating that agricultural land is cheaper to convert into urban land than a forest. Neighboring land systems can affect the attractions of other land systems close by. This effect is specifically relevant for urban development, as often new urban development takes place near existing urban areas. The details of the CLUMondo model are provided in Fig. S1 and equation 1 in supplementary material.

A land system can produce one or more services or products, and any single service or product can be produced by multiple land systems. Therefore, the CLUMondo model is able to simulate different land system change trajectories in response to the same demand. For example, an increase in demand for crop product can lead to expansion of agricultural area or intensification of existing agricultural land (Debonne et al., 2019; van Asselen and Verburg, 2013). The resulting land system changes (e.g. the choice between agricultural intensification or expansion) are therefore the result of a numerical procedure balancing multiple these demands, constraints, suitability and other specifications.

In this study, land system changes are driven by a demand for housing population and a demand for cropland area. Population demand reflects the main driver for urban development, while cropland demand represents the current agricultural land use policies that aim to preserve agricultural land (Angel et al., 2011; Lichtenberg and Ding, 2008). Changes in settlement systems are driven solely by the demand for housing population, although especially the village systems and towns also produce a significant amount of crops. Consistently, agricultural systems mainly produce crops, although they also accommodate some people (See Table S3). Both demands are allocated in two consecutive processes within each time step in the model. Specifically, each time step, population change is accommodated first by changes in different settlement systems, and agricultural land is subsequently satisfied in the areas not used as settlement systems. This change is a deviation from the original CLUMondo model, in which all demands were in competition for space, and reflects the precedence of urban land over other land uses in the competition for space (van Vliet, 2019).

To parameterize the model and assess its performance, we first simulated known land system changes between 2000 and 2015. As the change in built-up land area is a model result only, this metric was used for evaluation. Specifically, we assessed to what extent the model was able to translate population growth scenarios into either urban intensification or urban expansion. For example, a change from a clustered landscape to a sub-urban area represents a small increase in population

![Decision tree for the classification of land systems in China. Black cells indicate decisions dependent on input data, while colored cells indicate the resulting land systems.](image-url)
but a large increase in built-up land, thus mainly representing expansion. Conversely, a change from clustered landscape to peri-urban area represents mostly intensification and relatively little expansion. Table S3 indicates the characteristics of different land systems, i.e. population and built-up land, from which these changes are derived. Over the calibration period, the difference between observed and simulated changes in built-up land area was less than 0.1%. This suggests that the model can accurately simulate the extent to which population changes lead to intensification and expansion. Subsequently, the same set of parameters that best captured these dynamics was used to simulate changes between 2015 and 2050.

A detailed description of the CLUMondo model, including all parameter values adopted for this study, is provided in the Supplementary material.

2.3. Scenarios

To explore urbanization trajectories caused by population change and their impacts on other land systems, we designed four scenarios (see Table 2). The scenarios differ in their projected population changes (low projection vs. high projection) and their urbanization trajectories (constant density vs. gradual decline).

We used two population projections for the period 2015–2050, representing the upper and lower bound of the range of projections by the United Nations (United Nations, 2019). In the high projection, population peaks at 1518 million persons in 2044 and then decreases slightly to 1515 million in 2050, representing a net increase of 108 million persons over the entire simulation period (see Fig. 2). In the low projection, population increases at a peak of 1447 million persons in 2024 and subsequently declines to 1294 million persons in 2050. The decline exceeds the initial growth and thus leads to a net population decrease of 113 million persons until 2050, which is about 8.0% lower than in 2015 (see Fig. 2).

Drawing on observations in other countries and regions, we designed two kinds of urbanization trajectories in response to these population dynamics. In the Constant density trajectory, we assume that residential densities remain constant in all land systems. This scenario represents a trend-break as the density of urban systems has decreased consistently in China in recent years, due for various reasons. It effectively assumes that potential changes in wealth or family size do not affect residential density, and that all settlement changes are driven by a change in population only. Such constraints have been implemented in policies already in other countries, such as the aim to limit built-up area per person to 400 m² in Switzerland (Weilenmann et al., 2017). As some population decline takes place in all scenarios, this effectively requires a reverse development of urban areas, for example from low-density urban land to sub-urban land, representing a loss in built-up land together with a decline in population. Hence it is an opportunity to reduce built-up land and make it available for other land uses (Mascarenhas et al., 2019). In the Constant density scenarios, such reverse processes are explicitly allowed in the model set-up. Conversely, in the Gradual decline scenarios, population density for all land systems will continue to decline over time, following trends observed between 2000 and 2015 (population included in each land system in the start and end year are provided in Table S10). These trends reflect developments that have been observed in many countries throughout the world (Angel et al., 2010). Consistently, the Gradual Decline scenarios assume that reverse processes will not take place, i.e. urban development is seen as a one-directional process towards land systems that are more urban. This also means that hollow villages and abandoned houses will continue to exist.

In addition to population changes, scenarios are also driven by a demand for cropland. Specifically, we require the cropland area to at least remain constant at the 2015 level, indicating there cannot be any net cropland loss during study period. This is a simplified representation of the current cropland protection policy, the Cropland Dynamic Balance Policy, which is highlighted by the Chinese central government (Farmland Protection Division, 2017) and serves as a constraint for unrestricted urban sprawl. A much wider range of land use policies have been proposed in China in recent years, most notably also including the protections of natural areas via the Ecological Conservation Redlines (e.g. see Gao et al. (2020)). However, these have not been included in this study because this analysis focuses on potential urban development trajectories, while a complete policy analysis is beyond the scope of this paper.

### Table 1
Input data for the land system classification and characterization. Data listed here corresponds with those referred to in Fig. 1.

| Dataset | Format/ resolution | Time | Source |
|---------|--------------------|------|--------|
| Built-up data | TIFF/38 m | 2000, 2014 | Global human settlement layer produced by European Commission (Pesaresi et al., 2016) |
| Population | TIFF/250 m | 2000, 2015 | Global human settlement layer produced by European Commission (Pesaresi et al., 2016) |
| Cropping frequency | TIFF/1 km | 2015 | Chinese Academy of Sciences (DOI: https://doi.org/10.12078/2018060502) |
| Land cover data (Cropland, Grassland, Forest, Wetland, Water, et al.) | TIFF/30 m | 2000, 2015 | Chinese Academy of Sciences (DOI: https://doi.org/10.12078/2018070201) |
| Grain production | County, level | 2000, 2015 | Statistic yearbook (National Bureau of Statistics of China, 2001) |

### Table 2
Scenarios underlying land system change simulations for this study. Details for all scenarios are provided in the main text.

| Scenario | Population demand | Urban density | Cropland demand |
|----------|-------------------|---------------|-----------------|
| Scenario 1 (S1) | High projection | Constant | No net loss |
| Scenario 2 (S2) | High projection | Gradual decline | No net loss |
| Scenario 3 (S3) | Low projection | Constant | No net loss |
| Scenario 4 (S4) | Low projection | Gradual decline | No net loss |
3. Results

3.1. Urban land systems in China

China can be characterized by a gradient of land systems ranging from completely urban to completely rural. Fig. 3 shows the distribution of land systems in China for the year 2015, and provides an aerial image for a typical location for each urban system and each village system. High dense and low dense urban land systems are predominantly found in or close to large cities. They make up 0.3% and 0.2% of the total land surface of China, respectively. Surrounding these urban systems, there is a tapestry of mostly Peri-urban and Sub-urban areas, both occupying about 0.5% of the land. In addition to these urban systems, a much larger area of China is characterized as village systems. This group comprises Clustered landscapes and Spread landscapes (0.7% and 2.1% of the land area, respectively), and three different type of hinterland villages (3.4%, 0.3%, and 1.1% for Agricultural hinterland villages, Grazing hinterland villages, and Forest hinterland villages, respectively). These different types of village systems represent the more rural part of the urban-rural gradient, and are mostly agricultural land with villages and towns included in them. The rest of China has little to no built-up land and is therefore characterized as agricultural land systems and natural land systems.

Urban systems are predominantly characterized by built-up land, but they differ in the share of built-up land as well as in their population density. High density urban systems and Low density urban systems have 72% and 68% built-up land, respectively (See Table S3). Yet, the main difference between both systems is their population density. High dense urban systems are characterized by multi-story buildings and have on average have 10,199 inhabitants per km² in 2015 (see Table S3). An example of this is shown in Fig. 3a, which includes high-rise buildings that are typical for many of the larger cities in China. Low dense urban systems have on average a population density of 1967 persons per km² in 2015, about 5 times lower than High dense urban systems. A similar comparison can be made between Peri-urban areas and Sub-urban areas. Both are comparable in their share of built-up land (about 32%), but their average population densities in 2015 are 3951 and 887 persons per km², respectively. Similar to High density urban areas and Low density urban areas, this difference represent the difference between predominantly high-rise buildings and predominantly low rise buildings (see Fig. 3c-d for representative examples). Due to the presence of predominantly high-rise buildings in Peri-urban areas, the population density of this land system even exceeds that of Low dense urban area.

Village systems are determined by the amount of built-up land but differ in the number of settlements and the predominant non-built-up land cover. Both Clustered landscapes and Spread landscapes on average include 9% and 10% of built-up land, respectively. Yet, in Clustered landscapes this built-up land is concentrated in few settlements, typically including a town, while in a Spread landscape the built-up land is distributed over a larger number of settlements, mostly representing small villages (see Fig. 3e-f for representative examples). Hinterland villages have between 2% and 3% built-up land on average but these settlements differ in their surroundings (Fig. 3g-i). The population density of these systems ranges from 404 persons per km² for Forest hinterland systems to 588 persons per km² for Agricultural hinterland systems (see Table S3).

Agricultural systems and Natural systems by definition have <1% built-up land. Agricultural systems account for 31% of the total land area in China. Despite the near absence of built-up land, High-intensity, Medium-intensity, and Low-intensity agricultural systems have on average 151, 108, and 65 persons per km², respectively. Yet, their main difference is the amount of crops produced, ranging from 1.5 ton per hectare for low-intensity agricultural land to 5.6 ton per hectare for high-intensity agricultural land (see Table S3). Natural systems cover the remaining 60% of China. These systems contain a negligible amount of built-up land and depending on the system, their average population density ranges between 2 persons per km² (Other land) and 36 persons per km² (Wetlands) system, forest system, grass-forest mix system, wetland, water and other land are characterized by the share of grassland, forest, wetland, and water area.

3.2. Projected land system changes until 2050

The four land system change scenarios mostly differ in their settlement change trajectories, as a result of their different population demands and urban trajectories allowed. As a result of this, they also yield different changes in agricultural and natural land systems.

The first scenario, defined by a high population demand and a constant population density for all land systems, leads to a modest increase in all types of urban systems (24 × 10⁶ km² in total) as well as all types of village systems (47 × 10⁶ km² in total). Conversely, all agricultural land systems and all natural land systems see a net decrease of which are −47 × 10⁶ km² and −24 × 10⁶ km² respectively. Although all urban land systems increase, this increase is largest for the category Low density urban over the entire period. This is likely the result of the small decline in population in the last few years leading to a backwards conversion of High density urban to Low density urban. Despite the requirement for net loss in cropland, there is a decline in cropland systems, and this mostly affects High-intensity agricultural systems. This is possible because there is a large amount of cropland included in the village systems, which show a net increase in cropland area larger than the corresponding decrease in cropland systems. The loss in natural land systems is mainly the result of a conversion from Grassland-forest mixed systems to Forest hinterland villages and Grassland hinterland villages. Hence these numbers do not necessarily indicate a complete conversion of completely natural land to completely non-natural land, but instead a small step towards increasingly human-influenced land systems (see Table S12). This observation holds true for almost all simulated changes: rather than drastic conversions, the model mostly simulates land system change, and certainly settlement change, as an incremental process. For example, Agricultural systems change into Village systems, and Village systems into Peri-urban systems or Sub-urban systems (see Fig. S4).

The second scenario is also based on the high population projection, while it also assumes that the decrease in population density within each land system continues as observed in the period 2000–2015. Consequently, this scenario shows a much larger increase in urban systems as well as village systems, and a consistently large decrease in agricultural systems and natural systems (Fig. 4). Between 2015 and 2050 an additional 88 × 10⁶ km² of urban system is added to the 146 × 10⁶ km² that was found in 2015. In other words, the area of urban systems increases by 60%. Although the area of the simulated land systems changes is much larger, Scenario 2 follows the same pattern as Scenario 1, which is one of small and incremental changes towards increasingly urban systems, although hardly any agricultural systems or natural systems are converted into High dense urban systems or Low dense urban systems in this time period.

Under conditions of population decline, such as simulated in Scenario 3, simulation results become rather different. While there is a small net increase in Low-dense urban systems and Sub-urban systems (-3 × 10⁶ km² and +10 × 10⁶ km², respectively) there is a smaller sized decrease in High-dense urban systems and Peri-urban areas (-2 × 10⁶ km² and -4 × 10⁶ km², see Fig. 4). Similarly, there is large increase in Clustered landscapes (+132 × 10⁶ km²), complemented by an almost equally large decrease in Spread landscapes (-161 × 10⁶ km²). These changes are a direct result of the constant population density assumed within each systems, leading a conversion towards less dense urban systems under conditions of population decline, as is the case for the last 26 years in this scenario. As a direct result of this, this scenario is the only scenario with a net increase in agricultural systems as well as a small net increase in natural systems (Fig. 4). Consistent with the previous scenarios, changes towards less urban systems are also mostly small changes, such from a Spread landscape to a Clustered landscape.
Fig 3. Land systems in China in 2015. Figures a-i show representative examples of each settlement system. Imagery was taken from Google Earth Pro. The Hu-line represents the traditional division between the heavily populated east and sparsely populated western half of China. Note that pixels in our map are $2 \times 2 \text{ km}^2$ in size.
A combination of population decline and a continuation of the decrease in population density, as simulated in Scenario 4, leads to a net increase of $52 \times 10^3 \, \text{km}^2$ of urban systems. In other words, despite a net population decline of 113 million people between 2015 and 2050 according to the low population scenario (Fig. 2), the urban systems increased by 36% over this time period. Consistently, also village systems increased by $103 \times 10^3 \, \text{km}^2$, while both Agricultural systems and Natural systems showed a decline of $105 \times 10^3 \, \text{km}^2$ and $50 \times 10^3 \, \text{km}^2$ respectively (Fig. 4 and Fig. S4). Similar to Scenarios 1 and 2, the largest share of the loss in Agricultural systems is in High-intensity agricultural systems. In comparison with Scenario 1, these results show that a low population scenario with a continued decline of population density per land system leads to a larger loss of agricultural and natural systems than a Scenario with high population project and constant population density (Fig. 4).

The impact of different scenarios on local land system patterns differs between different types of settlements (Fig. 5). Fig. 5.1 illustrates this for the area around Beijing, which is representative for some of the very large urban conurbations in China. Relative to the situation in 2015 this figure shows mainly an increase in Low density urban systems for S1 and S4, and mainly an increase in High density urban systems in S2, while S3 shows mostly an increase in Sub-urban areas around the center. This example illustrates that scenarios differ in the extent of the urbanization process but also the changes in intensity. Fig. 5.2 shows the different scenario results for the polycentric urban areas in southern Jiangsu. Although the cities included here are smaller than Beijing (Fig. 5.1), a similar pattern is observed, with an increase in high-density urban areas as the most prominent feature of all scenarios except for S3, which is characterized by a changes towards Suburban areas as a result of the decline in population. Fig. 5.3 shows a landscape in the North China Plain including a mosaic of different urban and village systems. Changes in these areas show very well the incremental nature of urbanization in our scenarios: many locations become slightly more urbanized, as opposed to the development of large urban centers elsewhere. Fig. 5.4, by contrast, shows the context dependency of urban development trajectories. Due to the rugged terrain in the areas around Guangzhou, little change is observed in these surroundings, and the different scenarios mainly lead to different amounts of High density urban area in the city itself. Fig. 5.5 provides an example of a more rural area in Northeastern China, which changes in rather different ways in different scenarios. All scenarios show a local increase in Spread landscapes, representing the emergence and growth of villages as well as a small increase in the different Urban systems. Yet, especially S2 and S4 show a large increase in Agricultural and Grazing hinterland villages, while especially in S3 most of the rural areas remain uninhabited. These examples illustrate that different scenarios impact the landscape differently in terms of area affected and intensity of the urban land systems, depending on the existing landscape as well as the conditions within which these changes take place.

Land system maps for the initial year as well as for the end year of all 4 simulation results can be obtained from https://doi.org/10.34894/05ZHGT OR https://landscience.github.io/ (will be made available upon publication).

3.3. Land cover changes under different scenarios

Each land system is defined by its typical combination of land cover types, in addition to its population. In particular, land systems are characterized by their share of built-up land, crop cover, grass cover, and tree cover (Table S3). As a result, land system changes also lead to changes in the land cover types included, while the amount of land cover change is not known a priori.

Built-up land is mainly included in urban systems and village systems, and therefore differs between the different scenarios. Scenario 1, defined by high population projection and constant population density, leads to an increase in built-up area from $105 \times 10^3 \, \text{km}^2$ in 2015 to $121 \times 10^3 \, \text{km}^2$ in 2050. This increase is distributed over almost the complete range of urban and village systems, with a slightly larger growth in Low-density urban areas.
Conversely, Scenario 2 leads to an increase in built-up area of $51 \times 10^3 \, \text{km}^2$. While initially this scenario sees an increase in Low-density urban area, this is followed by a decline in this system and a large increase in High-density urban area (Fig. 6b). Consistent with the small decline in urban systems, the amount of built-up land in Scenario 3 also decreases by $2 \times 10^3 \, \text{km}^2$ in total, after an initial increase until about 2024. This pattern of increase and decrease is a result of a similar trend in most urban systems in which this built-up land is found (Fig. 6c). Also, this figure shows the change of Spread landscapes into Clustered landscapes towards the end of the simulation, which represents a decline in population as well as in built-up land. Scenario 4 shows a rapid increase in built-up land in the first ten years.
followed by an additional 25 years of only modest decrease, as a result of a population decline compensated by a decrease in population density per land system (Fig. 6d). In total, this leads to an increase of $31 \times 10^3$ km$^2$, or 30% between 2015 and 2050.

Changes in settlement systems also affect the area of crop cover, grass cover, and tree cover, both directly, because these land covers are included in the different settlement systems, and indirectly, because changes in settlement systems also lead to changes in agricultural systems and natural systems. Fig. 6 shows that despite simulated net losses in agricultural systems, the amount of land with crop cover increases slightly in all four scenarios. This is a result of especially the increase in village systems, which also contain a large amount of cropland, parallel to shifts also occurring from natural area to agricultural systems. For example, a conversion from a High-intensity agricultural systems to Agricultural village represents a conversion from Agricultural systems to Settlement systems, but in practice it mostly represents the emergence of villages in otherwise rural landscapes. Fig. 7 also shows a net decrease in grass cover and tree cover for all scenarios except S3. This decrease mainly results from the expansion of settlement systems at a cost of natural systems and agricultural systems, the latter of which also have a relatively high share of tree cover (Table S3 and Fig. S5). Distinctively, S3 shows the under conditions of constant density, population decline also offers the opportunity for adding grass and tree cover.

4. Discussion
4.1. Land system changes and their impacts after peak population

This study presents a series of land system change projections for China until 2050, driven primarily by two different population scenarios. In recent decades urban growth and population increase took place in parallel, but since population in China is expected to peak in the next decades, it is unsure what this will mean for future changes in settlement systems. In many locations across the world, population per
unit area of built-up land has decreased in parallel with a total population growth in the past decades (Xu et al., 2019). Examples from Europe also show that urban areas often continue to grow even in times of population decline (Haase et al., 2013; Kasanko et al., 2006; van Vliet et al., 2019). This process is also reflected in our Scenario 4, which shows that changes in residential density lead to an increase in all types of settlement systems, despite a net decrease in total population of China of 113 Million. Conversely, Scenarios 1 and 3 illustrate that the growth in settlement systems can be tempered when the population densities remain constant. In this case, urbanization processes can even revert. This could take place in the form of cleaning hollow villages, as has been reported (Huang, Zhang et al., 2019). This would require active land management policies and can eventually lead to an increase in natural land without compromising the amount of agricultural land.

Our simulations are based on a land system representation that includes multiple settlement systems along the rural–urban gradient, allowing such nuanced representation of settlement change processes (Wang, van Vliet et al., 2019). Consistently, we also differentiated between different productivities of agricultural land. Using this representation, we could simulate settlement changes as an incremental process with agricultural systems changing to village systems and village systems changing towards dense urban. These incremental change processes are consistent with observations from Li et al. (2019) who found that settlement systems typically changed gradually and incrementally in China between 1990 and 2010. Similarly, our results also show a continuation of earlier trends where urban expansion takes place on the more productive cropland (van Vliet, 2019), and which is consistent with other studies that analyze the relation between urban expansion and cropland loss (Bren d’Amour et al., 2017; van Vliet et al., 2017).

While the results show the relevance of representing the rural–urban gradient for analyzing urban development scenarios, it makes relatively simple assumptions of the drivers underlying changes in especially urban densities. Specifically, whether or not population density within a land system remains constant or not is included as input to the scenario, while underlying economic changes or policy drivers are not further specified. Consequently, our results show the possible outcomes of different urban development trajectories, but it does not assess how certain policies or socioeconomic development would lead there.

Next to population increase and economic development, rural to urban migration has been mentioned as a driver underlying recent urban development in China (Liu and Xu, 2017; Long and Wu, 2016). Simulation results in this study showed a mixed result in terms of migration. The decrease in population density in S2 and S4 effectively lead to a shift in population from village systems and agricultural systems to urban systems, while the amount of built-up land in these systems did not decline. Yet, this does not lead to a decrease in village systems themselves, but only to a relatively higher increase in the population in urban systems. Conversely, S3 shows a small net decrease in population in village systems and an increase in urban systems effectively representing rural-to-urban migration. These dynamics illustrate that rural-to-urban migration does not directly lead to a decrease in village systems themselves, but only to the population contained within these systems. This observation is consistent with the finding by Li et al. (2019) that villages in China contain a large share of the increase in built-up land.

Urban land has increased rather dramatically in China in recent decades. Therefore the trend in urban population density that was extrapolated in the gradual decline scenarios (S2 and S4), might be on the high side. At the same time, urban population has been declining in almost all countries globally (Gao and O’Neill, 2020; Xu et al., 2019). Therefore, the results of the constant density scenarios (S1 and S3) might be on the low side in terms of urban growth, even though the amount of built-up land per person is still much lower than in Europe, the US, see for example Li et al. (2020). Together, this set of scenarios therefore provides two rather contrasting but plausible extremes for future urban development in China. Specifically, the area of built-up land increased from $103 \times 10^{5}$ km$^2$ to $156 \times 10^{5}$ km$^2$ in 2050 in scenario 2, representing the largest increase of all scenarios. Conversely, Scenario 3 even projects a small decrease in built-up land in the same period. These changes represent a compound yearly growth rate for built-up land of 0.41%, 1.13%, −0.06% and 0.75%, respectively (see Table S12). By comparison, Chen et al. (2020) use the shared socioeconomic pathways (SSPs) considering global society, demographics and economic factors. Population amount is predicted between 1.200 million and 1.350 million for the year 2050, leading to a compound growth rate between 0.62% and 1.04% between 2020 and 2050. This study, however, assumes that built-up land is irreversible, and hence the population decline in the last years of this study do not lead to a decline in built-up land (Chen et al., 2020). Other scenario studies by Liu et al. (2018) and Huang, Li, and et al. (2019) report annual growth rates between 0.89% and 1.72%.

This comparison between our results and other studies of urban growth in China shows our estimates are on the lower side. This could suggest that our study underestimates built-up land, but another explanation is the modelling approach underlying our results. Existing models typically include one type of built-up land, resulting in outward expansion (Huang, Li, & et al., 2019), without considering their upward growth (intensification) (Mahendra & Seto, 2019). The different types of settlement systems included in this study differ in their share of built-up land, but also in their residential population density. All scenarios show a relatively large increase in the denser systems (such as High-density urban area and Low density urban area), and a smaller increase in the land systems with a lower residential density. This difference can explain why our approach leads to a lower increase in built-up land, even under the assumption of continued decrease in population density within each system. A binary urban / non-urban classification also constrains an assessment of the impacts of urban expansion on agricultural areas (Bren d’Amour et al., 2017; van Vliet et al., 2019), because village growth taking place in predominantly agricultural areas is also inherently neglected. Both processes illustrate the added benefit of a more nuanced representation of settlement systems for simulating land change scenarios.

4.2. Implications for sustainable urban development

Population density is frequently used to characterize urban structure (Mahtta et al., 2019; Stokes & Seto, 2019), and consequently it is also applied by policymakers from various cities or countries to set maximum or minimum thresholds to obtain compact development and control sprawl (Angel et al., 2018). For example, in Beijing’s detailed planning, population density in sub-urban centers should be restricted to less than 90 thousand persons per km$^2$ (the State Council, 2018). Another example was provided by Wellenmann et al. (2017) reporting a suggested upper limit 400 m$^2$/person in the Swiss strategy for sustainable development, while land consumption is currently 407 m$^2$/person. This study shows the relevance of such restrictions as the application of a constant population density over time, a simplistic representation of such policy, has a very large effect on the total change in built-up land. Such constraints become even more relevant when population decline is foreseen, as it could support efficient use of land and avoid hollow villages (Long & Wu, 2016; Zhang, Jiang, & Zhang, 2019; Long and Wu, 2016).

Underlying our assumption of constant population density in Scenario 1 and 3 is the necessity for built-up land to convert back to a less urban state. Experience from Detroit (US) for example shows that abandoned buildings are often demolished because they become dangerous to the surrounding communities (Xie et al., 2018). Haase and Nuijsel (2007) also show that population decline is an opportunity to increase the sustainability of land use by decreasing the further sealing of open areas for housing and transport. Left buildings in Leipzig are demolished for “temporary and interim uses” as a land manage strategy (Dubeaux & Cunningham-Sabot, 2018). However, these examples are exceptions. For instance, in suburbs in Serbia, many residential construction areas without building permit but with title to the land are left...
empty (Antonić & Djukić, 2018; Hirt & Stanilov, 2009), which could be explained by relatively weak policy enforcement in post-socialist countries (Rink et al., 2014). Also in Japan about 11% of the total land area is unclaimed (The Economist, 2018), so it’s difficult to achieve land consolidation or change of use (Matanle & Sáez-Pérez, 2019). Grădinaru et al. (2020) believes that missing or poor policy coordination could have unwanted effects, such as uneven development across the country and land-use conflicts, or could limit the effectiveness of the planning instruments in decision making.

Large-scale population decline, such as projected for China until 2050 is unprecedented, and its consequences for urban development remain speculative. This study therefore shows the possibility space for sustainable urban development, rather than the most likely outcome. The more sustainable development trajectories likely require strong land use policies, yet empirical evidence suggests that current policy targets, often referred to as compact urbanization and functional mix, do not suffice to halt land take (Cortinovis et al., 2019). This observation, in combination with our simulation results, further illustrates the need for policy guidance towards sustainable urban development, as well as enforcement thereof. Contrary to many other countries, the tradition of strong land use policies in China might therefore allow for a more sustainable urban development and thus enable the protection of agricultural and natural areas from further degradation. At present, several policies have been implemented to improve land use efficiency facing increasing built-up land demand and hollowing villages, such as “requisition-compensation balance of cropland”, “urban–rural built-up land increasing versus decreasing balance” and “land consolidation” (Liu, Fang et al., 2014; Long et al., 2012). Several provinces and cities have successfully put the urban–rural built-up land balance into practice, such as “exchange rural resident for house” in Tianjin, “land ticket trade” in Chongqing, “rural community” in Shandong, and “land quotas” in Zhejiang (Wang et al., 2011; Wen et al., 2017; Zhang et al., 2014). Yet, urbanization has been a mechanism to foster economic development and human well-being (Seto and Pandey, 2019). Therefore, urban land use efficiency becomes increasingly important in times of population decline. The revised Land Management Law, implemented from 2020 onwards, allows that built-up land owned by collectives may enter the land market, and that farmers can withdraw from rural settlement voluntarily, etc. (Standing Committee of the National People’s Congress, 2019). This law provides a legal possibility and basis for reducing built-up land in rural areas and thus concentrate built-up land to urban areas. Including population decline and the demand for housing could further improve land use efficiency.

5. Conclusion

Urban areas have increased dramatically in China in recent decades, and many scenario studies suggest this expansion is likely to continue in the next few decades. Urban expansion mostly leads to a conversion of agricultural land, and indirectly to a decrease in natural areas, especially under the current cropland protection policies. However, projections indicate that population growth is expected to peak somewhere before 2050 and decline afterwards, and this change offers an opportunity for managing urban change. Results of this study show that under conditions of constant population density, population decline would allow to decrease the amount of built-up land and thus save space for natural land systems. However, results also show that a continuation of the current decline in population per area of built-up land leads to a large increase in urban area, even in the low population scenario. Hence, population decline alone doesn’t automatically lead to a reduction in built-up land and policies or other measures are needed to avoid further losses of natural areas as a result of urban development in China.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Y. Wang et al. Landscape and Urban Planning 209 (2021) 104045

11
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