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Original Research

Mapping Urban Sprawl and Land Use Dynamics in Central China Through Random Forest-Based Remote Sensing: A Comparative Analysis of Luoyang and Zhengzhou

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Abstract

This study presents a comparative spatiotemporal analysis of land use and land cover (LULC) changes from 1990 to 2024 in two fast-growing Chinese cities, Luoyang and Zhengzhou. Based on multi-temporal satellite imagery from Landsat-7, Random Forest classification was conducted on the Google Earth Engine (GEE) platform. Classification accuracies between 85 and 91% were achieved through high-resolution visual interpretation and confusion matrix validation. Our findings show opposite trends in the growth of the cities. Driven by aggressive infrastructure and economic zoning, Zhengzhou saw a spectacular 223% rise in built-up area, mostly at the cost of cropland, which fell by more than 22%. As Luoyang also grew, it showed more gradual change, with a 12% decline in cropland and a 222% increase in built-up land, indicating a more restrained urban planning process. The two cities also showed significant growth of surface water by more than 100%, which means that hydrological infrastructure or urban planning priorities have changed. The forest cover was quite intact, and there were slight improvements in Zhengzhou, implying increased concern about greening urban areas. Meanwhile, land degradation or stagnant building sites emerge as a result of the emergence of barren land, especially in Zhengzhou. These results highlight the variation in urban development within the same area, which is shaped by geography, policy, and planning culture.

Keywords: random forest, remote sensing, machine learning, land degradation

Introduction

Urbanization in China has been one of the fastest processes ever to occur in human history. The urban population has increased to almost 67% by 2024 and 75-80% by 2035 since the late 1970s, when its urban population was less than 20% [1]. Although the resultant transformative development has led to economic prosperity, it has also contributed to land use issues, especially in plain areas, where peri-urban ecosystems and cropland are under intense pressure [2, 3]. Between 1990 and 2019, approximately 120,000 km² of Chinese

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cropland was converted to urban purposes, creating a strong need to balance development, food security, and environmental sustainability.

The recent developments in remote sensing and machine learning have contributed significantly to the monitoring and analysis of the dynamic nature of urban land and its environmental effects. For example, machine learning-based studies have shown significant correlations between land use change and land surface temperature, and how urban sprawl increases the intensity of thermal stress and the urban heat island effect [4, 5]. Similarly, the ecosystem services-based assessments have established that land transformation has implications for air quality control, ecological stability, and environmental sustainability at the regional level [6].

The necessity of studying vegetation dynamics and ecological resilience in response to urbanization and climate variability has also been pointed out in recent research. Studies based on NDVI and landscape resilience models have indicated that urban sprawl changes the health of the vegetation, its functions, and environmental stability [7]. These results have highlighted the significance of combining land use analysis and environmental sustainability perspectives.

Recent literature has become increasingly focused on the interrelationship between urbanization, ecosystem services, and environmental hazards [8, 9]. The approaches followed by spatial planning illustrate that rapid land change has a profound impact on the provisioning and regulating ecosystem services that can be quantified in terms of their economic worth, especially in overcrowded areas undergoing structural change. In a comparable context, land surface temperature (LST) evaluations conducted seasonally during land cover change conditions indicate that urban sprawl increases the exposure to heat and enhances heat-related risk [10, 11], particularly in megaregions where infrastructure development is happening at a faster rate. Indicators based on vegetation, like NDVI, have also been applied to quantify the interactive effects of land use change and climatic fluctuations on ecological stability, and the adaptive cycling and resilience models are used to illustrate the responses of landscape systems to anthropogenic pressure in the long run. These studies highlight the fact that land transformation is not only a spatial process but also a dynamic ecological process that can affect climate regulation within the urban environment, biodiversity stability, and long-term sustainability. A combination of these views highlights why comparative and long-term LULC analysis is necessary in fast urbanizing plains like Central Henan, where agricultural productivity, ecosystem services, and urbanization are in direct conflict.

There is little literature on the comparative analysis of cities with varied urbanization trends in the same regional and policy setting. Such divergence needs to be understood to identify viable urban development strategies and enhance land management planning.

However, the consequences of this speedy urbanization are never evenly distributed. Rapid urbanization in cities such as Zhengzhou, a provincial capital and a logistics center, has been caused by mega-infrastructure projects and changes in the planning paradigm [12]. The urban area in Zhengzhou grew by more than 590 km² between 1990 and 2020, most of which occurred on agricultural land and water bodies [13]. Instead, in the historic city of Luoyang, less frenetic urban development within geographic limits and under heritage-driven conservation policies has been observed, although the city is continuously growing.

Although the urbanization of mega-regions such as the Yangtze and Pearl River Deltas has already been investigated at length [12], there are no empirical studies that compare cities with divergent urbanization trajectories in the region of Central China. There are not many studies that trace how various paths, one fast and outward-oriented and another slower and more controlled, result in land conversion, agricultural loss, and environmental change. This gap represents a critical void in knowledge of how the form of cities and policy selection can determine the outcomes of sustainable development.

To fill this gap, our research question is how and why LULC varies over time in Luoyang and Zhengzhou using multi-temporal Landsat images and supervised classification for the period between 1990 and 2024. Our objectives are to measure the extent and speed of the LULC change, deconstruct urbanization tendencies, and assess their environmental impacts. The study's objectives are:

- To map and quantify changes in agricultural land, forest, green spaces, water bodies, urban areas, and barren land over time.
- To compare the intensity and pattern of land conversion between Luoyang and Zhengzhou, focusing on urban expansion and cropland decline.
- To interpret these dynamics within the context of recent national urbanization plans, land policy reforms, and environmental conservation efforts.

This study has several levels of importance. It provides a comparative perspective in urban studies to examine divergent trajectories of urban settings that are proximate but ultimately different. In practice, it provides an empirical foundation upon which municipal planners and policymakers can balance urban growth strategies in Central China. Lastly, it also contributes to discussions around sustainable urbanization at the global level, providing an example of how urbanization patterns influence ecosystem services, the resilience of farmland, and the sustainability of settlements in the long term.

The present research fills some of the most important gaps in knowledge of urban land transformation in rapidly growing cities and its effects. In particular, the following scientific questions should be answered in this study:

– What are the magnitude, rate, and spatial patterns of land use and land cover (LULC) changes in Luoyang and Zhengzhou between 1990 and 2024?
– How do urban expansion trajectories differ between a historically constrained city (Luoyang) and a rapidly industrializing provincial capital (Zhengzhou)?
– What are the environmental implications of these land use transitions, particularly regarding cropland loss, ecosystem stability, and landscape sustainability?
– What urban development processes and structural differences may explain the observed divergence in land transformation patterns?

To address these questions, this study applies a Random Forest machine learning classification approach using multi-temporal Landsat imagery within the Google Earth Engine platform. Despite the widespread use of Random Forest classification and Google Earth Engine in land use research, the value of this study is the creation of a balanced framework for long-term comparative analysis exceeding the past three decades (1990-2024). In contrast to one-year or short-term analysis, this analysis provides inter-sensor consistency between Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI/TIRS datasets through standardized preprocessing, seasonal alignment, and cross-temporal validation. Moreover, the research does not concentrate only on classification accuracy but is rather based on the comparative analysis of the urban trajectories of two structurally different cities belonging to the same provincial policy system. This study minimizes time classification bias by ensuring that training conditions and validation methods are consistent at all five time points, thereby increasing longitudinal reliability. Scalability and reproducibility of the workflow are also ensured by the integration of cloud-based processing in Google Earth Engine, as it makes it possible to perform systematic multi-decadal monitoring of urban transformation patterns. Such methodological consistency enhances the strength of comparative land transformation assessment, as opposed to traditional single-period RF use.

The objectives of this study are:
– To quantify and map long-term LULC changes from 1990 to 2024.
– To compare the intensity, direction, and spatial structure of urban expansion between the two cities.
– To evaluate the environmental implications of land transformation, including cropland loss, ecological stability, and urban landscape restructuring.
– To interpret these changes within the broader context of urban development patterns, planning strategies, and sustainability challenges.

This approach provides both quantitative and interpretive insights into how different urban growth models shape land transformation and environmental sustainability.

The change in land use in urban areas is an interaction of various factors other than population growth [14]. The policies, economic structural reorganization, infrastructure investments, industrial growth, and regional planning strategies are the key determinants of urban growth patterns. The climate variability might also impact the vegetation, water availability, and land productivity indirectly on land use decisions [15, 16]. Environmental forces like migration, industrialization, housing demands, and economic motivation only increase the processes of land conversion. Thus, land transformation cannot be viewed without taking into account the processes of urbanization as well as more global socio-economic and environmental factors.

Moreover, the study area was chosen to be Central Henan, which gives the study wider applicability beyond the Chinese scope. Luoyang and Zhengzhou are located in the North China Plain, which is structurally similar to other fast urbanizing agrarian plains in the Global South, including the Indo-Gangetic Plain in India and new urban corridors in Southeast Asia. The characteristics of these areas include fertile agricultural land, dense population, and the rapid rate of infrastructure development, which poses significant competition between food security and urban development. Like these areas, Central Henan is a transitional zone where traditional agricultural landscapes are still rapidly changing into industrial and urban areas. Thus, the study of divergent urbanization processes within the provincial policy framework provides useful comparative advantages for sustainable land governance in densely populated agrarian areas across the globe. The location of Luoyang and Zhengzhou in this larger Global South context helps the study fit into current arguments on how emerging economies can achieve economic growth and protect cropland, ecosystem stability, and long-term urban sustainability.

Materials and Methods

Study Area

This study focuses on central China, with particular consideration of two major cities in Henan Province, Luoyang and Zhengzhou. The two cities not only contrast in terms of geographical features, but they are also at different stages of the urbanization process in China and represent different aspects of the country (Fig. 1).

Luoyang is a historic city, commonly known as the cradle of Chinese civilization. It used to be the capital of 13 ancient dynasties, and it is a mixture of rich cultural heritage and modern development. Luoyang is a city in western Henan, and the geographical features of the area include mountains and rivers, which have influenced its spatial evolution. Even though it was more industrial and less intensively urbanized in the past, Luoyang has not been spared from changes in recent decades [17]. It has more than 7 million people, but its urban growth has been gradual and regulated to some extent due to

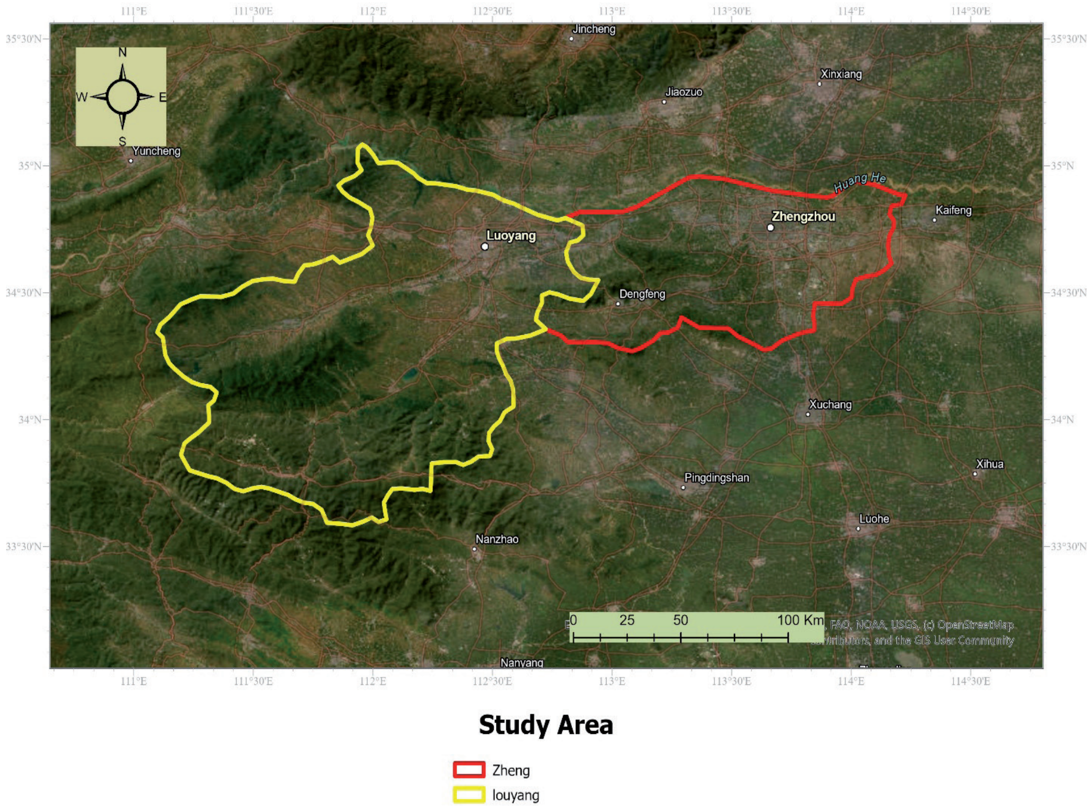

Fig. 1. Map of the study area of Luoyang and Zhengzhou. Google; Map data: Maxar Technologies; Map imagery: Google Earth.

natural topography and historical preservation policies. This equilibrium makes Luoyang an effective example for studying urban development without uncontrolled sprawl.

Zhengzhou, on the other hand, is the heartbeat of modern Henan, a rising megacity that is the provincial capital and a major national transportation center. Zhengzhou is located strategically on the South-North and East-West rail and road networks, and has developed very fast to become a hub of logistics, trade, and high-tech industries. Its population has already expanded to more than 12 million, and the city landscape has changed drastically in the past few decades. Massive infrastructure projects, such as the development of the Zhengdong New District, have turned previously rural centers into new urban centers almost overnight [18]. The pace and magnitude of change in Zhengzhou provide a good opportunity to examine the more intensive trends of land reclamation and urban sprawl.

The two cities were not selected solely for their suitability for comparative analysis; rather, their selection is not determined by scale or location alone, but by the differences in their urbanization patterns. Although both of them are located in the same province and subject to the same set of national policies, land use choices, environmental limitations, economic forces, and urban planning strategies have varied greatly. The development of Luoyang is more characteristic of a traditional economic pattern: slow, consistent, and culturally constrained. Zhengzhou, in turn, is an example of the current Chinese city pursuing speed, scale, and visibility [18].

Geographically, both cities are located in the North China Plain, which is a fertile and historically important area, and has sustained agriculture for thousands of years. The flat terrain, coupled with the local climate, has made it appealing to farming and urban development, and is subject to development-conservation conflicts. These attributes make the land use dynamics discussed in this paper more complex.

In choosing Luoyang and Zhengzhou, this study not only reflects patterns of urbanization in the heart of China, but it also shows that closely related urban centers might take divergent turns when urbanization pressure, policy changes, and globalization are put into play.

Data Acquisition and Preprocessing

Multi-temporal cloud-free Landsat images for the years (1990, 2000, 2010, 2020, and 2024) were used to measure long-term LULC. Google Earth Engine (GEE) (code.earthengine.google.com) was used to access the images [11], with Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI/TIRS being used depending on the time point (Fig. 2).

All images were selected for the same season, preferably summer (June to August), to minimize

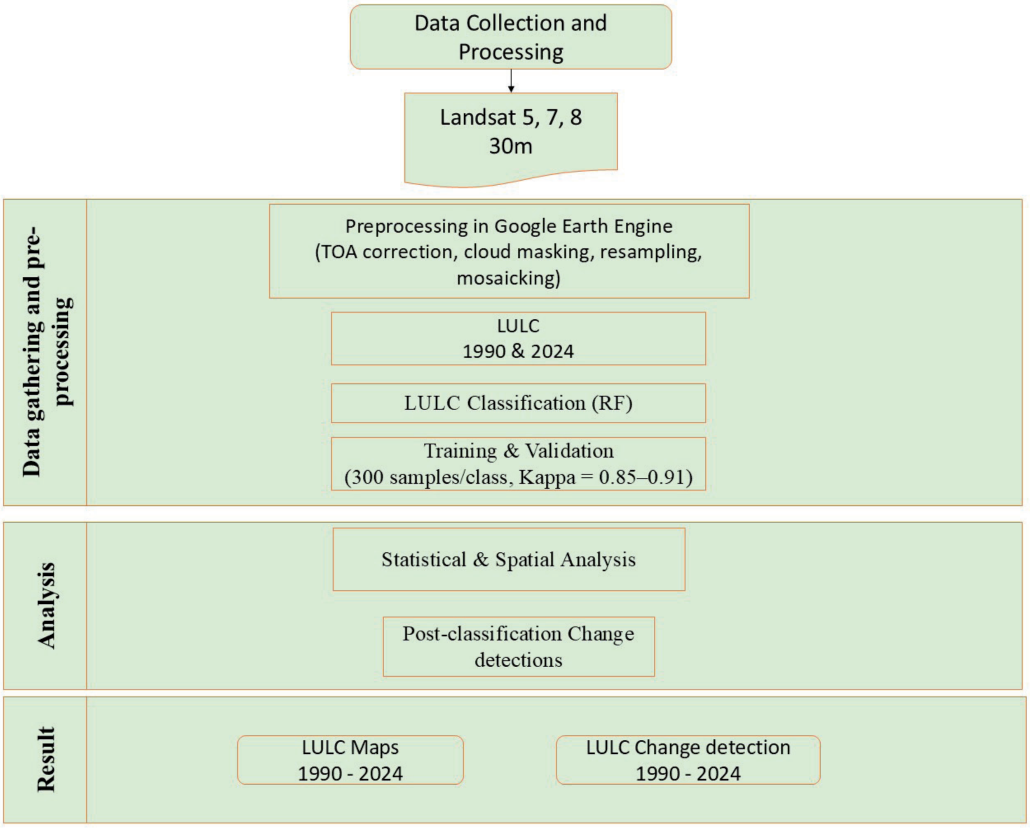

Fig. 2. Flow diagram of the methodology.

seasonal changes and allow comparison. The preprocessing of images was performed in the GEE platform, and it consisted of:

- Top-of-atmosphere (TOA) correction, to standardize radiometric values.
- Cloud and shadow masking, using the QA_PIXEL quality band.
- Image mosaicking and compositing, where needed, to fill gaps.

Imagery containing less than 10 percent cloud contamination was retained.

Land Use/Land Cover Classification

To classify LULC, we applied the popular and powerful machine learning algorithm Random Forest (RF), as it is able to perform effective high-dimensional data classification and does not overfit [14]. This was done using GEE classification, which facilitated efficient processing of large-scale satellite data during the multi-decadal period. Previous studies defined seven major land cover classes: Cropland, Forest, Rangeland, Water Bodies, Built-up Area, Barren Land, and Snow/Ice.

Training and Validation

High-resolution base maps in Google Earth were used to collect training samples manually every year. Each LULC class had about 300 training samples, and these were collected to ensure both spatial and thematic representation of the cities. The samples were distributed to capture variability across urban, rural, and natural environments. About 70% of the samples were used to train the model, and 30% were used to determine accuracy [19].

Confusion matrices and the Kappa coefficient were used as metrics to assess classification accuracy, with values between 0.85 and 0.91 over the five years, which is high in terms of reliability of the classified maps. In the Results section, detailed accuracy metrics and class-wise performance are presented. Classification robustness across the years and classes was also tested using cross-validation.

Results

The findings provide land use and land cover (LULC) data for Luoyang and Zhengzhou in 1990, 2000, 2010, 2020, and 2024, which were generated using supervised classification methods with Landsat imagery. They identify substantial spatial and temporal fluctuations, especially the growth of built-up regions and the subsequent reduction of cropland (Table 1).

In both Zhengzhou and Luoyang, cropland has steadily decreased over the last 34 years. In Luoyang,

Table 1. The area distribution (in km²) of land use and land cover of Luoyang and Zhengzhou between 1990 and 2024.

Class Type	Year	Luoyang	Zhengzhou	Class Type	Year	Luoyang	Zhengzhou
Cropland	1990	8,971	8,279	Water	1990	116	56
	2000	8,371	6,820		2000	144	90
	2010	7,957	6,820		2010	198	90
	2020	7,865	6,342		2020	239	114
	2024	7,869	6,417		2024	247	112
Forest	1990	8,981	453	Built-up	1990	419	735
	2000	8,944	445		2000	902	2,128
	2010	8,844	445		2010	1,313	2,128
	2020	8,868	495		2020	1,355	2,437
	2024	8,859	497		2024	1,349	2,378
Rangeland	1990	1,393	330	Barren land	1990	0	0
	2000	1,519	368		2000	0	1
	2010	1,567	368		2010	1	1
	2020	1,552	455		2020	2	11
	2024	1,554	437		2024	3	12

the area under agriculture declined to 7,869 km² in 2024 compared to 8,971 km² in 1990, which shows a moderate decrease (Fig. 3). Conversely, Zhengzhou experienced a larger decline, from 8,279 km² in 1990 to 6,417 km² in 2024, implying greater pressure on agricultural land, likely due to the high rate of urbanization (Fig. 4). The variation in the pace of decline suggests that Zhengzhou has experienced more vigorous land conversion, perhaps due to accelerated urbanization as well as industrialization.

In Luoyang, forest cover was relatively stable, and it fluctuated slightly, decreasing from 8,981 km² in 1990 to 8,859 km² in 2024. This suggests that forest conservation or reforestation has been achieved. Zhengzhou, on the other hand, had very low forest cover, which averaged 453 km² in 1990 and marginally rose to 497 km² in 2024. This small increase may indicate either urban greening or afforestation efforts, but the extent of forest cover in Zhengzhou is low (Table 1).

There was a slight increase in rangeland in both cities. Luoyang expanded from 1,393 km² in 1990 to 1,554 km² in 2024, and Zhengzhou expanded from 330 km² to 437 km² in the same period. Such trends may indicate land that has ceased to be cropland, yet has not been urbanized or reforested. The increase is not very large but is steady, which could indicate land left fallow or semi-natural.

These two cities witnessed a rise in water bodies. The area of water in Luoyang expanded to 247 km² in 2024, and in Zhengzhou to 112 km², compared to 116 km² and 56 km² in 1990, respectively. These patterns imply the creation or enlargement of water infrastructure (reservoirs, lakes, urban water bodies). This may also indicate improved water management or the incorporation of water features in urban design.

In both cities, there was a massive development of built-up areas, albeit to varying degrees. The built-up area increased by a factor of three, expanding to 1,349 km² by 2024 from 419 km² in 1990 in Luoyang. However, even more drastic growth took place in Zhengzhou, where built-up land grew from 735 km² to 2,378 km², representing a threefold growth. This highlights that Zhengzhou is a rapidly developing regional urban hub. The figures clearly indicate urban sprawl, whereby built-up land is growing at the cost of cropland.

In 1990, barren land was insignificant in the two cities, yet in 2024, Luoyang had 3 km² of barren land, and Zhengzhou had 12 km² of barren land (Table 2). The slow development of barren land may indicate poor or unproductive regions, which could result from construction, deforestation, or incomplete land conversion. These are relatively low values, but they reveal a trend that may require further monitoring. Comprehensively, the data indicate typical trends of urban sprawl: increasing built-up areas and declining cropland areas, as well as water and forest cover remaining stable or slightly growing. The degree of land use change in Zhengzhou has been more severe than that of Luoyang, especially in terms of cropland loss and increases in built-up areas. These developments reflect the anticipated pressures of population growth, economic development, and urbanization in the heart of China, particularly in provincial capitals such as Zhengzhou.

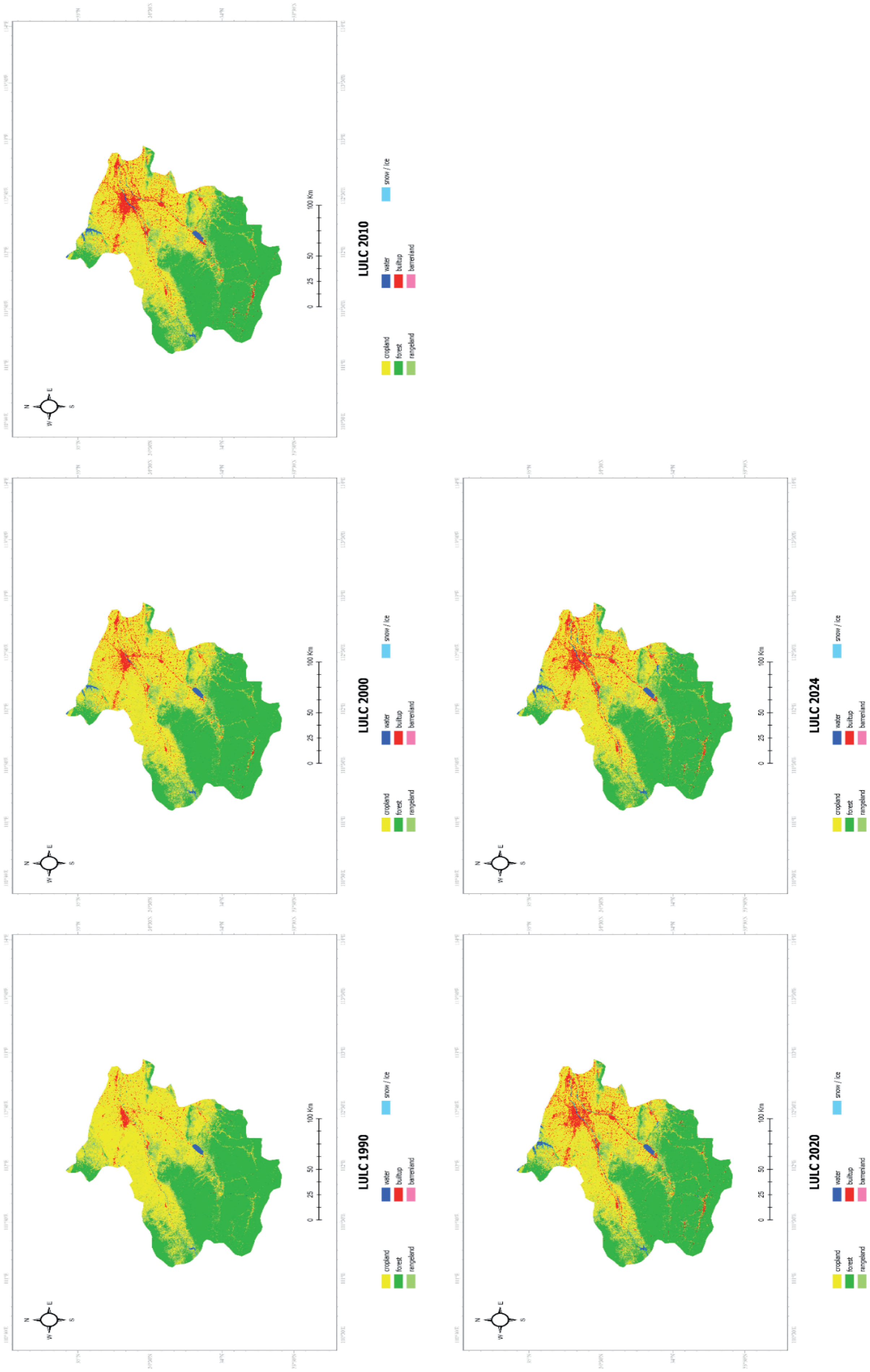

Fig. 3. LULC 1990-2024 of Luoyang based on Landsat imagery by Random Forest classification (Processed in GEE, mapped in ArcGIS Pro 3.4).

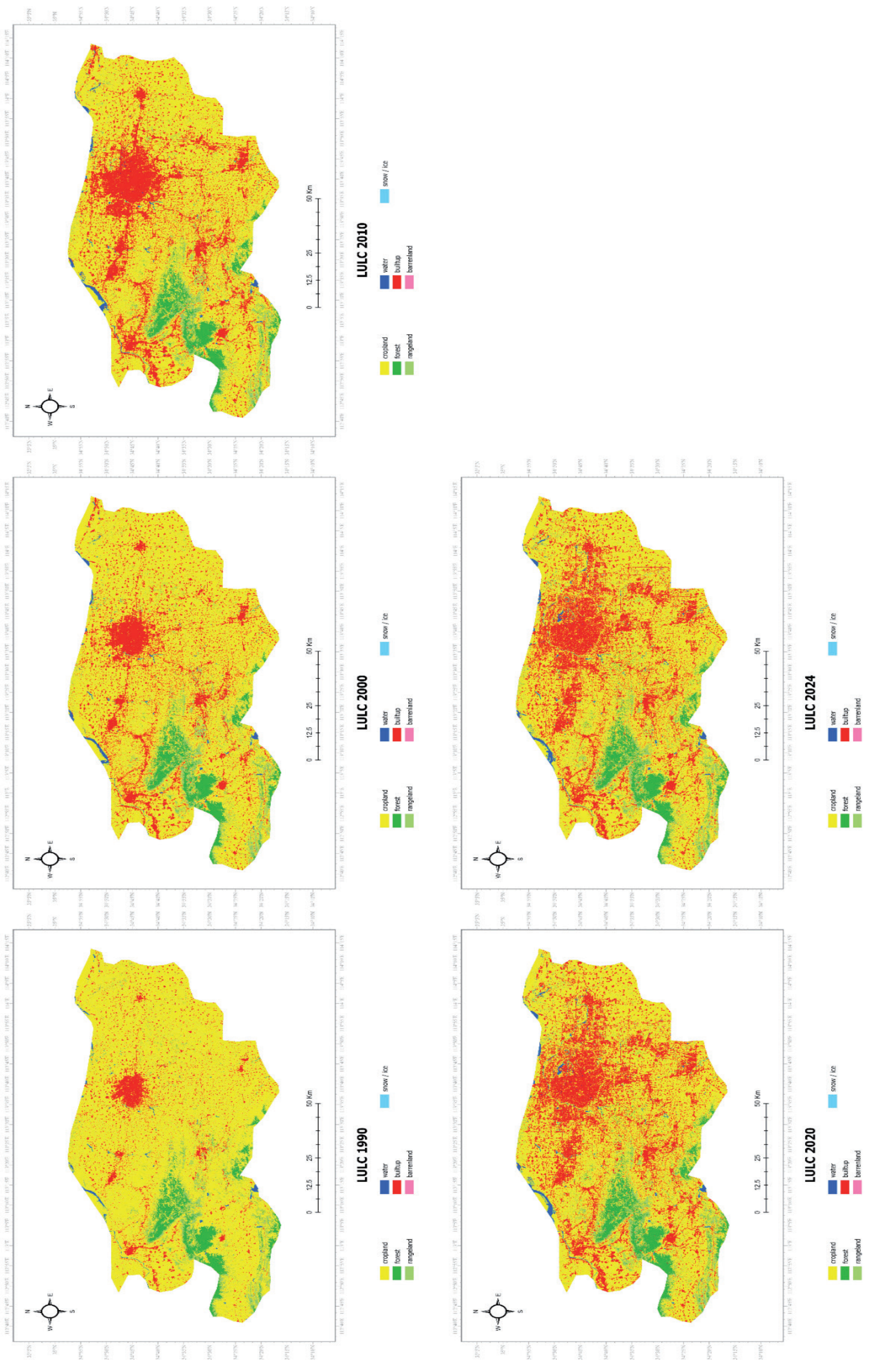

Fig. 4. Zhengzhou LULC 1990-2024 based on Landsat imagery with the help of Random Forest classification (Processed in GEE, mapped in ArcGIS Pro 3.4).

In addition to numerical variations, it is evident that the spatial distribution patterns of the two cities demonstrate different patterns of urban expansion in Fig. 3 and Fig. 4. In Zhengzhou, there is a high level of spatial clustering of built-up areas around the historical urban core, followed by sharp outward expansion along major transportation corridors, especially in the eastern and southeastern directions. Such a corridor-focused expansion implies infrastructure-driven urban sprawl, which is consistent with the development of new areas and transport centers. The growth appears fairly continuous, indicating that peri-urban agricultural lands are rapidly being consolidated into continuous urban space.

Luoyang, on the other hand, has a more scattered and geographically limited expansion pattern. The growth of the city is mainly along river valleys and fairly level ground, while mountainous regions in the west and south restrain outward expansion. The spatial structure indicates infill development and moderate edge growth, as opposed to aggressive corridor-based sprawl. Patch dispersion and edge irregularity are more evident in Luoyang, as opposed to Zhengzhou, indicating incremental and spatially constrained urbanization.

Moreover, the fact that the urban core of Zhengzhou is slowly encircled by disappearing cropland shows concentric replacement, and in Luoyang, the loss of cropland seems to be more spatially selective and not continuous. These spatial differences depict disparities in the directionality of expansion, the intensity of clustering, and landscape reorganization between the two cities. Based on the trends observed, the development of Zhengzhou can be assumed to be infrastructure-based and outward-oriented, whereas Luoyang's development is somewhat limited by topography and the historical city form.

Luoyang and Zhengzhou have experienced observable land use changes in the past 34 years, between 1990 and 2024, but the magnitude and nature of these changes are different in each category.

There was a large loss of cropland in both cities, with declines in Zhengzhou and Luoyang being 22.5% and 12.3%, respectively (Table 2). This drastic reduction in agricultural land is an indicator of increasing strain from urban development and infrastructure construction, particularly in Zhengzhou, which is now one of the major economic centers of Central China. The shrinking of cropland indicates the traditional trade-off that cities incur between development and food security.

Linear regression analysis was conducted on time-series data from 1990 to 2024 in order to statistically test the difference in cropland decline between the two cities. The findings suggest that the average loss in cropland in Luoyang and Zhengzhou was 31.79 km²/year ($p = 0.018$) and 49.33 km²/year ($p = 0.046$), respectively. These trends are statistically significant at the 5% level, and this confirms that agricultural land loss in both cities has a systematic downward trend. The land conversion strength is, however, significantly higher in Zhengzhou, which shows a stronger magnitude of conversion compared to Luoyang.

Table 2. Changes in LULC classes in Luoyang and Zhengzhou (per cent) 1990 to 2024.

	Year	Luoyang	Zhengzhou
Cropland	1990	8971	8279
	2024	7869	6417
	Change %	-12.2	-22.4
Forest	1990	8981	453
	2024	8859	497
	Change %	-1.3	9.7
Rangeland	1990	1393	330
	2024	1554	437
	Change %	11.5	32.4
Water	1990	116	56
	2024	247	112
	Change %	112.9	100
Built-up	1990	419	735
	2024	1349	2378
	Change %	221.9	223.5
Barren land	1990	0.1	0.1
	2024	3	12
	Change %	2900	11900

On the same note, regression analysis was applied to measure the expansion of built-up area. The growth rate of Luoyang was found to be 27.18 km²/year with a p-value of 0.021, and that of Zhengzhou was 42.41 km²/year with a p-value of 0.068. Despite the fact that there was rapid urban growth in both cities, the steeper slope for Zhengzhou indicates a stronger urbanization trend, especially in the initial years of expansion (1990-2000). These statistical results support that the land transformation disparities between the two cities are not just descriptive but can be quantitatively differentiated.

The forest cover in Luoyang was also quite stable and only fell by 1.36%, indicating some form of conservation or sustainable land management. Surprisingly, Zhengzhou recorded a small increase of 9.7% in forest cover, which was perhaps a result of greening urban areas or reforestation. Although the total forest cover in Zhengzhou remains small, this signals an increase in environmental awareness in urban design.

Rangeland increased in both cities, but Zhengzhou recorded the highest growth of 32.4%, and Luoyang recorded the second at 11.6%. This growth may represent transitional land yet to be developed or a region where mixed or low-impact land uses have been utilized. It might also indicate land reclamation or changes in agricultural activities, which leave more land in semi-natural conditions.

Water bodies have experienced the most dramatic positive transformation. The water area of Luoyang increased more than twice (112.9% increase), whereas the water area of Zhengzhou increased by 100%. Such changes may be related to the construction of reservoirs, better urban water infrastructure, or natural surface water management to address environmental problems such as floods and drought. It can also indicate attempts to make urban living greener by incorporating water into design [20].

The fundamental indicator of urban sprawl is the rapid expansion of built-up areas. The built-up area of Luoyang increased by 222%, and that of Zhengzhou increased by 223.5%. This sharp growth demonstrates that the two cities have developed at a very high rate, transforming huge portions of land into residential, industrial, and commercial areas. The growth is bound to push the other types of land, particularly the cropland, to their limit.

The amounts are still quite low, but barren land areas are increasing rapidly. In Luoyang and Zhengzhou, the barren land area expanded from 0.1 km² to 3 km² (2,900% increase) and from 0 km² to 12 km² (an 11,900% increase), respectively. These unproductive land areas may include ruined land, unused construction sites, or post-industrial areas, and they emphasize potential environmental degradation associated with rapid development.

Zhengzhou demonstrates more radical change on a smaller scale in almost all categories than Luoyang, which reflects quicker and more intensive urbanization. Although both cities are modernizing, Zhengzhou seems to be developing in a more resource-intensive and aggressive manner, with increasing losses in cropland and growing gains in built-up and barren land. Such tendencies indicate that city planning, environmental conservation, and sustainable development must be more closely integrated, particularly in fast-developing cities such as Zhengzhou.

These divergent patterns of land transformation are attributed to several interacting mechanisms. Economic growth and industrial development lead to increased demand for land for housing, transport, and infrastructure. Government planning policies, including economic development zones and urban expansion strategies, have a direct impact on land allocation and spatial growth trends.

In order to put the observed divergence into a broader perspective, geographic and socioeconomic variables can be considered explanatory dimensions that can be measured [21]. Topographically, Luoyang is partly limited by mountainous terrain in its western and southern areas, limiting its ability to expand outward on a large scale. Conversely, Zhengzhou is mostly located on flat alluvial plains in the North China Plain, which minimizes physical constraints on horizontal sprawl. This geographic advantage may also have led to the greater and more geographically expansive growth observed in Zhengzhou.

In terms of socioeconomic status, Zhengzhou has experienced dramatic population and GDP growth in the last 30 years, due to its role as a provincial capital and national transport center. Rapid industrialization, infrastructure construction, and the creation of

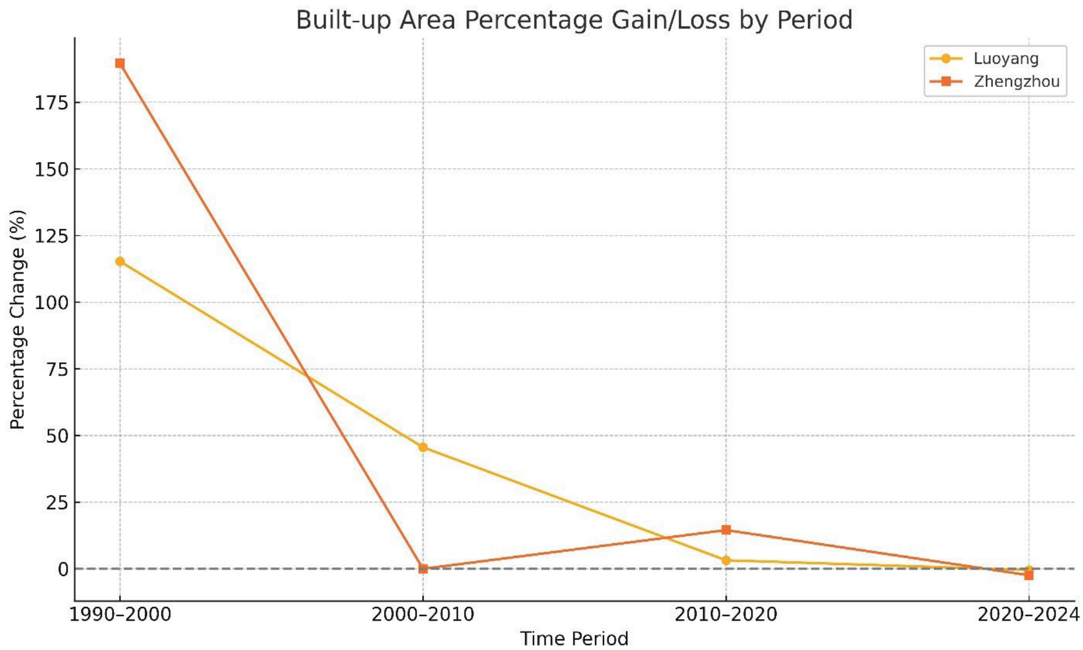

Fig. 5. The dynamics of built-up area growth and contraction in Luoyang and Zhengzhou over time, showing high levels of urban growth and recent indications of stagnation or regression.

economic development zones have increased land demand and prompted the rapid transformation of agricultural land into urban land. In comparison, the structure of Luoyang's economy is more diversified and historically oriented, resulting in relatively moderate demographic growth. These structural variations help explain the steeper regression slope of cropland change in Zhengzhou, as indicated in the statistical analysis.

Although this research does not use spatial econometric modeling to assess the marginal contribution of slope, distance to roads, and socioeconomic indicators, the combination of spatial distribution patterns and time trend analysis provides indirect but consistent evidence of infrastructure-driven expansion in Zhengzhou compared to geographically constrained expansion in Luoyang. Future studies can include logistic regression or geographically weighted regression (GWR) models to measure the relative importance of terrain, accessibility, and economic factors in built-up expansion likelihood.

Increased population and rural–urban migration, resulting in higher housing demand, accelerate land conversion. The development of transportation infrastructure, such as highways and railways, encourages spatial growth and urban sprawl. Land market trends and investment incentives further stimulate land transformation.

The influence of such drivers in Zhengzhou is more intense because of its strategic economic position and favorable policy conditions, whereas the growth pattern in Luoyang is more moderate and limited by geographic and cultural preservation factors.

The 1990-2024 trends in built-up area give a clear picture of urban growth in Luoyang and Zhengzhou, but the cities followed different paths. The greatest boom occurred in 1990-2000, when Zhengzhou increased its built-up area by 189.5%, and Luoyang by 115.3%. This was a major phase of urban change, likely driven by economic reforms, infrastructure investments, and population increases (Fig. 5).

During the next decade (2000-2010), Luoyang experienced robust growth, with an increase in built-up area of 45.6%, but Zhengzhou did not record similar growth. The stagnation of Zhengzhou may be due to constraints in central areas or changes in land use planning policies.

The period 2010-2020 registered slower urban growth in both cities. The urban area of Luoyang increased by 3.2%, and that of Zhengzhou by 14.5%, which suggests that the cities were at a mature stage of urbanization. However, in 2020, the two cities recorded a minor drop in built-up areas, with Luoyang decreasing by 0.4% and Zhengzhou by 2.4%. Although the causes of this slight decrease cannot be identified solely from the data, they may be related to the reclassification of urban areas, changes in development policy, or an emphasis on densification instead of further expansion.

Discussion

Reading the story of Luoyang and Zhengzhou is like observing the lives of two brothers from separate families. Both have expanded out of their city centers, though the growth of Zhengzhou has been more rapid and intensive, literally devouring agricultural land more intensively [22]. Between 1990 and 2024, it was estimated that Luoyang lost approximately 12% of total cropland, while Zhengzhou lost over 22%. These changes reflect national trends. In 1990–2019, urban sprawl in China consumed around 120,000 km² of farmland, primarily in rich plains such as those surrounding these two cities [23, 24].

These land-use changes reflect broader socio-economic restructuring [25]. The fast growth of Zhengzhou can be directly associated with the fact that it is a provincial capital, transportation center, and industrial hub that attracts large population inflows, infrastructure investments, and economic growth. The conversion of agricultural land is driven by economic development zones and transportation corridors, which have intensified the shift toward urban land use [26, 27]. Conversely, the slower growth rate in Luoyang reflects its varied economic structure, historical conservation, and geographical limitations. It has mountainous terrain and policies protecting its cultural heritage that have constrained uncontrolled growth. This has made land transformation in Luoyang slower and spatially limited.

From an ecological perspective, the loss of cropland diminishes food production as well as ecosystem services, including carbon sequestration and temperature regulation [28, 29]. The spread of urban areas also changes hydrological processes, surface runoff, and the urban heat island effect. Although increases in forests and water bodies can partly counteract environmental loss, rapid urban growth can nevertheless expose the ecological environment to multiple risks if not properly managed.

Due to the rapid increase in constructed land between 1990 and 2000, the built-up area of Zhengzhou increased by almost 190%, and the urban area of Luoyang increased by almost 115%. The size of urban land nationwide increased by a significant multiple of the urban population growth, as rapid growth has been compared to real estate speculation on the outskirts of planned areas [30]. It appears that Zhengzhou has been caught up in this wave, transforming previous cropland into urban sprawl. Meanwhile, Luoyang seems to have experienced stagnation after 2010, and the accumulated gains began to decline slightly after 2020, indicating a more developed land-use policy.

However, growth does not only occur at the expense of fields; it also alters the environment. The data indicate that the two cities increased water bodies twofold, with growth exceeding 100% between 1990 and 2024. This reflects investment in water retention, reservoirs, and blue-green infrastructure, but expanded surface waters may also disrupt downstream flows or aggravate urban flood risk, particularly during wetter seasons when groundwater recharge is already under pressure [31].

On the other hand, vegetation represents environmental robustness. Luoyang preserved forest cover, with a decline of only 1.4%, whereas Zhengzhou gained almost 10% by 2024. This is in line with the National Forest City project, an initiative of China introduced in the 2000s, which promoted the idea of forested cities through urban forestry and pocket parks [32]. This is also supported by satellite data tracking an overall greening trend in the country since 2010 [33], indicating that greening efforts in Zhengzhou still have a visible effect, although the scale remains small in absolute terms.

At the same time, the emergence of abandoned land in boom-and-bust cycles reflects another trend. Barren patches have appeared in both cities, with Zhengzhou experiencing almost 12,000% growth in barren land. Such areas may result from neglected construction sites or underutilized peri-urban areas and can cause visual pollution or erosion, highlighting inefficiencies in urban expansion and contraction [34].

In addition to the metrics, livelihoods are affected by these changes. City development alters places of residence and work. Long commutes, fragmented agricultural areas, and urban heat islands are part of everyday life for residents [35]. Doubling water features may help buffer heat, but only if they are properly managed; more forest patches are beneficial for air quality and mental well-being, but only when they are evenly distributed [36, 37].

By 2010, urban development in China entered a new phase. The rate of urban expansion in the country decelerated due to cropland preservation and a focus on cropland densification [38]. This transition is reflected in the plateauing built-up area of Luoyang and even contraction in Zhengzhou after 2020. These changes are, however, just the beginning of a new era, not the conclusion. There is a need for sustained planning to safeguard farmland, improve green and blue infrastructure, and address uneven spatial development [39].

In summary, Luoyang and Zhengzhou represent two facets of rapid and expansive urbanization in the nation, with national development goals on one hand and a new stage of maturity with sustainability as a priority on the other. Their next challenge is to find the right balance between development and ecological health, food security, and population, not to expand ad hoc, but to grow sustainably.

Conclusions

This paper aimed to discuss how two fast-developing cities in China, Luoyang and Zhengzhou, have changed their landscapes over thirty years. The findings provide a clear picture of the trade-offs associated with urbanization, which are necessary for economic growth and modernization. Cropland has continued to diminish, and urban areas have expanded at the expense of forests and farmland, with built-up areas now occupying land that could have been used for agriculture or forest cover. In Zhengzhou, aggressive and unchecked sprawl has prevailed, whereas in Luoyang, urban transformation was more restrained and more planned. Beyond figures and maps, this work addresses broader realities. It is not merely a matter of housing and infrastructure, but also one of sustainability, food security, water management, and livability [40]. Cities such as Zhengzhou and Luoyang are not the only ones experiencing this pressure, but the differences in their development paths provide valuable lessons. One city is expanding rapidly, while the other is more cautious. Every decision, whether policy-related, geographic, or economic, has a long-term impact on land, population, and ecosystems.

The contrasting land transformation patterns observed in Luoyang and Zhengzhou highlight the importance of city-specific urban planning approaches. Zhengzhou's rapid expansion reflects strong economic growth but also raises concerns regarding cropland loss and ecological sustainability. Luoyang's more gradual growth demonstrates how geographic constraints and planning policies can help maintain ecological balance.

These findings emphasize that urban planning strategies significantly influence land transformation outcomes. Cities experiencing rapid expansion require stronger land management policies to protect agricultural land and ecological resources, while balanced growth strategies can help maintain long-term sustainability.

Based on these findings, several policy recommendations can improve urban land sustainability:

– Implement strict cropland protection policies to prevent excessive agricultural land conversion.
– Promote compact urban development to reduce urban sprawl and improve land use efficiency.
– Integrate green infrastructure, including urban forests and water systems, to enhance ecological resilience.
– Strengthen land use monitoring using remote sensing and machine learning technologies for evidence-based planning.

In addition to overall land protection, specific planning policies must be embraced based on the structural nature of each city. In the case of Zhengzhou, where growth has been fast and infrastructure-based, policy orientation needs to be shifted to Transit-Oriented Development (TOD) frameworks in order to curb peripheral sprawl and promote more intensive, mixed-use development around key transportation hubs. Urban growth boundaries and vertical densification can be used to limit the overextension of urban growth and preserve surrounding cropland. Moreover, focus should be placed on the redevelopment of underutilized or barren peri-urban land before further outward expansion.

Luoyang, on the other hand, is facing the challenge of heritage protection and industrialization. Urban planning must combine cultural landscape protection with controlled distribution of industrial land so that economic development does not lead to the destruction of historical resources and ecological corridors. By providing incentives for brownfield redevelopment and compact industrial clustering, pressure on agricultural and forested land can be alleviated. Considering its topographic limitations, Luoyang can adopt a polycentric development model where growth is directed toward secondary nodes without affecting mountainous ecological buffers.

Through the customization of strategies to local spatial, economic, and geographical circumstances, land governance can move from homogeneous policy prescriptions to adaptive and context-sensitive sustainable urban development.

This research has a number of limitations. Random Forest classification is very accurate; however, some uncertainties are likely to arise when classifying mixed land use types, transitional areas, as well as spectrally similar land classes. Classification inconsistencies may also be caused by seasonal and temporal variation in satellite acquisition. Lack of ground-based v alidation data is also a weakness, as field validation may enhance the reliability of classification. Moreover, this research was mainly based on satellite imagery, and it did not include socio-economic factors, including population density, economic variables, and land use policies. These aspects play significant roles in driving land transformations and would improve the interpretation of causal drivers. Further studies are recommended to combine higher-resolution satellite imagery, ground validation, and socio-economic data in order to enhance classification accuracy and support the interpretation of urban land transformation processes.

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Conflict of Interest

The author declare no conflicts of interest.

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