

Research on Land Use Change and the Contribution Degree of its Driving Force Factors: A Case Study of the Yangtze River Delta, China

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Abstract. In recent decades, global land use change has had a profound impact on ecosystems, economic development and environmental quality. The study of land use change plays an important role in promoting the optimization of land resource management and urban planning and achieving the United Nations Sustainable Development Goals (SDGs). Based on the random forest method, this study classifies and interprets seven periods of remote sensing images in the Yangtze River Delta from 2000 to 2020, and systematically analyzes the spatio-temporal characteristics of land use change in this region and the contribution rate of its driving factors. From 2000 to 2020, the developed land increased significantly by 54.60%, while the areas of plowland, woodland and grassland decreased by 8.89%, 1.25% and 2.95% respectively. The areas of unused land and water bodies increased by 5.80% and 403.62% respectively. The analysis of the contribution degree of driving force factors indicates that natural factors such as precipitation, temperature and slope, along with socio-economic factors such as shopping services, medical services and catering services, jointly drive land use change. Among them, what is particularly prominent is that the contribution of precipitation to the expansion of woodland is as high as 0.164, and the contribution of the shopping service industry to the expansion of urban land is 0.149. It reveals the dual driving mechanism of "natural basis - humanistic traction" of land use change, providing a scientific basis for regional land resource management and sustainable development.

Keywords: Enter ke Land use; Driving force factor; Random forest; The Yangtze River Delta; Spatio-temporal big data.

1. Introduction

The AR6 Synthesis Report released by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations: *Climate Change 2023* points out that current land use change has become one of the main sources of global greenhouse gas emissions, having a significant impact on the global climate system and being related to the sustainable development of human society (Lee et al., 2023). In recent years, land use change has attracted widespread attention worldwide, and its impact on economic growth, social development and ecological environment protection has become increasingly significant. Land use, as an important issue in urban planning, its dynamic changes have become one of the significant driving forces for the future development of cities. Land use change is not only a dynamic representation of land cover types, but also a direct reflection of the social development process, and has a profound impact on climate regulation, ecological environment and urban layout. There are a series of social problems brought about by land use change gradually emerge, the issue of its governance has become a common challenge for countries around the world (Matej et al., 2025).

Urban agglomerations with a relatively high level of economic development and a faster urbanization process show more significant manifestations in land use changes. Under the influence of multiple factors such as natural factors, policy regulation and economic activities, land use in urban agglomerations changes rapidly, and the distribution patterns of various land use types in cities are constantly updated. These changes directly affect the pattern of regional land use (Yin et al., 2023).

Furthermore, land use change also has a wide-ranging impact on the ecological environment, greatly influencing the living environment and quality of life of urban residents (Xie et al., 2022).

There are complex and diverse driving factors behind land use change. The vast majority of changes in land use are the result of the combined drive of natural and socio-economic factors (Luo, Zhang, Gao, Liu, Meng, et al., 2024). Natural factors often play a fundamental role in land use, and their influence cannot be ignored. However, with the acceleration of urbanization, a series of socio-economic factors, including policy regulation and economic services, have an increasingly profound impact on the land use pattern (Duan et al., 2024). Therefore, an in-depth exploration of the dynamic characterization of land use and its driving factors is of great significance for optimizing the allocation of regional land resources and the future development planning of cities.

2. Literature Review

2.1. Interpretation of land use types

Remote sensing technology, as one of the most mainstream geospatial detection tools, has currently been widely applied in the interpretation of land use types. The traditional methods for interpreting this type of problem include maximum likelihood classification (MLC) and unsupervised classification methods, and so on. In the research of Roy et al. (2022), they used MLC to classify remote sensing images and successfully distinguished different land use types such as farmland, woodland and towns. However, when the dimension and complexity of spectral data are high, such traditional methods usually have difficulty ensuring high classification accuracy.

Wang et al. (2025) effectively distinguished seven types of land use by adopting the feature-enhanced convolutional neural network (CNNs-FA), and improved the classification accuracy. However, the demand of this method for high-quality remote sensing images and rich spectral indices makes it difficult to be applied in situations where data acquisition is challenging.

Furthermore, Zhao et al. (2025) adopted the time series method to construct a framework of vegetation index and its synergy with climatic characteristics, which has an outstanding interpretation effect on land types in areas with complex terrain and crop diversity. However, its application scope is mostly limited to large-scale agricultural planning areas.

2.2. Analysis of driving factors for land use change

In the field of land use research, the analysis of driving force factors in the past was mostly qualitative analysis, and systematic quantitative analysis was relatively rare. Deng et al. (2016) took the Three Gorges Reservoir Area as the case site and selected the CLUE-S model to analyze the land cover changes in this area. It was concluded that the main driving factors were population growth and transportation layout, but no in-depth quantitative analysis was conducted on the contribution degrees of each driving factor.

In the research of Rangel-Peraza et al. (2024), they adopted quantitative analysis methods to analyze the impact of land use change on surface warming in an agricultural area of Mexico, and clarified the prominent driving role of agricultural activities and urban expansion therein. However, the quantitative analysis of the driving force factors in this study is still at a preliminary stage and has not delved deeply into the relative contribution degrees among different driving force factors.

Furthermore, Allan et al. (2022) conducted a systematic review and organization of the past driving force factor analysis methods, emphasizing the need to pay attention to the complex interactions among various driving force factors in order to deepen its understanding of the impact on land use change.

2.3. Selection of research areas and international attention

In addition to the interpretation of land types and the analysis of driving force factors, the current related research in this field still has limitations in the selection of research areas and lacks analysis from a global perspective. Wu et al. (2021) analyzed the driving factors of land use change in Wuhan,

using POI data and clarified the prominent contribution degrees of factors such as population density, economic development status, and transportation accessibility. In the research on land use change, Wang et al. (2022) selected the Bortala region as the research area and revealed the impact of climate change and human activities on land use change.

However, the studies mentioned above mostly select specific cities or regions as case sites, which have limitations and particularities, and have not yet focused on the issue of land use change in a global context.

Overall, the existing research on the interpretation of land use types and the analysis of driving factors has achieved certain results and progress, but there are still the following deficiencies:

1) There are deficiencies in the interpretation of land use types in terms of accuracy and the generalization of methods. These methods are difficult to achieve high-classification interpretation or have overly high requirements for data, resulting in uneven applicability of the methods in different type regions and making it hard to be promoted.

2) Insufficient analysis of driving force factors. Existing studies have relatively few quantitative analyses of driving force factors, especially the quantitative analysis of the synergistic effect of multiple driving forces, and the classification methods are relatively simple, making it difficult to comprehensively reflect the complexity of land use change.

3) Limitations of the research area. Additionally, most studies focus on small regions or specific cities, with less attention paid to larger-scale urban agglomerations and insufficient international attention.

Therefore, this study systematically analyzes the land use change and its driving factors in the Yangtze River Delta and adopts the random forest method, aiming to overcome the above-mentioned deficiencies. The study not only improves the accuracy and applicability of the interpretation of land use types, but also reveals the complex mechanism of land use change through quantitative analysis of driving force factors. Furthermore, this study focuses on the Yangtze River Delta, a representative urban agglomeration, which can provide important references for the sustainable development of other similar regions.

3. Research Materials and Methods

3.1. Site of research

The Yangtze River Delta in China is one of the world's six major urban agglomerations and also one of the regions with the highest economic development level in China, consisting of a total of 41 prefecture-level cities. The total area of this region is approximately 358,000 square kilometers, with a permanent resident population of over 150 million. Its GDP accounts for nearly 20% of the national total (Yu et al., 2021). The Yangtze River Delta enjoys a superior geographical location and abundant natural resources. This area has a flat terrain, a dense network of rivers, excellent climatic conditions, and favorable conditions for agricultural and urban development (Wu et al., 2024).

In terms of economic structure, the Yangtze River Delta mainly focuses on the development of manufacturing, services and high-tech industries (Kang et al., 2020). In terms of urban driving, Shanghai, as the leading city in the region, has a strong radiating and driving effect on the surrounding areas. In addition, cities such as Nanjing, Hangzhou, Suzhou and Wuxi have outstanding economic development levels and also play an indispensable role in driving regional development. However, in recent years, phenomena such as the reduction of agricultural land, the increase of industrial land, and the outward expansion of cities have been significant, profoundly influencing the regional land use pattern and also having a profound impact on regional land resource allocation, ecological environment protection, and so on (Song et al., 2021).

Overall, the Yangtze River Delta, as one of the areas with the highest urbanization level in China and even the world, has highly representative and complex land use changes (Luo, Wang, et al., 2024). It is of great significance to study the land use change and its driving factors in this area. This can not only provide theoretical and practical basis for regional land resource management and urban

planning and development, but also help to offer references for other regions around the world from a global perspective.

3.2. Research material

The data used in this study is divided into three types, containing land use (LUCC) data, panel data, and geographic information data.

LUCC data is sourced from the Landsat series of satellites, spanning from 2000 to 2020, with a resolution of 30 meters, which was obtained through the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (Luo, Zhang, Gao, Liu, Song, et al., 2024). The data is used to analyze the dynamic process of land use change, and there are six major categories of it, including plowland, woodland, grassland, water bodies, developed land and unused land (Y. Chen et al., 2024).

The panel data covers population and GDP, which is sourced from the "China Statistical Yearbook" and the statistical yearbooks of various provinces and cities in the Yangtze River Delta. These data are obtained from the public data of the National Bureau of Statistics and the statistics bureaus of various provinces and cities, and they are used for the quantitative analysis of driving force factors to reveal the impact of socio-economic factors on land use change (Zhang et al., 2023).

Geographic information data contains precipitation, temperature, water system distribution, DEM, POI, and so on, which are sourced from the United States Geological Survey, as well as Chinese geographic information public service platforms such as the National Qinghai-Tibet Plateau Data Center and the Open Street Map (OSM) platform. These data are used to reveal the restrictive effects of natural geographical conditions and the layout of regional functional points on land use changes (Luo et al., 2023).

3.3. Research methods

3.3.1. Data preprocessing

This study uses GIS technology to preprocess remote sensing image data, mainly including reclassification, resampling, kernel density analysis and Euclidean distance calculation, and so on.

Reclassification ensures the consistency and comparability of the data by re-encoding the land use types of the source data LUCC into a unified six categories.

Resampling is used to unify the resolution of each raster data, making the row and column numbers of the data consistent and preparing for the recognition of the data in the PLUS model.

Kernel density analysis is used to identify the hotspots of each POI. By calculating the density of land use change within a certain radius around each pixel, the concentrated areas of change are revealed, providing important information for understanding the spatial distribution characteristics of land use change (McDonnell et al., 2015).

For point features, the calculation formula of the kernel density at the position of each output raster cell (x, y) is:

$$\rho(x, y) = \sum_{i=1}^n W_i \cdot K\left(\frac{d_i}{r}\right) \quad (1)$$

Among them, $\rho(x, y)$ is the density value at the position (x, y) ; n is the number of points within the search radius r ; W_i is the weight value of the point i ; d_i is the distance from the point i to the position (x, y) ; $K\left(\frac{d_i}{r}\right)$ is the value of the kernel function. Usually, a quartic kernel function is used, and its expression is $K(u) = (1 - u^2)^2$ for $u \leq 1$.

The quartic kernel function takes the value of 0 when $u > 1$.

The search radius determines the influence range of the kernel function. The formula used to calculate the search radius in ArcGIS is:

$$r = \min \left(2.5 \cdot SD, \frac{D_m}{\sqrt{n}} \right) \quad (2)$$

Among them, SD is the standard distance; D_m is the weighted median of the distance; n is the number of points or the weighted sum. This method can avoid the "ring" phenomenon in sparse datasets and has a certain resistance to spatial outliers.

Euclidean distance calculation is used to analyze specific features. This paper is used to analyze the impact of the three-level roads of national highways, provincial highways and county highways in this area on land use change. By calculating the distance from each pixel to the nearest ground object, the restrictive effect of distance on land use change is revealed, providing quantitative support for understanding the impact of urban expansion and transportation network expansion on land use change (Luo, Gao, et al., 2024).

There are two points $P_1(x_1, y_1)$ and $P_2(x_2, y_2)$ in the two-dimensional Cartesian coordinate system, and the formula for calculating the Euclidean distance d between them is:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (3)$$

3.3.2. Random forest algorithm

The random forest algorithm achieves classification by constructing decision trees. It is an ensemble learning method with high accuracy and stability (Sun et al., 2024). This method performs well in handling complex feature interaction problems and can avoid the risk of overfitting (Salman et al., 2024). Meanwhile, the random forest algorithm, by taking advantage of its function of calculating the importance of features, can quantitatively analyze the influence of various driving factors on land use change and provide a scientific basis for the driving mechanism of dynamic land use change.

In the analysis of land use change, this algorithm can not only identify the main driving factors, but also generate the area expansion potential maps of each land use type, which can provide an effective reference for the realization of future land use speculation (Cheng et al., 2023). Furthermore, the random forest algorithm has unique advantages when dealing with high-resolution images and can effectively identify land classification in complex areas, achieving high-precision classification (Tikuye et al., 2023).

This study adopts the above methods, aiming to comprehensively understand the trend of land use change and its driving mechanism in the Yangtze River Delta from 2000 to 2020, and provide guidance for future regional land resource planning and urban management.

4. Results Analysis

4.1. Analysis of land use change

Table 1. shows the profound changes in the land use pattern in the Yangtze River Delta from 2000 to 2020. The changes in the area of various types of land use not only reflect the trend of rapid urbanization and the transformation of regional economic structure, but also reveal the dynamic relationship between ecological protection and resource constraints (Luo, Zhang, Liu, et al., 2024).

Table 1. The area changes of land use types in the Yangtze River Delta from 2000 to 2020

Land Use Type	Year 2000 (km ²)	Year 2020 (km ²)	Change Quantity (km ²)	Change ratio (%)
Plowland	183355.99	167066.59	-16289.40	-8.89
Woodland	101346.60	100084.41	-1262.20	-1.25
Grassland	12020.22	11665.46	-354.76	-2.95
Water Bodies	25043.85	26495.97	+1452.12	+5.80
Urban Res. Land	5774.04	15719.80	+9945.75	+172.25
Rural Res. Land	23514.26	27298.98	+3784.72	+16.10
Other Dev. Land	1962.31	5295.73	+3333.41	+169.87
Unused Land	64.12	322.91	+258.80	+403.62

4.1.1. Analysis of the trend of land use change

Figure 1 shows the changes in the growth rate of land use type area in the Yangtze River Delta from 2000 to 2020. First of all, developed land shows a significant expansion trend and is the core force driving the transformation of the regional land use structure. In 2000, the total developed land in the Yangtze River Delta was 31,250.61 square kilometers. By 2020, it had expanded to 48,314.50 square kilometers, with an increase of 54.6%. Among them, the areas of urban residential land, rural residential land and other developed land increased by 9,945.75 square kilometers, 3,784.72 square kilometers and 3,333.41 square kilometers respectively. From 2000 to 2005, the growth rate of urban residential land kept accelerating, mainly due to the rapid influx of foreign capital under the background of economic globalization (Sun et al., 2020). However, with the increasingly tight land resources and the adjustment of the real estate market, the disorderly expansion of urban land has been controlled (Lei et al., 2024). From 2005 to 2008, the growth rate of its area slowed down somewhat. After the global financial crisis broke out in 2008, a series of economic stimulus policies implemented by the government once again promoted the construction of urban infrastructure (Zhang & Huang, 2019). Until 2020, the urban residential land in the Yangtze River Delta showed a significant growth trend, but gradually slowed down in the later period due to the advancement of new urbanization. During the same period, the area of rural residential land changed relatively steadily and maintained a steady upward trend throughout the period from 2000 to 2020. In addition, the area growth of other developed land was also very significant, and its growth rate was basically the same as that of urban land. However, during the outbreak of the global financial crisis in 2008, export-oriented industries were severely impacted, resulting in a rapid decline in the growth rate of the area of other developed land during that period.

In contrast, the areas of plowland, woodland and grassland have generally shown a continuous downward trend, indicating that urban development has continuously squeezed the space of traditional agriculture. From 2000 to 2020, the areas of plowland, woodland and grassland decreased by 16,289.40 square kilometers, 1,262.20 square kilometers and 354.76 square kilometers respectively. From 2000 to 2020, the decrease rates were 8.89%, 1.25% and 2.95 respectively. Among them, the plowland area decreased the most between 2000 and 2005. During this period, the economic development in the Yangtze River Delta was rapid, and a large amount of plowland was instead used for urban construction and industrial development (She et al., 2021). Since then, the promulgation of the National Land Use Master Plan Outline (2006-2020) has clarified the goals of plowland protection and to a certain extent slowed down the rate of reduction in plowland area (Zhou et al., 2017). Affected by projects such as returning farmland to forest and natural forest protection, although the woodland area continued to decline from 2000 to 2018, the decline rate showed a fluctuating and decreasing trend, and achieved positive growth in 2020 (W. Li et al., 2022). Furthermore, from 2000 to 2020, the growth rate of grassland area in the Yangtze River Delta fluctuated significantly. Except for the period from 2015 to 2018, it was negative growth. Among them, the decline was the greatest from 2005 to 2010, mainly due to the impact of agricultural structure adjustment at that time (Piao et al., 2015).

In contrast, the water bodies gradually increased during phased fluctuations, rising from 25,043.85 square kilometers to 26,495.97 square kilometers, with an increase rate of 5.80%. From 2000 to 2010,

Jiangsu Province implemented the "Eastward Diversion of River Water" project and a series of wetland ecological restoration projects (Ren et al., 2022). The water bodies in the Yangtze River Delta was in a stage of positive growth. Furthermore, during the period from 2008 to 2010, the coastal areas of the Yangtze River Delta vigorously promoted the reclamation and development projects of tidal flats, increasing the water bodies (Li et al., 2020). From 2010 to 2020, the water bodies in the Yangtze River Delta showed a negative growth. This is mainly due to the influence of urbanization and industrialization processes, with some water bodies being filled in for developed land. In 2018, the "Several Opinions on Delimiting and Strictly Observing Ecological Conservation Red Lines" was issued and implemented (Gao et al., 2020). By 2020, the water bodies in the Yangtze River Delta had seen a certain recovery.

Compared with the above-mentioned land use types, the area of unused land in the Yangtze River Delta fluctuated significantly from 2000 to 2020, showing an overall upward trend. The growth rate reached 403.62% from 2000 to 2020. Especially during the period from 2008 to 2010, the area of unused land increased significantly, mainly from Lianyungang City, Yancheng City and Nantong City, which are located in the coastal areas of the Yangtze River Delta. During this period, Jiangsu Province vigorously promoted the reclamation and development project of coastal tidal flats (L. Li et al., 2022). However, a large area of reclaimed tidal flats had not yet been planned and utilized, thus turning into unused land. Since 2010, such unused land has gradually been planned and utilized. By 2015, its area had gradually decreased. From 2015 to 2018, the growth rate of unused land area reached another peak. At this stage, the Yangtze River Delta has intensified the control over ecological land use. In the Chaohu Lake Basin, a large number of governance projects such as returning farmland to forest and fishery to wetland have been implemented (Chen et al., 2023). Some land, after restoration, is temporarily in an unused state, resulting in an increase in the area of unused land. After 2018, with the acceleration of new urbanization construction and the efficient utilization of land resources, the area of unused land in the Yangtze River Delta decreased rapidly again (Yu, 2021).

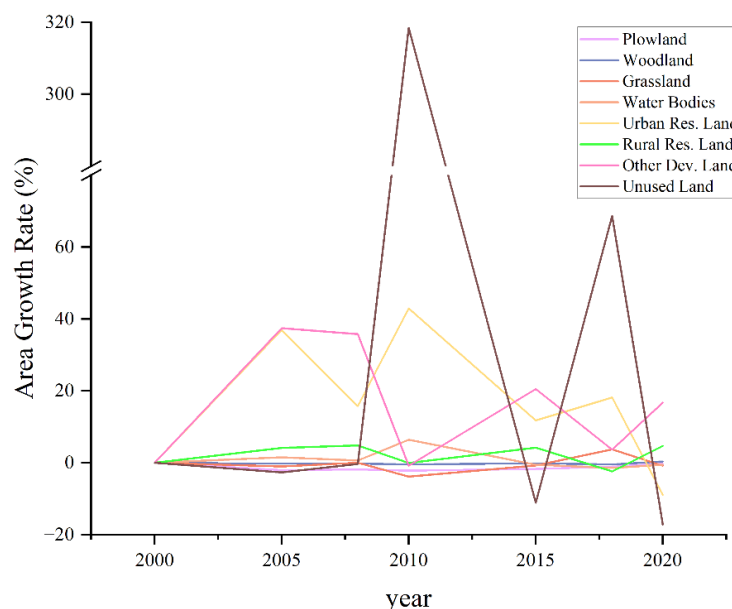


Figure 1. The changing trend of the growth rate of land use type area in the Yangtze River Delta from 2000 to 2020

Overall, during the period from 2000 to 2020, the land use changes in the Yangtze River Delta showed the characteristics of expansion of developed land, compression of agricultural land, fluctuation of water bodies and significant rise and fall of unused land. These changes reflect the dynamic relationship between regional development and ecological protection, highlighting that future land management needs to seek a balance in promoting coordination, ensuring security, and

maintaining the ecology, optimize resource allocation, and achieve equal emphasis on protection and development.

4.1.2. Analysis of the probability of Land use expansion

It can be known from the probability of plowland development in the Yangtze River Delta from 2000 to 2020 (Fig.2-a) that the areas with a relatively high probability of plowland area development are mainly concentrated in the southwest mountainous belt mainly composed of cities such as Lu 'an, Anqing and Chizhou. Apart from the relatively superior precipitation conditions in this area, this is mainly influenced by the implementation of high-standard farmland construction projects (Zhu et al., 2022). In addition, the implementation of land reclamation has transformed some abandoned industrial and mining land and unused land into construction sites, effectively supplementing the area of plowland occupied due to urbanization and industrialization (M. Chen et al., 2024). On the contrary, the probability of the development of plowland area in cities with a relatively high level of urbanization such as Shanghai, Suzhou and Wuxi and their surrounding areas is relatively low.

The probability of woodland development in the Yangtze River Delta from 2000 to 2020 (Fig.2-b) shows that the probability of woodland area development presents obvious regional differentiation. Overall, the probability of woodland area development in the northern part of the Yangtze River Delta is significantly higher than that in the southern part. This is mainly because the original forested area in the north was relatively small, while plowland and wasteland were relatively concentrated, presenting greater potential for the development of forested land (Zhang et al., 2020). Furthermore, taking Shanghai as an example, the probability of woodland development in its core urban areas such as Puxi and Pudong is low, but it shows a relatively high probability in the far suburbs. This is mainly because while the economy is developing rapidly, Shanghai has implemented the "Thousand Parks Project" and the construction of a park city system in the suburbs (Zeng et al., 2024). Similarly, the probability of woodland area development in Jiangsu Province, Zhejiang Province and Anhui Province is relatively low in their core metropolitan areas and relatively high in the rest of the regions.

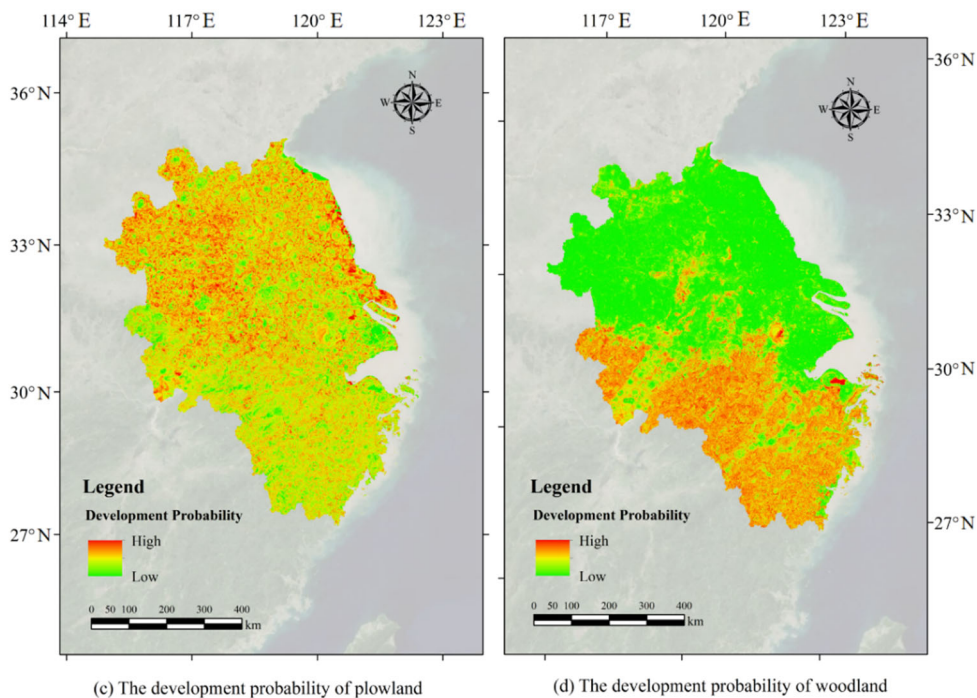


Figure 2. The development probability of various land use types in the Yangtze River Delta from 2000 to 2020

According to the grassland development probability in the Yangtze River Delta from 2000 to 2020 (Figure.3-c), the vast majority of areas in the Yangtze River Delta have a relatively high probability of grassland area development. Among them, in the open plain areas, especially in the northern plains

of Jiangsu and the northern plains of Anhui, the probability of grassland development is extremely high. In contrast, the probability of grassland development in the mountainous areas of the southwestern part of the Yangtze River Delta is relatively low. This is mainly due to the provisions of the "Interim Measures for the Management of the Project of Returning Farmland to Forest in Anhui Province", which stipulates that land with a slope of more than 25° must be returned to forest within a specified time limit and not to grassland (Zhang et al., 2018). In addition, the development of grassland in water bodies such as Chaohu Lake is also restricted by natural factors and the probability is relatively low.

It can be known from the probability of water bodies development in the Yangtze River Delta from 2000 to 2020 (Figure.3-d) that the northern parts of Jiangsu, Anhui and Zhejiang provinces all have a relatively high probability of water bodies development. This is mainly because the water network in these areas was originally relatively sparse and the terrain was low and flat, which was suitable for the construction of reservoirs, fish ponds and other projects (Yu et al., 2022). Influenced by the encouraging policies related to the waterfront renovation in the suburbs of cities, large cities such as Shanghai, Nanjing and Hangzhou and their surrounding areas also have certain potential for water bodies development (Hartog, 2021). In contrast, the development probability of water bodies at existing water bodies such as Taihu Lake, Chaohu Lake and the estuary of the Qiantang River is relatively high.

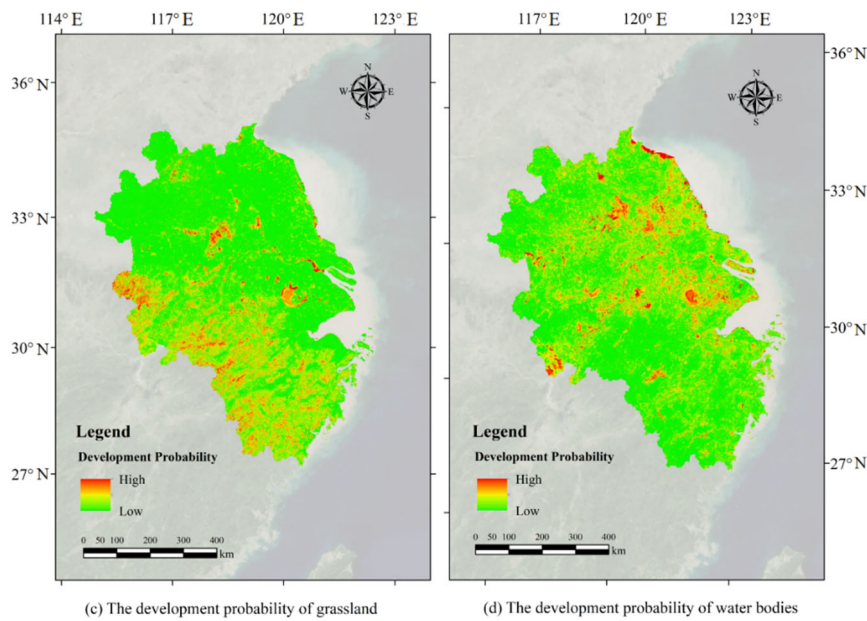


Figure 3. The development probability of various land use types in the Yangtze River Delta from 2000 to 2020 (continue)

The development probability of urban land in the Yangtze River Delta from 2000 to 2020 (Figure. 4-e), the development probability of rural residential land in the Yangtze River Delta from 2000 to 2020 (Figure. 4-f), and the development probability of other developed land in the Yangtze River Delta from 2000 to 2020 (Figure. 4-g) present the development probability of developed land. Among them, the development probability of urban land shows a distinct circular high value in the metropolitan area. Its high-potential areas are mainly distributed in a ring around central cities such as Shanghai, Nanjing, Hangzhou, Suzhou and Ningbo. This reflects the requirements put forward in the "National New-Type Urbanization Plan (2014-2020)", such as giving full play to the radiation and driving role of central cities (Sun et al., 2017). In contrast, the areas with high development probabilities of rural settlements are mainly distributed in the southern part of the Yangtze River Delta, mainly in Zhejiang Province. This is because since 2015, Zhejiang Province has become one of the first pilot provinces in China for the reform of "rural collective business land entering the market" (Shen et al., 2024). A large number of idle rural homesteads have been revitalized,

significantly enhancing the development potential of local rural residential land. Other developed land, on the other hand, has high development potential in areas other than their existing occupied land areas. The high potential characteristics are particularly prominent at transportation nodes and in the radiation zone of the central city. Overall, the high-potential areas of developed land in the Yangtze River Delta are mainly driven by the joint efforts of national policies such as new urbanization and rural revitalization.

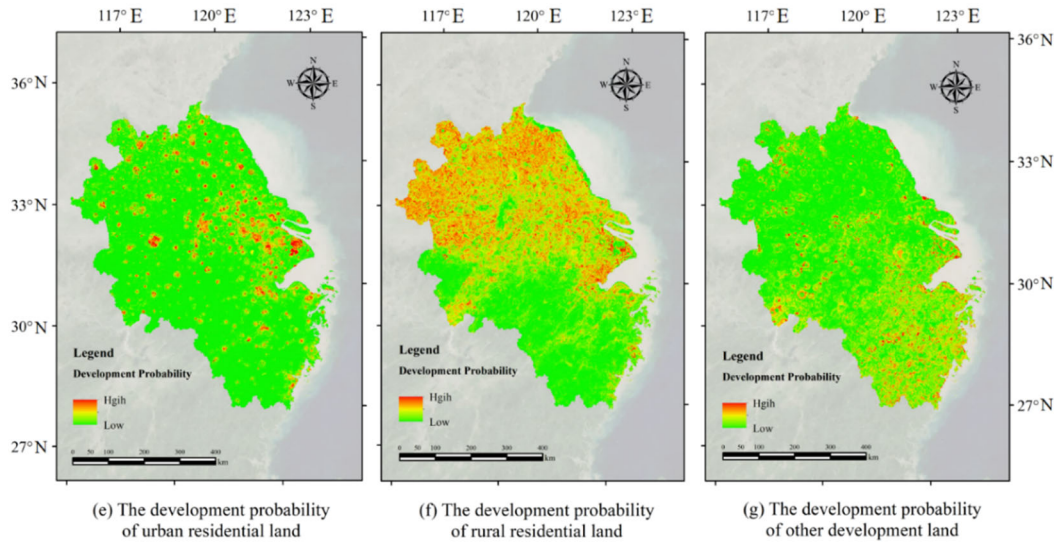


Figure 4. The development probability of various land use types in the Yangtze River Delta from 2000 to 2020 (continue)

According to the development probability of unused land in the Yangtze River Delta from 2000 to 2020 (Figure. 5-h), the high-value areas of the development probability of unused land are widely distributed, especially in the northern plains, wastelands, and coastal tidal flats. The more prominent low-value areas are mostly waters such as Chaohu Lake and Taihu Lake.

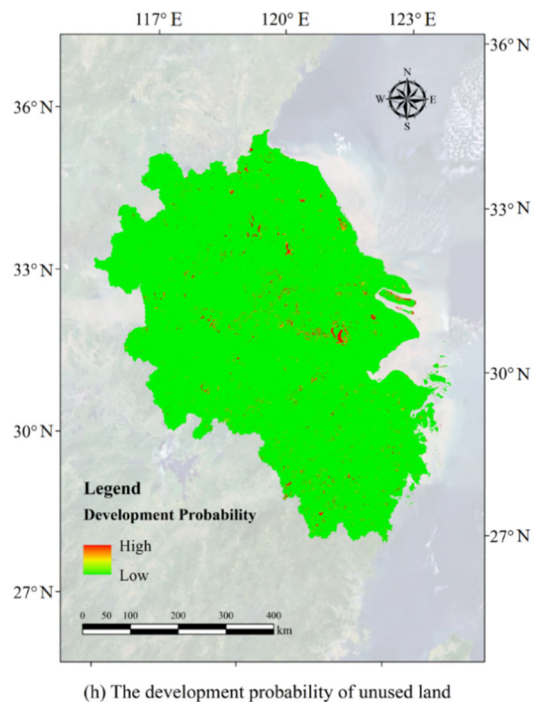


Figure 5. The development probability of various land use types in the Yangtze River Delta from 2000 to 2020 (continue)

4.2. Analysis of Driving Factors for Land Use Change

Table 2 shows the significant adjustments in the spatial pattern of land use types in the Yangtze River Delta from 2000 to 2020. The expansion of different types of land use was jointly driven by various natural environmental factors and human activity factors (Luo, Zhang, Liu, et al., 2024). The expansion of different types of land use was jointly driven by various natural environmental factors and human activity factors. The analysis results of driving force contribution degree show that there are significant differences in the driving mechanism of various land use expansions, presenting strong type dependence and spatial functional orientation characteristics.

The change of plowland is significantly influenced by natural factors. Among them, the contribution degrees of temperature and precipitation are 0.123 and 0.111 respectively, which play a key supporting role in its stability and also provide favorable conditions for agricultural production. Among the socio-economic factors, the contribution of public facility services is the highest, reaching 0.126, reflecting the significant impact of infrastructure expansion on the occupation of plowland. The contribution degree of the slope factor is 0.089, indicating that the terrain conditions restrict the distribution of plowland to a certain extent.

In the changes of woodland, the role of natural factors is particularly significant. The contribution degree of precipitation is 0.164, providing sufficient water sources for the lush vegetation. The contribution degree of temperature reaches 0.133, ensuring the suitability of climatic conditions. At the socio-economic level, shopping services ranked first with a contribution of 0.114, highlighting the demand of urban residents for ecological recreational Spaces (Zhang et al., 2022). However, a slope contribution degree of 0.113 significantly restricts the expansion of woodland in the topographic dimension.

Grassland changes are also influenced by the combined effects of natural conditions and socio-economic factors. In terms of natural factors, the contribution of precipitation was 0.118, providing a stable water source for grassland growth. The temperature contribution is 0.112, which prolongs the growth period. At the socio-economic level, the contribution of medical services was the highest, reaching 0.126, reflecting the close integration of the layout of rehabilitation green Spaces and health service facilities. The contribution degree of terrain slope is 0.107, which limits the expansion of grassland to a certain extent.

In terms of natural factors, the contribution of temperature to water bodies changes is as high as 0.136, reflecting the key role of heat in the thermodynamic equilibrium and ecological processes of water bodies. The precipitation contribution degree is 0.129, providing continuous replenishment for the water balance of the basin. Among the socio-economic factors, shopping services ranked first with a contribution of 0.124, highlighting the trend of the expansion of artificial water features and urban leisure water bodies centered on commercial clusters. The contribution degree of slope is 0.100, revealing the restrictive effect of topographic undulation on water collection efficiency, flow velocity distribution and spatial connectivity (Yang et al., 2024).

Developed land covers three types: urban land, rural residential land and other developed land. Their driving mechanisms have both commonalities and differences. In urban land use, the contribution of catering services is 0.161, which is the most important driving force. In terms of natural conditions, precipitation contributes 0.106 to ensure the urban microclimate and water resource replenishment, and the temperature contribution is 0.105, maintaining the thermal balance of the urban area (Pati et al., 2022). The reliance of rural settlements on natural factors is more prominent. The contribution of precipitation reaches 0.141, the contribution of temperature is 0.123, and the contribution of slope is 0.089, jointly laying the climatic and topographic foundation of rural settlements. The contribution of shopping services is 0.114, guiding the layout of rural commercial nodes and basic supporting facilities. The contribution degree of road distribution is 0.079. While promoting interconnection, it also intensifies the fragmentation of land use. The requirements for environmental suitability of other developed land are the most significant. The contribution of temperature is as high as 0.176, and the contribution of precipitation is 0.137, providing ecological conditions for the site selection of industrial parks and logistics bases. Industrial expansion

contributes 0.111 to promoting industrial agglomeration. The contribution degree of slope at 0.046 and that of road distribution at 0.056 play a restrictive role in terms of spatial flexibility and connectivity (Yang et al., 2019).

The changes of unused land are also jointly driven by the constraints of natural conditions and social and economic demands. Among them, the contribution of precipitation reaches 0.162, providing an important support for surface water replenishment. The contribution degree of road distribution is 0.127, significantly improving the accessibility of the plot (Ahmadzai, 2020). Among the socio-economic factors, the contribution of shopping services is as high as 0.323, highlighting the strong attraction of commercial development to idle plots.

Overall, the driving mechanism of land use expansion in the Yangtze River Delta is characterized by the coexistence of a dual mechanism of "natural foundation - humanistic traction". Natural factors, especially climatic and topographic conditions, still play a fundamental role in the expansion of land types with significant natural attributes such as plowland, woodland and grassland. With the acceleration of regional urbanization, humanistic service factors represented by shopping, medical care and catering have shown a relatively high contribution in most land types, indicating that the evolution of urban functional structure has become an important force influencing the reconstruction of land spatial utilization pattern. This transformation of the driving structure reflects the realistic path of coordinated advancement in ecological protection, urban-rural integration and spatial function optimization in the Yangtze River Delta.

Table 2. Contribution degree of driving factors for land use change in the Yangtze River Delta from 2000 to 2020

Land Use Type	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Plowland	0.089	0.092	0.102	0.089	0.109	0.126	0.079	0.111	0.123	0.080
Woodland	0.113	0.077	0.091	0.088	0.062	0.097	0.114	0.164	0.133	0.061
Grassland	0.107	0.085	0.091	0.126	0.064	0.099	0.110	0.118	0.112	0.088
Water Bodies	0.100	0.075	0.080	0.097	0.075	0.091	0.124	0.129	0.136	0.093
Urban Res. Land	0.025	0.079	0.118	0.097	0.161	0.091	0.149	0.106	0.105	0.070
Rural Res. Land	0.089	0.081	0.104	0.086	0.085	0.098	0.114	0.141	0.123	0.079
Other Dev. Land	0.046	0.094	0.111	0.098	0.108	0.095	0.079	0.137	0.176	0.056
Unused Land	0.034	0.053	0.056	0.056	0.064	0.083	0.323	0.162	0.043	0.127

*F1: Slope; F2: Commercial & Residential; F3: Factory; F4: Medical service; F5: Catering service; F6: Public facilities service; F7: Shopping service; F8: Precipitation; F9: Temperature; F10: Road.

5. Conclusion and Discussion

In this study, the PLUS model was used to interpret a total of 7 periods of remote sensing images in the Yangtze River Delta from 2000 to 2020. The 7 periods of land use classification data in this region were extracted, and the dynamic changes of land use and the contribution of driving factors were analyzed. The main conclusions are as follows:

1) The land use pattern in the Yangtze River Delta has changed significantly, with the expansion of developed land and the compression of agricultural land becoming the main features. In addition, the area of water bodies fluctuates periodically, while unused land shows drastic changes due to the alternating effect of reclamation and restoration policies.

2) Land use change is driven by both natural environment and socio-economic factors, and the dominant factors vary among different land use types. Natural environmental factors such as temperature, precipitation and topographic conditions play an important role in the changes of ecological land such as plowland, woodland, grassland and water bodies, while socio-economic factors profoundly affect the expansion of developed land.

3) Future land use needs to achieve a higher level of coordination and optimization between economic development and ecological protection. The land use changes in the Yangtze River Delta

have revealed the increasingly prominent practical problem of the contradiction between resource utilization and ecological protection in regional development. In the future, the spatial planning and land use control system should be further improved to promote the intensive development of towns.

In conclusion, this study has explored the mechanism and driving factors of land use change in the Yangtze River Delta. However, there are still certain deficiencies in the research, which need to be improved in future studies:

1) This study focused on the Yangtze River Delta and failed to fully consider the comparisons and differences among regions. Future studies can compare the land use change patterns of different regions to reveal regional differences and the reasons behind them.

2) The analysis of driving force factors mainly relies on correlation analysis and does not deeply explore the causal relationship. Future research can combine methods such as qualitative interviews and case analysis to deeply explore the causal mechanism behind driving force factors.

3) This study mainly focuses on the changes in land use types and their driving forces. There is relatively little discussion on the impact of land use changes on ecosystem services and human well-being. Future research should further analyze the impact of land use changes on ecosystem services and human well-being to provide more comprehensive decision support for achieving regional sustainable development.

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References

- [1] Ahmadzai, F. (2020). Analyses and modeling of urban land use and road network interactions using spatial-based disaggregate accessibility to land use. *Journal of Urban Management*, 9(3), 298-315.
- [2] Allan, A., Soltani, A., Abdi, M. H., & Zarei, M. (2022). Driving forces behind land use and land cover change: A systematic and bibliometric review. *Land*, 11(8), 1222.
- [3] Chen, M., Tan, Y., Xu, X., & Lin, Y. (2024). Identifying ecological degradation and restoration zone based on ecosystem quality: A case study of Yangtze River Delta. *Applied Geography*, 162, 103149.
- [4] Chen, P., Luo, J., Xiong, Z., Wan, N., Ma, J., Yuan, J., & Duan, H. (2023). Can the establishment of a protected area improve the lacustrine environment? A case study of Lake Chaohu, China. *Journal of Environmental Management*, 342, 118152.
- [5] Chen, Y., Zhang, L., Yan, M., Wu, Y., Dong, Y., Shao, W., & Zhang, Q. (2024). Spatiotemporal evolution and future simulation of land use/land cover in the Turpan-Hami Basin, China. *Journal of Arid Land*, 16(10), 1303-1326.
- [6] Cheng, K., Su, Y., Guan, H., Tao, S., Ren, Y., Hu, T., . . . Guo, Q. (2023). Mapping China's planted forests using high resolution imagery and massive amounts of crowdsourced samples. *ISPRS Journal of Photogrammetry and Remote Sensing*, 196, 356-371.
- [7] Deng, H., Shao, J., Wang, J., Gao, M., & Wei, C. (2016). Land use driving forces and its future scenario simulation in the Three Gorges Reservoir Area using CLUE-S model. *Acta Geographica Sinica*, 71(11), 1979-1997.
- [8] Duan, L., Yang, S., Xiang, M., Li, W., & Li, J. (2024). Spatiotemporal evolution and driving factors of ecosystem service value in the Upper Minjiang River of China. *Scientific Reports*, 14(1), 23398.
- [9] Gao, J., Zou, C., Zhang, K., Xu, M., & Wang, Y. (2020). The establishment of Chinese ecological conservation redline and insights into improving international protected areas. *Journal of Environmental Management*, 264, 110505.
- [10] Hartog, H. d. (2021). Shanghai's regenerated industrial waterfronts: urban lab for sustainability transitions? *Urban Planning*, 6(3), 181-196.

- [11] Kang, J., Xu, W., Yu, L., & Ning, Y. (2020). Localization, urbanization and globalization: Dynamic manufacturing specialization in the YRD mega-city conglomeration. *Cities*, 99, 102641.
- [12] Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., . . . Barret, K. (2023). IPCC, 2023: Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.
- [13] Lei, Z., Cai, S., Zhuo, S., Lau, Y.-y., & Lim, M. K. (2024). Analysis of the differences and spatial-temporal dynamic evolution of the environmental sustainability of the Yangtze River Economic Belt in China. *International Journal of Shipping and Transport Logistics*, 19(5), 1-41.
- [14] Li, L., Li, G., Du, J., Wu, J., Cui, L., & Chen, Y. (2022). Effects of tidal flat reclamation on the stability of coastal wetland ecosystem services: A case study in Jiangsu Coast, China. *Ecological Indicators*, 145, 109697.
- [15] Li, W., Wang, W., Chen, J., & Zhang, Z. (2022). Assessing effects of the Returning Farmland to Forest Program on vegetation cover changes at multiple spatial scales: The case of northwest Yunnan, China. *Journal of Environmental Management*, 304, 114303.
- [16] Li, X., Zhang, X., Qiu, C., Duan, Y., Liu, S. a., Chen, D., . . . Zhu, C. (2020). Rapid loss of tidal flats in the Yangtze River Delta since 1974. *International Journal of Environmental Research and Public Health*, 17(5), 1636.
- [17] Luo, H., Gao, X., Liu, Z., Liu, W., Li, Y., Meng, X., . . . Sun, L. (2024). Real-time characterization model of carbon emissions based on land-use status: A case study of Xi'an city, China. *Journal of Cleaner Production*, 434, 140069.
- [18] Luo, H., Li, Y., Gao, X., Meng, X., Yang, X., & Yan, J. (2023). Carbon emission prediction model of prefecture-level administrative region: A land-use-based case study of Xi'an city, China. *Applied Energy*, 348, 121488.
- [19] Luo, H., Wang, C., Li, C., Meng, X., Yang, X., & Tan, Q. (2024). Multi-scale carbon emission characterization and prediction based on land use and interpretable machine learning model: A case study of the Yangtze River Delta Region, China. *Applied Energy*, 360, 122819.
- [20] Luo, H., Zhang, Y., Gao, X., Liu, Z., Meng, X., & Yang, X. (2024). Multi-scale electricity consumption prediction model based on land use and interpretable machine learning: A case study of China. *Advances in Applied Energy*, 16, 100197.
- [21] Luo, H., Zhang, Y., Gao, X., Liu, Z., Song, X., Meng, X., & Yang, X. (2024). Unveiling land use-carbon Nexus: Spatial matrix-enhanced neural network for predicting commercial and residential carbon emissions. *Energy*, 305, 131722.
- [22] Luo, H., Zhang, Y., Liu, Z., Yu, Z., Song, X., Meng, X., . . . Sun, L. (2024). Deciphering the point source carbon footprint puzzle: Land use dynamics and socio-economic drivers. *Science of The Total Environment*, 957, 176500.
- [23] Matej, S., Weidinger, F., Kaufmann, L., Roux, N., Gingrich, S., Haberl, H., . . . Erb, K.-H. (2025). A global land-use data cube 1992–2020 based on the Human Appropriation of Net Primary Production. *Scientific Data*, 12(1), 511.
- [24] McDonnell, J., Schunck, N., Higdon, D., Sarich, J., Wild, S., & Nazarewicz, W. (2015). Uncertainty quantification for nuclear density functional theory and information content of new measurements. *Physical review letters*, 114(12), 122501.
- [25] Pati, S., Borah, A., Boruah, M. P., & Randive, P. R. (2022). Critical review on local thermal equilibrium and local thermal non-equilibrium approaches for the analysis of forced convective flow through porous media. *International communications in heat and mass Transfer*, 132, 105889.
- [26] Piao, S., Yin, G., Tan, J., Cheng, L., Huang, M., Li, Y., . . . Peng, S. (2015). Detection and attribution of vegetation greening trend in China over the last 30 years. *Global change biology*, 21(4), 1601-1609.
- [27] Rangel-Peraza, J. G., Sanhouse-García, A. J., Flores-González, L. M., Monjardín-Armenta, S. A., Mora-Félix, Z. D., Rentería-Guevara, S. A., & Bustos-Terrones, Y. A. (2024). Effect of land use and land cover changes on land surface warming in an intensive agricultural region. *Journal of Environmental Management*, 371, 123249.

- [28] Ren, L., Song, S., & Zhou, Y. (2022). Evaluation of river ecological status in the plain river network area in the context of urbanization: A case study of 21 Rivers' ecological status in Jiangsu Province, China. *Ecological Indicators*, 142, 109172.
- [29] Roy, P. S., Ramachandran, R. M., Paul, O., Thakur, P. K., Ravan, S., Behera, M. D., . . . Kanawade, V. P. (2022). Anthropogenic land use and land cover changes—A review on its environmental consequences and climate change. *Journal of the Indian Society of Remote Sensing*, 50(8), 1615-1640.
- [30] Salman, H. A., Kalakech, A., & Steiti, A. (2024). Random forest algorithm overview. *Babylonian Journal of Machine Learning*, 2024, 69-79.
- [31] She, Q., Cao, S., Zhang, S., Zhang, J., Zhu, H., Bao, J., . . . Liu, Y. (2021). The impacts of comprehensive urbanization on PM_{2.5} concentrations in the Yangtze River Delta, China. *Ecological Indicators*, 132, 108337.
- [32] Shen, D., Zhou, X., Xie, S., Lv, X., Peng, W., Wang, Y., & Wang, B. (2024). Paths and mechanisms of rural transformation promoted by rural collectively owned commercial construction land marketization in China. *Land*, 13(4), 416.
- [33] Song, Y., Chen, B., Ho, H. C., Kwan, M.-P., Liu, D., Wang, F., . . . Xu, Y. (2021). Observed inequality in urban greenspace exposure in China. *Environment International*, 156, 106778.
- [34] Sun, D., Zhou, L., Li, Y., Liu, H., Shen, X., Wang, Z., & Wang, X. (2017). New-type urbanization in China: Predicted trends and investment demand for 2015–2030. *Journal of Geographical Sciences*, 27, 943-966.
- [35] Sun, L., Chen, J., Li, Q., & Huang, D. (2020). Dramatic uneven urbanization of large cities throughout the world in recent decades. *Nature communications*, 11(1), 5366.
- [36] Sun, Z., Wang, G., Li, P., Wang, H., Zhang, M., & Liang, X. (2024). An improved random forest based on the classification accuracy and correlation measurement of decision trees. *Expert Systems with Applications*, 237, 121549.
- [37] Tikuye, B. G., Rusnak, M., Manjunatha, B. R., & Jose, J. (2023). Land use and land cover change detection using the random forest approach: the case of the upper Blue Nile River Basin, Ethiopia. *Global Challenges*, 7(10), 2300155.
- [38] Wang, Y., Zhang, W., Liu, X., Peng, H., Lin, M., Li, A., . . . Wang, L. (2025). A Deep Learning Method for Land Use Classification Based on Feature Augmentation. *Remote Sensing*, 17(8), 1398.
- [39] Wang, Z., Li, X., Mao, Y., Li, L., Wang, X., & Lin, Q. (2022). Dynamic simulation of land use change and assessment of carbon storage based on climate change scenarios at the city level: A case study of Bortala, China. *Ecological Indicators*, 134, 108499.
- [40] Wu, H., Lin, A., Xing, X., Song, D., & Li, Y. (2021). Identifying core driving factors of urban land use change from global land cover products and POI data using the random forest method. *International Journal of Applied Earth Observation and Geoinformation*, 103, 102475.
- [41] Wu, H., Yang, C., Liang, A., Qin, Y., Dunchev, D., Ivanova, B., & Che, S. (2024). Urbanization and Carbon Storage Dynamics: Spatiotemporal Patterns and Socioeconomic Drivers in Shanghai. *Land*, 13(12), 2098.
- [42] Xie, L., Wang, H., & Liu, S. (2022). The ecosystem service values simulation and driving force analysis based on land use/land cover: A case study in inland rivers in arid areas of the Aksu River Basin, China. *Ecological Indicators*, 138, 108828.
- [43] Yang, F., Jiang, Y., Li, H., Hui, X., & Xing, S. (2024). Accurate model development for predicting sprinkler water distribution on undulating and mountainous terrain. *Computers and Electronics in Agriculture*, 224, 109196.
- [44] Yang, R., Xu, Q., Xu, X., & Chen, Y. (2019). Rural settlement spatial patterns and effects: Road traffic accessibility and geographic factors in Guangdong Province, China. *Journal of Geographical Sciences*, 29, 213-230.
- [45] Yin, R., Li, X., & Fang, B. (2023). The relationship between the spatial and temporal evolution of land use function and the level of economic and social development in the Yangtze River Delta. *International Journal of Environmental Research and Public Health*, 20(3), 2461.
- [46] Yu, B. (2021). Ecological effects of new-type urbanization in China. *Renewable and Sustainable Energy Reviews*, 135, 110239.

- [47] Yu, Z., Chen, L., Li, L., Zhang, T., Yuan, L., Liu, R., . . . Shi, S. (2021). Spatiotemporal characterization of the urban expansion patterns in the Yangtze River Delta region. *Remote Sensing*, 13(21), 4484.
- [48] Yu, Z., Wang, Q., Xu, Y., Lu, M., Lin, Z., & Gao, B. (2022). Dynamic impacts of changes in river structure and connectivity on water quality under urbanization in the Yangtze River Delta plain. *Ecological Indicators*, 135, 108582.
- [49] Zeng, P., Shi, D., Liu, Y., Tian, T., Che, Y., & Helbich, M. (2024). Parks may not be effective enough to improve the thermal environment in Shanghai (China) as our modified H3SFCA method suggests. *Building and Environment*, 253, 111291.
- [50] Zhang, D., Wang, X., Qu, L., Li, S., Lin, Y., Yao, R., . . . Li, J. (2020). Land use/cover predictions incorporating ecological security for the Yangtze River Delta region, China. *Ecological Indicators*, 119, 106841.
- [51] Zhang, J., Zheng, Y., Wen, T., Yang, M., & Feng, Q. m. (2022). The impact of built environment on physical activity and subjective well-being of urban residents: a study of core cities in the Yangtze River Delta survey. *Frontiers in Psychology*, 13, 1050486.
- [52] Zhang, Q., Song, C., & Chen, X. (2018). Effects of China's payment for ecosystem services programs on cropland abandonment: A case study in Tiantangzhai Township, Anhui, China. *Land use policy*, 73, 239-248.
- [53] Zhang, W., Tian, J., Zhang, X., Cheng, J., & Yan, Y. (2023). Which land cover product provides the most accurate land use land cover map of the Yellow River Basin? *Frontiers in Ecology and Evolution*, 11, 1275054.
- [54] Zhang, X., & Huang, X. (2019). Human disturbance caused stronger influences on global vegetation change than climate change. *PeerJ*, 7, e7763.
- [55] Zhao, H., Chang, C., Wang, Z., & Zhao, G. (2025). A Large-Scale Agricultural Land Classification Method Based on Synergistic Integration of Time Series Red-Edge Vegetation Index and Phenological Features. *Sensors*, 25(2), 503.
- [56] Zhou, Y., Huang, X., Chen, Y., Zhong, T., Xu, G., He, J., . . . Meng, H. (2017). The effect of land use planning (2006–2020) on construction land growth in China. *Cities*, 68, 37-47.
- [57] Zhu, J., Wang, M., & Zhang, C. (2022). Impact of high-standard basic farmland construction policies on agricultural eco-efficiency: Case of China. *Natl. Account. Rev*, 4, 147-166.