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Spatiotemporal Evolution of Urban Expansion and Ecological Sustainability in Hangzhou: A Multidimensional Analysis Based on Land Use and Ecological Footprint

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Abstract. In recent years, Hangzhou has experienced significant urbanization, which has increased the pressure of human activities on natural ecosystems. The spatiotemporal limitations of traditional statistical data restrict high-resolution ecological sustainability assessments, while remote sensing technology provides a new solution for ecological footprint research. Combing diverse remote sensing datasets from 2010, 2015, and 2020, this study analyzes the land use classification and urban expansion characteristics of Hangzhou and combines the ecological footprint model with Pearson correlation analysis to reveal the spatiotemporal coupling relationship between the expansion of construction land and ecological environmental pressure during the rapid urbanization process in Hangzhou. The study found that the built-up area of Hangzhou increased rapidly from 2010 to 2020, and the ecological footprint showed an expanding trend; the correlation analysis revealed that the expansion of urban hardened surface directly aggravated the heat island effect, and the urban expansion was accompanied by increased resource consumption, and ecological pressure continued to accumulate. This research generates theoretical and methodological references for ecological preservation and spatial governance in Hangzhou, with potential applications in sustainability assessment for cities facing similar developmental challenges.

Keywords: RS, urban expansion, ecological footprint

1. Introduction

With the evolution of urbanization, anthropogentic stressors on ecosystems have become increasingly prominent. As a key metric for assessing regional sustainability, the ecological footprint theory can effectively quantify the balance between human demand and natural supply[1]. As one of the core cities in the Yangtze River Delta urban agglomeration, Hangzhou has developed rapidly in population, economy, and urban construction from 2010 to 2020[2], and has gradually become a digital economy innovation center in China and an international comprehensive transportation hub city. This rapid urbanization process has affected land utilization alternations, leading to the expansion of build-up area and the growth of energy consumption. These changes have driven the growth of the ecological footprint and put significant pressure on local ecosystems.

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Traditional ecological footprint research relies on statistical yearbook data, such as indicators such as land use and energy consumption. These data are usually published on an annual basis and have limitations such as low temporal and spatial resolution, delayed updates, and limited public data, making it difficult to reflect the dynamic changes of ecological footprint during urbanization. Remote sensing technology, with its all-round, multi-temporal, and high-precision observation advantages, provides a new technical path for ecological footprint research and presentation[3]. Current research by Yan J et al. has investigated land cover dynamics and associated ecological pressure in Borneo through remote sensing and ecological footprint methods[4]. Eva I et al. evaluated the drought footprint of European ecosystems through vegetation phenology and productivity obtained by remote sensing technology[5]. Lin Cong et al. conducted a spatial analysis of the ecological footprint patterns in the Yangtze River Delta's core urban cluster utilizing multi-source remote sensing products[6]. However, the existing studies on the dynamics of high-resolution ecological footprint in Hangzhou City are mostly concentrated on the period before 2015. Secondly, the source of remote sensing data is single, and the fusion analysis method with statistical data needs to be optimized.

This study conducts a dynamic analysis of Hangzhou's ecological footprint derived from complementary geospatial data (Landsat and Copernicus DEM) from 2010, 2015, and 2020. The focus is on solving the following three scientific problems: the spatiotemporal evolution of ecological deficit/surplus in Hangzhou's urbanization process; the relationship between changes in remote sensing parameters (normalized difference vegetation index, land surface temperature, and impervious surface), and the temporal variations in ecological footprint; and the driving mechanism of natural geographical factors and human and economic factors on the time-series fluctuations in ecological footprint. The findings can offer decision-making recommendations for Hangzhou's national land space planning and ecological protection red line delineation, and at the same time have reference significance for the evaluation of sustainable development of similar cities.

2. Data and methods

2.1. Overview of the study area

Hangzhou, Zhejiang's political and economic center, is situated in China's economically vibrant southeastern coastal region, serving as a critical node in the southern Yangtze River Delta megalopolis (latitudinal range: 29°11′-30°34′N; longitudinal range: 118°20′-120°37′E). Hangzhou has a well-developed water system. In addition to the Qiantang River and West Lake, there are also important water bodies such as Qiandao Lake (Xin'anjiang Reservoir) and Xixi Wetland. The forest coverage rate exceeds 65%, and there are nature reserves such as Tianmu Mountain and Qingliang Peak, with a superior ecological environment.

Functioning as a principle economic hub in the Yangtze River Delta region, Hangzhou has a developed economy and is famous for its digital economy, tourism, and high-end manufacturing. However, in the past decade, it has faced many ecological problems, including natural habitat fragmentation caused by urbanization expansion, water pollution (such as the eutrophication of some rivers and lakes), and atmospheric pollution such as seasonal haze. In addition, the rapid development of tourism has also brought protection pressure to sensitive ecosystems such as West Lake and Xixi Wetland.

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2.2. Data source

2.2.1. Remote sensing data

Based on the needs of the temporal and spatial scale of the paper, this study used multi-source remote sensing data from 2010, 2015, and 2020. Landsat satellite images and MODIS satellite Land Surface Temperature (LST) data were downloaded from the "NASA Earthdata Search" website. In addition, when processing impervious surface data, the base map selected Copernicus DEM data, which was obtained from the "Copernicus Browser" website.

2.2.2. Statistical data

Based on the needs of the time scale research of the paper, it is necessary to count the footprint consumption of ecological resources occupied by Hangzhou in 2010, 2015, and 2020, involving product consumption and land area data of agriculture, forestry, animal husbandry, fishery and energy industries, and the amount of data is large. Among them, the biological resource data were obtained from Zhejiang Provincial Statistical Yearbook and Hangzhou City Statistical Yearbook, the average productivities were sourced from the FAO website, the energy data were obtained from Hangzhou City Statistical Yearbook and Zhejiang Provincial Energy Report, and the energy-to-land ratios were sourced from China Energy Statistical Yearbook.

Since some data are updated late and there is a lack of data on smaller scale areas, only the data of Hangzhou as a whole are collected, and the research time ends in 2020.

2.3. Research methods

2.3.1. Land use classification

This paper mainly uses ArcGIS 10.8 to process and analyze remote sensing data. The following is the specific process:

(1) Data download: Download the Landsat satellite cloud cover data below 10% in 2010, 2015 and 2020 through the "National Geospatial Data Cloud" website. In addition, when processing impervious surface data, the base map selects Copernicus DEM data, which is obtained from the Copernicus browser website.

(2) Data correction: To eliminate various distortion processes and radiation errors in the image data, radiation correction and atmospheric correction are performed to improve accuracy.

(3) Stitching and cropping: The corrected multiple sets of data are stitched together, and the image is cropped according to the administrative boundaries of Hangzhou City.

(4) Remote sensing interpretation: Remote sensing interpretation is performed by combining supervised classification with visual interpretation, and the classification results are corrected to form a land use classification result map.

(5) Other operations: Based on the downloaded tif format data and land use classification result map, further data processing is performed, such as obtaining NDVI and impervious surface.

2.3.2. Ecological footprint analysis

The computation of ecological footprint requires classifying the biologically productive land according to different types and establish different resource accounts. Generally, ecological footprints are divided into two major categories: biological resource consumption accounts and

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energy consumption accounts. According to the Hangzhou Statistical Yearbook and the actual situation in Hangzhou, this paper divides the resource accounts required for ecological footprint calculation into two types, six categories, and 17 sub-items. Table 1 illustrates the precise classification methodology.

Table 1: Consumption account of ecological footprint resources in Hangzhou

Items	Land use type	Consumption items
Biological resource consumption account	Cropland	Grains, Vegetables, Oilseeds, Cotton, Pork, Poultry eggs
	Forest land	Fruits, Tea leaves, Silkworm cocoons
	Grazing land	Beef, Mutton, Milk
	Fishing grounds	Aquatic products
Energy consumption account	Built-up land	Raw coal, Refined oil, Natural gas
	Fossil energy land	Electricity

Equation (1) demonstrates the conversion algorithm from biological resources to ecological footprint:

$$ef_1 = \sum_{i=1}^{n} r_i[(P_i - E_i + I_i)/Y_i] \tag{1}$$

Where ef_1 is the per capita ecological footprint of biological resources, P_i is the per capita production of the i-th biological resource, E_i is the per capita export of the i-th biological resource, I_i is the per capita import of the i-th biological resource, r_i is the equilibrium factor of the i-th type of land, and Y_i is the world average productivity of the i-th biological resource.

Taking into account the changes in land productivity in recent years and the geographical location of the study area, the equilibrium factor of this paper is the equilibrium factor of various land types in the country and different provinces calculated by Liu Moucheng[7] in 2009 based on the net primary productivity of vegetation.

The calculation model for converting energy resources into ecological footprint is shown in formula (2):

$$ef_2 = \sum_{i=1}^{n} K_i * r_i * \frac{Q_i}{P_i} \tag{2}$$

Where ef_2 is the per capita ecological footprint of energy resources, K_i is the conversion coefficient of the i-th energy, r_i is the equilibrium factor of the i-th type of land, Q_i is the per capita consumption of the i-th energy, and P_i is the energy-to-land ratio of the i-th energy.

The consumption of fossil fuels is accompanied by the generation of various wastes. Among the wastes generated, plants have a relatively obvious absorption capacity for CO_2 due to photosynthesis. Therefore, fossil fuel consumption can be translated into corresponding productive land area based on vegetation carbon sequestration capacity. When calculating the land used for energy consumption, this paper adopts the energy-land ratio obtained by Liu Moucheng[8] by dividing the carbon absorption capacity of China's forests by the carbon emission factor.

The individual ecological footprint is expressed by the formula (3):

$$ef = ef_1 + ef_2 \tag{3}$$

The personal sustainable resource threshold is quantified through formula (4):

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$$ec = \sum_{i=1}^{6} a_i * r_i * y_i \tag{4}$$

Where ec is the per capita ecological footprint, a_i is the per capita biological production area of the i-th type of land, r_i is the equilibrium factor of the i-th type of land, and y_i is the yield factor of the i-th type of land.

In the ecological footprint model, comparative analysis across regions proves challenging given variations in selected study areas and differential land productivity. Consequently, the ecological footprint methodology incorporates the yield factor as a critical parameter. The bioproductive land area is converted into a globally comparable overall area, and its conversion coefficient is called the yield factor. Based on previous research, this paper adopts the yield factor of Zhejiang Province calculated by Liu Moucheng[9] in 2010 based on net primary productivity.

Regions are classified as ecologically surplus or deficit based on footprint-capacity comparisons. The calculation method is shown in formula (5):

$$ed = ec - ef \tag{5}$$

Where ed is the ecological deficit (surplus), ec is the per capita ecological carrying capacity, and ef is the per capita ecological footprint. When $ed < 0$, it is an ecological deficit, that is, the socio-economic development of the region is in an unsustainable state; when $ed > 0$, it is an ecological surplus, that is, the production and consumption activities in the region do not exceed the carrying capacity of the ecosystem.

2.3.3. Correlation analysis

The Normalized Difference Vegetation Index(NDVI), a widely adopted remote sensing metric, quantifies vegetation cover density. Its computational expression is:

$$NDVI = \frac{(NIR-Red)}{(NIR+Red)} \tag{6}$$

NDVI exhibits a value range between -1 and 1. Values greater than zero indicate the presence of vegetation, with magnitude positively correlated with vegetation density. Negative values may correspond to water bodies, bare soil, clouds and snow, etc.

Impervious surfaces are land surfaces hardened by impervious materials or weakly permeable materials. Their permeability coefficient is usually less than 1 mm/h. They are commonly found in areas such as building roofs, roads, squares and parking lots. The change of impervious surfaces is one of the core indicators of urbanization. Its changes exerts a major effect on the ecological environment, hydrological cycle and human health. The calculation formula is:

$$NDISI = \frac{TIR-(MIR+NIR+Red)}{TIR+(MIR+NIR-Red)} \tag{7}$$

The value range of NDISI is between -1 and 1. The higher the value, the greater the possibility of impervious surfaces. In this study, areas with $NDISI > 0.3$ were selected as impervious surfaces.

As a key remote sensing parameter, land surface temperature(LST) quantifies the thermal infrared radiation emitted from the ground surface.that is, the temperature of the surface of the ground, buildings, vegetation, etc. The measurement of LST is mainly achieved through remote sensing technology. This paper uses the LST data of the MODIS satellite using the split-window algorithm.

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3. Results analysis

3.1. Analysis of Hangzhou land use classification and urban expansion

Using ArcGIS software, the land use classification of Hangzhou in 2010, 2015 and 2020 is analyzed as shown in Figure 1. It can be seen that Hangzhou has a large forest coverage area, which occupies most of the urban area of Hangzhou, with a small grassland area, towns are concentrated in the northeast, and cultivated land is distributed around the city. From the area occupied by each land type, from 2010 to 2015, the construction land in Hangzhou continued to expand, accompanied by a significant reduction in the area of cultivated land outside the city, a slight decrease in forest land, and little change in water bodies. From 2015 to 2020, the growth rate of construction land slowed down, indicating that urban expansion gradually shifted from extensive growth to internal potential, cultivated land continued to decrease, and the area of forest land recovered, proving that ecological restoration measures are effective.

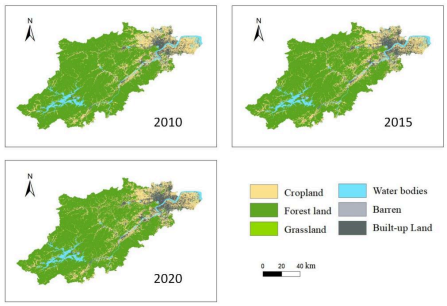

Figure 1: Land use classification results in Hangzhou city

Based on the urban expansion from 2010 to 2020, the Getis-Ord Gi*Z-Score Hot Spot Analysis method was used to produce a Construction land expansion area hot spot map, which is used to identify significant high-value agglomeration areas (hot spots) and low-value agglomeration areas (cold spots) of urban expansion. Hot spots, that is, agglomeration areas where the rate or intensity of urban expansion is significantly higher than that of surrounding areas, indicate that the urbanization process in this area is active; cold spots, that is, agglomeration areas where the rate or intensity of urban expansion is significantly lower than that of surrounding areas, indicate that the urbanization process in this area is slow or limited, as shown in Figure 2.

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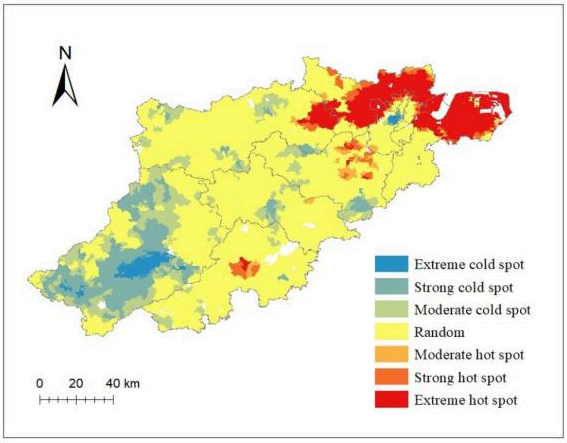

Figure 2: 2010-2020 construction land expansion area hotspot map

When analyzing the expansion of construction land in Hangzhou, hot spots point to the main axis of urban development, while cold spots reflect ecological protection areas or areas of lagging development. Combined with the land use classification map, Hangzhou's urban expansion is mainly concentrated in the northeast, while the vast waters and nearby wetlands in the west limit the urbanization process in this area.

3.2. Ecological sustainability assessment

3.2.1. Calculation of the ecological footprint of Hangzhou

Based on the data collected in Hangzhou in 2010, 2015, and 2020, the ecological footprint of Hangzhou was calculated, and the results are shown in Table 2.

Table 2: Ecological footprint in Hangzhou (gha/cap)

	Land use type						
Year	Cropland	Forest land	Grazing land	Fishing grounds	Built-up land	Fossil energy land	Total
2010	1.0099	0.0847	0.0004	0.0024	1.1600	0.3062	2.5637
2015	0.9576	0.0889	0.0004	0.0032	1.2158	0.5945	2.8604
2020	0.9003	0.0898	0.0003	0.0021	1.3273	0.8423	3.1622

As shown in Table 2, alongside the accelerated development of socio-economic structures, the per capita ecological footprint of Hangzhou has changed significantly from 2.5637 gha/cap to 3.1622 gha/cap, with a compound annual growth rate (CAGR) of 2.11% in the 10 years from 2010 to 2020. This shows that Hangzhou’s rapid socio-economic development in recent years come with rising resource consumption. In this decade, the CAGR of the first five years (2.21%) was slightly greater than the CAGR of the last five years (2.03%), which may be related to the "Five Water Governance" action in 2014 and the strengthening of environmental regulations after the G20 Summit in 2016. At the same time, Hangzhou's industrial structure has been continuously optimized, and the strict control of pollution sources and the breakthrough of the circular economy has reduced the expansion rate of the ecological footprint, reflecting the initial results of environmental governance and economic transformation.

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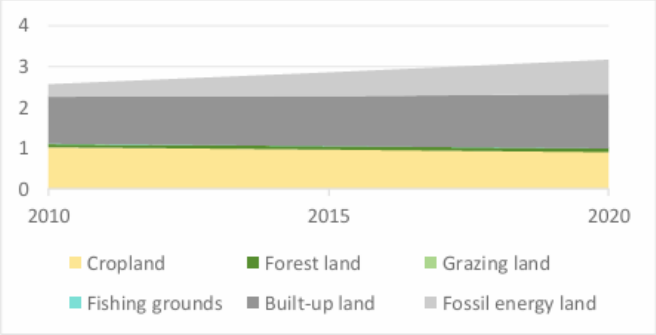

Figure 3: Per capita ecological footprint composition map of Hangzhou

As evidenced by Figure 3, the ecological demand profile per inhabitant in Hangzhou is mainly composed of cultivated land, construction land and fossil energy land, while forest land, water area and grassland account for a relatively small proportion. The trend of changes in the area of various types of productive land is roughly the same as the trend of changes in the per capita ecological footprint. The changes in the per capita ecological footprint structure can reflect the changes in the industrial structure and consumption structure of Hangzhou. The relative weight of cultivated land in personal ecological footprint calculations shows consistent diminishment, which shows that the proportion of the primary industry in Hangzhou's economic development is gradually decreasing. The continuous increase in the ecological footprint of fossil energy land and construction land is related to the drive for industrialization and urbanization. From 2010 to 2020, Hangzhou's digital economy and high-end manufacturing industry developed rapidly, and the total energy consumption such as electricity consumption increased, which directly reflected the deepening of the expansion of economic scale on resources. The increase in forest ecological footprint represents the increase in demand for specialty agricultural products represented by fruits and tea, which indirectly reflects the improvement of residents' living standards.

3.2.2. Calculation of ecological carrying capacity of Hangzhou

Statistical outputs from the prescribed algorithm (Formula 4) reveal Hangzhou's regional carrying capacity metrics in Table 3, with triennial comparisons.

Table 3: Biocapacity in Hangzhou (gha/cap)

	Land use type						
Year	Cropland	Forest land	Grazing land	Fishing grounds	Built-up land	Fossil energy land	Total
2010	0.4280	0.9227	0.0046	0.0223	0.2819	0.0000	1.6596
2015	0.3861	0.8875	0.0042	0.0218	0.3122	0.0000	1.6118
2020	0.2951	0.9342	0.0039	0.0221	0.3662	0.0000	1.6216

Table 3 shows that from 2010 to 2020, the per capita ecological carrying capacity of Hangzhou showed a trend of first decreasing and then slowly recovering. Forest land consistently dominates the biocapacity composition, contributing over 50% annually, with the remaining capacity sequentially distributed among cropland, built-up areas, water bodies, and grassland.

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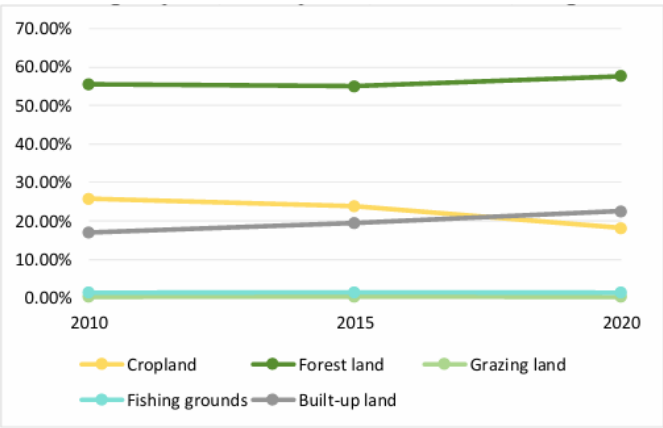

Figure 4: Contribution rate of ecological carrying capacity of various types of productive land

From the trend of the ecological carrying capacity contribution rate of various types of productive land in Figure 4, the ecological carrying capacity contribution rate of cultivated land has been decreasing from 2010 to 2020, the ecological carrying capacity contribution rate of forest land and construction land has been increasing year by year, and the ecological carrying capacity of grassland and water has not changed much. The per capita ecological carrying capacity of cultivated land decreased from 0.4285 gha/cap in 2010 to 0.2951 gha/cap in 2020, and the contribution rate decreased by 7.59%. The ecological carrying capacity of construction land increased from 0.2819 gha/cap in 2010 to 0.3662 gha/cap in 2020 and exceeded the ecological carrying capacity of cultivated land in the same year. This shows that in the development process of Hangzhou in the past 10 years, cultivated land has been continuously occupied, the intensity of development and utilization of construction land has increased, and the level of urbanization is constantly improving.

3.2.3. Calculation of ecological deficit or surplus in Hangzhou

According to formula 5, combined with the previously calculated ecological footprint and ecological carrying capacity, the calculation results of Hangzhou's ecological deficit from 2010 to 2020 are shown in Table 4.

Table 4: Ecological deficit in Hangzhou (gha/cap)

	Land use type						
Year	Cropland	Forest land	Grazing land	Fishing grounds	Built-up land	Fossil energy land	Total
2010	-0.5819	0.8380	0.0042	0.0199	-0.8781	-0.3062	-0.9041
2015	-0.5715	0.7986	0.0039	0.0186	-0.9036	-0.5945	-1.2485
2020	-0.6052	0.8444	0.0036	0.0200	-0.9611	-0.8423	-1.5405

As shown in Table 4, from 2010 to 2020, the ecological situation in Hangzhou has been in an ecological deficit. The per capita ecological deficit has increased from 0.9041 gha/cap in 2010 to 1.5145 gha/cap in 2020, with a compound annual growth rate of 5.29%. The ecological situation is not optimistic. There are large differences in the ecological carrying capacity of various types of productive land. Forest land, grassland and water areas show an ecological surplus, while cultivated land, construction land and fossil energy land are in deficit.

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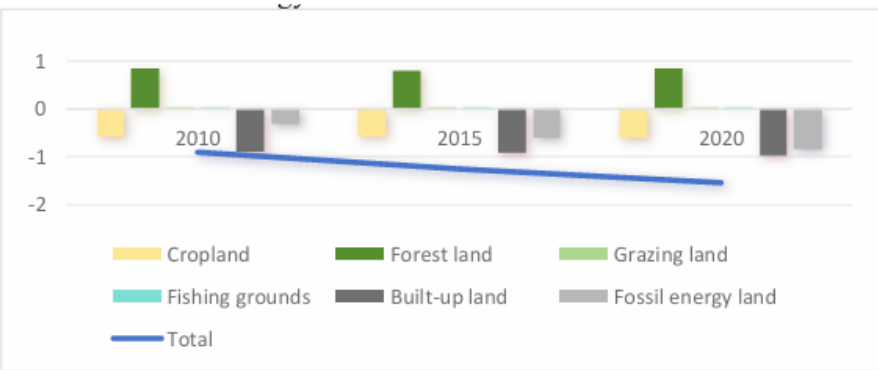

Figure 5: Ecological deficit or surplus of various types of productive land in Hangzhou

From the ecological status of various types of land in Figure 5, the ecological deficit of cultivated land and construction land accounts for a large proportion of the ecological deficit in Hangzhou, and the ecological deficit of construction land and fossil energy land has gradually increased in recent years. Its changing pattern reflects that on the one hand, the urbanization process has squeezed out high-quality agricultural space, resulting in a decline in local food production capacity and increased dependence on external resources; on the other hand, the simultaneous increase in construction land and fossil energy deficits directly points to the fact that the extensive land use mode and high-carbon energy structure in the rapid urbanization process have not been fundamentally reversed.

3.3. Correlation analysis

3.3.1. NDVI analysis

Through formula 6 and data processing, the NDVI data of Hangzhou in 2010, 2015, and 2020 can be obtained, as shown in Figure 6.

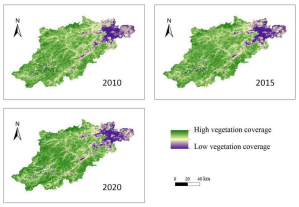

Figure 6: NDVI Map of Hangzhou city

Analyzed spatially, the vegetation coverage rate in the northeast of Hangzhou is low, and the area is constantly expanding. From the perspective of temporal changes, the average NDVI values of Hangzhou in 2010, 2015, and 2020 obtained from ArcGIS software are: 0.7654, 0.7636, and 0.7679, respectively. This shows that the overall vegetation coverage of Hangzhou in the past ten years is stable, and the ecosystem is relatively stable; the trend of a slight decline in the short term and then a rebound may be due to the early urbanization expansion leading to the invasion of urban development into green zones, and then the implementation of ecological restoration projects, which led to an increase in vegetation coverage.

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3.3.2. Impervious surface analysis

Through formula 7 and data processing, the distribution of impervious surfaces in Hangzhou in 2010, 2015, and 2020 can be obtained, as shown in Figure 7:

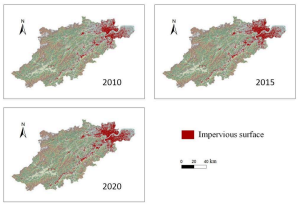

Figure 7: Impervious surface area in Hangzhou city

In terms of temporal changes, the proportion of impervious surfaces in Hangzhou in 2010, 2015, and 2020 was 8.5350%, 10.1638%, and 11.1799%, respectively, showing a growing trend. Regarding geographical dispersion, it presents the characteristics of "continuous expansion of the core area + leapfrog growth of the marginal area", and more than half of the new impervious surfaces come from cultivated land. Its socio-economic driving mechanisms include real estate investment, transportation infrastructure construction, industrial park construction, and population agglomeration, which lead to an intensification of the heat island effect and a reduction in biodiversity.

3.3.3. Surface temperature analysis

Based on the acquired LST images, the average LST values of Hangzhou during the day in May 2010, 2015, and 2020 were calculated and compared, as shown in Figure 8:

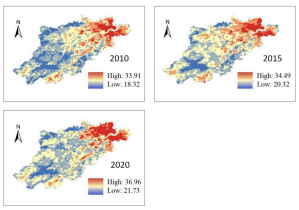

Figure 8: LST map of Hangzhou city

The results indicate that the average daytime surface temperature in Hangzhou in May 2010, 2015 and 2020 was 25.0786℃, 26.9794℃ and 28.3574℃, respectively, showing a gradual upward trend. This is firstly due to the expansion of construction land. Secondly, industrial heat emissions, decreased vegetation coverage and the background of global warming also have a certain impact on the growth of surface temperature.

3.3.4. Correlation analysis

The NDVI, impervious surface ratio, LST and per capita ecological footprint were subjected to Pearson correlation analysis[10], and the generated correlation coefficient table is shown in Table 5.

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Table 5: Correlation coefficient table

	NDVI Mean	Percentage of Impervious Surface	LST Mean	Per capita ecological footprint
NDVI Mean	1(0.000***)	0.466(0.692)	0.502(0.665)	0.583(0.604)
Percentage of Impervious Surface	0.466(0.692)	1(0.000***)	0.999(0.026**)	0.991(0.088*)
LST Mean	0.502(0.665)	0.999(0.026**)	1(0.000***)	0.995(0.062*)
Per capita ecological footprint	0.583(0.604)	0.991(0.088*)	0.995(0.062*)	1(0.000***)

Note: ***, **, * represent significance levels of 1%, 5%, and 10%, respectively.

As quantified by Pearson correlation analysis, the correlation coefficients between NDVI Mean and Percentage of Impervious Surface, LST Mean, and Per capita ecological footprint are 0.466, 0.502, and 0.583, respectively, and the corresponding p values are all greater than 0.1, indicating that these relationships are not statistically significant. Percentage of Impervious Surface is strongly positively correlated with LST Mean (r=0.999, p=0.026), which is significant at the 5% level; it is highly correlated with Per capita ecological footprint (r=0.991, p=0.088), which is significant at the 10% level. The correlation coefficient between LST Mean and Per capita ecological footprint is 0.995 (p=0.062), which is significant at the 10% level. It can be concluded that the proportion of impervious surface and surface temperature (LST) is almost completely collinear, and both are significantly and highly positively correlated with per capita ecological footprint, while the correlation between vegetation cover (NDVI Mean) and other variables is not significant, and the regulatory effect is limited.

The results show that the increase in impervious surfaces during urbanization is the main contributor to the sharp increase in surface temperature, but anthropogenic heat emissions may further amplify their correlation, and the changes in the two have exacerbated the pressure of the ecological footprint. In other words, the urbanization process and the deterioration of the thermal environment have grown in tandem with the consumption of residents' resources, revealing the resource-driven nature of economic expansion. The regulatory role of vegetation cover has no significant impact on the ecological footprint, which may be since the current green space planning does not effectively serve heat mitigation, cities are concentrated in the northeast, and vegetation is unevenly distributed in the vast area of the west.

4. Conclusions

Based on the ArcGIS platform, this paper analyzes the land use classification and urban expansion characteristics of Hangzhou from 2010 to 2020 and combines the ecological footprint model with the Pearson correlation analysis to reveal the spatiotemporal coupling relationship between the expansion of construction land and ecological environmental pressure during the rapid urbanization process of Hangzhou. The conclusions are as follows:

(1) Land use classification and urban expansion characteristics: From 2010 to 2020, the construction land in Hangzhou increased rapidly, while the agricultural land decreased sharply. The urban expansion in Hangzhou showed a "center-periphery" gradient distribution, and the spatial distribution was relatively concentrated.

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(2) Ecological pressure continued to rise: From 2010 to 2020, the ecological status of Hangzhou showed an ecological deficit, and the compound annual growth rate of the per capita ecological deficit was 5.29%. The ecological situation is not optimistic.

(3) Urban expansion and ecological pressure rose simultaneously: The calculated correlation metrics demonstrate that the expansion of urban hardened surface directly aggravates the heat island effect, and the urbanization process is accompanied by increased resource consumption, and ecological pressure continues to accumulate.

(4) The regulatory role of vegetation is limited: Vegetation coverage is not significantly correlated with changes in ecological footprint, which may be due to: the spatial distribution of vegetation being concentrated in the suburbs rather than the core area of the heat island, the vegetation type is inefficient, and the speed of urban expansion far exceeds the green space restoration capacity, resulting in a lag in ecological service functions.

In summary, this study provides an important scientific basis and practical guidance for the sustainable development of rapidly urbanizing areas through a comprehensive analysis of multiple scales and multiple indicators. The study innovatively constructed a quantitative assessment framework of "urban expansion-ecological pressure", providing data support and decision-making tools for national land space planning and ecological protection policy formulation, which has demonstration value for facilitating quality-oriented urbanization in the Yangtze River Delta Megaregion alongside eco-civilization advancement, and also provides a scalable technical path and policy inspiration for achieving urban transformation under the "dual carbon" goal.

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