Postprint: Ecological and Environmental Impacts of Urban Expansion in Bangkok

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Abstract

Based on four phases of Landsat data from 1990, 2000, 2010, and 2015, and MODIS NDVI data from 2000-2015, this study conducted an analysis of urban expansion in the Bangkok metropolitan area of Thailand over the past 25 years, encompassing spatiotemporal variation and pattern analysis of urban construction land expansion, analysis of eco-environmental effects of expansion, and driving force analysis. The results demonstrate: (1) Since 1990, the area of urban construction land in Bangkok has exhibited continuous growth, undergoing a process of initially rapid, then slowed, and subsequently accelerated expansion. Urban expansion has been predominantly oriented toward the northeast, with the most pronounced expansion occurring within the 14-20 km range from the city center, primarily through edge-expansion and infill patterns. (2) Throughout the urbanization process, vegetation and heat islands have exhibited distinct responses to urban expansion. Vegetation greenness has demonstrated an overall declining trend, with significant decreases concentrated within 10-20 km from the city center—precisely the areas experiencing substantial urban construction land expansion. The spatial distribution of heat islands exhibits consistency with that of urban built-up areas. Since the 1990s, the heat island effect has generally intensified, though local variations have become increasingly indistinct. (3) Bangkok' s urban expansion is influenced by multiple factors, including natural geographical conditions, socioeconomic elements, and urban layout.

Full Text

Urban Expansion and Its Ecological Environmental Effects in Bangkok, Thailand

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Abstract

Based on Landsat images acquired in 1990, 2000, 2010, and 2015, and MODIS NDVI datasets from 2010 to 2015, we analyzed urban expansion in Bangkok, Thailand, including the spatio-temporal characteristics of built-up land, ecological-environmental effects (including vegetation greenness and land surface temperature), and the main driving factors of urban expansion. The results showed that: (1) The built-up land area in Bangkok has expanded continuously since 1990, showing a rapid-slow-rapid change trajectory. Urban expansion occurred mainly in the northeast direction and within the range of 14–20 km from the city center. The expansion patterns followed infilling pattern and edge-expansion pattern. (2) Urbanization affected vegetation greenness and heat island. Vegetation greenness declined overall, and a significantly decreased area was in the range of 10–20 km from the city center, which was in accordance with the main urban expansion area. Similarly, the spatial distribution of the heat island was coincident with urban expansion. The heat island increased overall, although local variations were less obvious. (3) Geographical conditions, social economy, and city layout were the main driving factors in urban expansion.

Keywords: urban expansion; vegetation greenness; heat island; driving factors

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Introduction

Global urbanization has entered a stage of comprehensive development. With the rapid development of economic construction and continuous growth of urban population, environmental problems have become increasingly prominent. Compared with inland cities, port cities develop more rapidly due to their convenient transportation conditions, with expanding building clusters. However, port cities are distributed in ecologically fragile coastal zones, and their expansion places a heavy burden on both coastal and urban internal ecological environments. Clarifying the characteristics of port city development, the status of land resources and ecological environment, and understanding the impact of port city expansion on coastal terrestrial ecological environments is crucial for exploring the influence of human socio-economic activities on coastal ecological environments and for formulating rational port city development and coastal ecological protection plans.

Urbanization rapidly changes the material composition and characteristics of underlying surfaces, affecting the physiological and ecological conditions of surface ecological elements and exerting significant impacts on resource consumption and ecological environmental quality. Researchers have primarily focused on capital cities worldwide as study areas, using remote sensing data sources such as Landsat, SPOT, HJ, and MODIS to study urban land use change and driving forces, urban vegetation change, urban expansion morphology and patterns, heat island effects, and atmospheric pollution. Studies on the ecological impacts of urban expansion have also examined water pollution, soil carbon cycling, and urban waterlogging. In research on port city expansion and ecological environmental effects, most scholars have followed research methods used for inland cities, focusing on temporal and spatial changes in urban land use structure and energy consumption. Some scholars have also studied the ecological environment of coastal areas, such as shoreline changes, important economic circles, and land reclamation.

As the main body of terrestrial ecosystems, vegetation is highly sensitive to surface environmental and climate changes, while urban heat island is one of the most significant urban environmental problems caused by ecological environmental imbalance in cities. Urban vegetation change and urban heat island are two major issues in all studies of urbanization' s ecological environmental effects.

Bangkok, the capital of Thailand and the largest city in the Indochina Peninsula, is an important node city on the 21st Century Maritime Silk Road. With rapid industrial development, Bangkok' s economy has improved and urbanization has gradually emerged. The period since 1990 has been an important stage of urban development for Bangkok. The city exhibits extremely high primacy, accommodating more than half of Thailand' s urban population, with the phenomenon of "false urbanization" being rare worldwide. Bangkok' s urban population reached 9.27 million in 1990 and grew by approximately 2.258 million people by 2015. Rapid population urbanization has caused land urbanization, leading to reduced urban green space, increased surface temperature, and prominent ecological problems such as water pollution.

Numerous scholars have conducted research on urban expansion and its ecological environmental impacts in domestic port cities. However, such research remains scarce for Bangkok, Thailand. To comprehensively understand the expansion of built-up land and the impacts of urban expansion on the urban environment during Bangkok' s rapid urbanization process, this study utilizes multi-temporal Landsat and MODIS data to monitor land cover/use changes in Bangkok, examine urban expansion patterns, and investigate the spatio-temporal variation patterns of multiple environmental elements including vegetation and near-surface temperature during the urbanization process. This research aims to provide reference for urban planning, development, and ecological civilization construction in China.

1. Study Area Overview

Bangkok is Thailand' s only prefecture-level municipality, located in the lower reaches of the Chao Phraya River, facing the Pacific Ocean with the Gulf of Thailand to its south. It is the capital of Thailand, the largest city in the Indochina Peninsula, and one of the world' s most popular tourist destinations. Geographically situated at 13°29 -13°58 N, 100°19 -100°57 E, the region has flat terrain and a tropical monsoon climate with prevailing southwest winds, an average annual temperature of 27.5°C, and annual precipitation of approximately 1500 mm.

Bangkok serves as both an important node city in the China-Indochina Peninsula Economic Corridor and a crucial port city on the Maritime Silk Road. Bangkok Port is a river port located on the east bank of the lower Chao Phraya River, approximately 25.75 km from the river mouth. To develop foreign trade, Thailand moved its capital to Bangkok, and foreign trade occupies an important position in the national economy. As Thailand' s largest port, Bangkok Port plays a dominant role in the development of Bangkok and Thailand, and also serves as an important transportation hub connecting China with Southeast Asia and the South Pacific.

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2. Methods

2.1 Urban Built-up Land Information Extraction

To extract thematic information on Bangkok' s built-up land and monitor land use/cover changes in the study area, we collected four periods of Landsat TM and Landsat 8 OLI images from 1990, 2000, 2010, and 2015. After preprocessing including geometric correction and clipping, we used the maximum likelihood supervised classification method to classify land types into six categories (built-up land, water bodies, vegetation, bare land, etc.) to extract thematic information on built-up land. By generating random points and comparing them with Google Earth images for verification, the overall classification accuracy for all four periods exceeded 85%.

2.2 Urban Built-up Land Expansion Analysis

Based on the obtained four-period built-up land thematic information data, we used the 1990 built-up land centroid as the origin and employed quadrant bearing method and buffer zone analysis to divide the study area into circular buffer zones at 2 km intervals. We introduced the built-up land proportion, expansion intensity index (AI), and annual growth rate index (AGR) to quantitatively analyze the spatial distribution characteristics and spatio-temporal changes of built-up land in each quadrant and buffer zone.

The built-up land proportion equals the ratio of built-up land area to total land area within a certain range. AI is used to compare the intensity of built-up land expansion in the same region across different periods, while AGR is used to compare the expansion rate of built-up land in different regions during the same period. Their calculation formulas are:

$$AI = \frac{U_{end} - U_{start}}{d} \times 100\%$$

$$AGR = \frac{U_{end} - U_{start}}{U_{start}} \times 100\%$$

where U_{start} and U_{end} are the built-up land areas at the beginning and end of the study period, respectively, and d is the time interval.

The Landscape Expansion Index (LEI) quantitatively identifies urban spatial expansion types based on buffers generated from new built-up land patches. This index is defined as the ratio of the area of old built-up land patches within the buffer of new built-up land patches to the remaining area of the buffer after removing old built-up land patches. Patches with $LEI = 0$ are defined as outlying (new patches separated from old built-up land), patches with $LEI \in (0, 50)$ are defined as edge-expansion (new patches expanding along old built-up land), and patches with $LEI \in [50, 100]$ are defined as infilling (new patches filling within old built-up land).

2.3 Urban Expansion Ecological Environmental Effects Analysis

Vegetation Spatio-temporal Change Monitoring. This study selected the Normalized Difference Vegetation Index (NDVI) to characterize vegetation growth status and dynamic changes. We used NASA' s MOD13Q1 annual maximum value composite vegetation index product with 250 m spatial resolution. Using a linear regression equation, we analyzed vegetation change trends. First, we performed maximum value compositing on the annual data, with time phases including 2000–2015. The regression slope is calculated as:

$$slope = \frac{n \times \sum_{i=1}^{n}(i \times M_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} M_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where n is the length of the monitoring time series, M_i is the NDVI value in year i, and i is the year. A positive *slope* indicates vegetation growth or improvement, while a negative *slope* indicates vegetation decline or degradation. Based on vegetation change trend analysis, we used buffer analysis to study vegetation gradient characteristics along the urban-rural gradient, with the built-up land centroid as the center and 2 km intervals for circular buffer zones, statistically analyzing average NDVI changes in each annular buffer.

Heat Island Effect Monitoring. Using Landsat thermal infrared imagery, we employed Qin Zhihao' s mono-window algorithm to retrieve land surface temperature. Data preprocessing included radiation calibration and atmospheric correction. The main steps for retrieving land surface temperature based on the mono-window algorithm include: (1) calculation of land surface emissivity, (2) calculation of near-surface temperature and atmospheric parameters, and (3) retrieval of land surface true temperature (LST).

Based on the retrieved land surface temperature data, we introduced the Urban Thermal Field Variation Index (TFVI) to quantitatively analyze the heat island effect. TFVI is defined as the ratio of the difference between the temperature at a certain point and the average temperature of the study area to the average temperature of the study area:

$$TFVI = \frac{T - \bar{T}}{\bar{T}}$$

where $TFVI$ is the urban thermal field variation index, T is the temperature at a certain point, and $\bar{T}$ is the average temperature of the study area. To visually describe the heat island effect, we used the threshold method to first classify the urban thermal field into non-heat island ($TFVI \leq 0$) and heat island ($TFVI > 0$), with heat island further subdivided into weak ($TFVI \in (0, 0.15]$), strong ($TFVI \in (0.15, 0.3]$), and extreme heat island ($TFVI > 0.3$). We also introduced the urban heat island proportion index to characterize the impact degree of urban heat island, which is the ratio of urban heat island area to study area. A larger proportion index indicates more severe heat island effect.

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3. Results

3.1 Spatio-temporal Changes and Expansion Patterns of Urban Built-up Land

Overlaying the four-period urban built-up land images revealed significant changes in built-up land across different time phases, with obvious expansion phenomena. Bangkok' s built-up land area continued to grow from 1990 to 2015, showing characteristics of first rapid, then slow, and then rapid again expansion. In terms of annual expansion intensity (AI), the AI for 1990–2000 was 18.84 km², for 2000–2010 was 13.26 km², and for 2010–2015 was 18.62 km². The expansion intensity during 2000–2010 was weaker than the other two stages.

Built-up land was mainly distributed in the second and fourth quadrants (northeast and southwest directions), but the area with the largest built-up land proportion was located in the second quadrant (west). The annual expansion intensity (AI) and annual growth rate (AGR) of built-up land in each quadrant showed that all quadrants experienced expansion, but with obvious spatio-temporal heterogeneity. The AI values in the first quadrant were the maximum in all three time periods, indicating that Bangkok experienced rapid urbanization at the end of the 20th century. The annual expansion rates in each quadrant during 1990–2000 were significantly greater than those in 2000–2010 and 2010–2015. Urban built-up areas mainly expanded along the northeast direction, while expansion along the northwest direction was relatively insignificant.

Buffer analysis results showed that the proportion of urban built-up area decreased with distance from the city center. In areas within 2–4 km of the city center, the built-up proportion did not reach the maximum due to the presence of park green spaces. The maximum built-up proportion occurred in the range of 10–26 km from the city center. Expansion was most significant in the 14–20 km range. Temporally, the AI values showed: 2010–2015 > 1990–2000 > 2000–2010. The AI peak corresponding to 14–20 km indicated that urban expansion is moving toward the urban fringe, with expansion intensity decreasing in the city center area. Spatially, the average expansion rate increased with distance from the city center, indicating that urban built-up expansion is developing outward. The AI values in areas far from the city center were much greater than those near the city center, suggesting that future urban expansion intensity may increase in areas beyond the current city center.

[Figure 1: see original paper] Spatio-temporal changes of built-up land in 1990, 2000, 2010 and 2015 in Bangkok
Built-up land areas, proportion and Annual Increase in 1990, 2000, 2010 and 2015 in Bangkok
[Figure 2: see original paper] Urban built-up land areas and built-up land areas proportion in four sectors
[Figure 3: see original paper] Annual increase and annual growth rate of built-up land areas in four sectors
[Figure 4: see original paper] Spatio-temporal change characteristics of urban built-up land areas along urban-rural gradient

3.2 Expansion Pattern Analysis

Statistical results of urban expansion patterns showed that infilling expansion was mainly distributed in near-urban areas, approximately within 14 km of the city center, while edge-expansion patterns were distributed in areas farther from the city center. Analysis of the peak positions of infilling expansion patterns across the four periods revealed a clear movement toward the urban outer edge. The urban expansion patterns in all three periods were dominated by edge-expansion and infilling, with infilling expansion significantly increasing in the 14–20 km range from the city center.

As urban expansion progressed, infilling expansion patterns showed an increasing trend in both patch number and area, while edge-expansion patterns showed a decreasing trend, indicating that the aggregation degree of built-up land is increasing. Infill-dominated urban expansion has both advantages and disadvantages: while it can improve land use intensity and avoid land resource waste, it also increases internal urban pressure, such as insufficient open space and environmental pollution. Research on Bangkok and its surrounding areas from 1988–2009 showed that Bangkok' s metropolitan expansion was dominated by edge-expansion, while this study found Bangkok' s urban expansion is dominated by edge-expansion and infilling. This fully demonstrates that infilling expansion patterns mainly exist within Bangkok' s inner city. Combined with typical urban problems such as traffic congestion and environmental pollution in Bangkok, this expansion pattern will inevitably attract more people to the inner city, which is very unfavorable for alleviating Bangkok' s excessively high primacy. How to seek a balance between making full use of urban land and alleviating internal urban pressure should be considered in Bangkok' s urban planning.

[Figure 5: see original paper] Areas of three expansion patterns based on buffer zones
The number patches and areas of three expansion patterns

Comparing the results of this study with Estoque' s research on Bangkok' s metropolitan area, both found that new built-up land patches expanded along old urban areas, gradually expanding outward, indicating that Bangkok' s urban development still belongs to the spread pattern from center to periphery. There are many similarities between Shanghai and Bangkok' s urban expansion: the status of Shanghai Port to China is equivalent to that of Bangkok Port to Thailand; both cities have farmland as the main land type at their edges; both expand away from the coastline; both have flat terrain. However, the differences are that Shanghai' s urban development effectively alleviates central city pressure while driving the common development of surrounding areas, whereas Bangkok has extremely high primacy with underdeveloped surrounding areas and obvious regional economic disparities. In this regard, Bangkok could learn from Shanghai' s development model by creating new urban centers in lagging areas to disperse urban population and drive the common development of Bangkok' s surrounding regions, thereby alleviating traffic pressure in Bangkok' s city center.

3.3 Impacts of Urban Expansion on Vegetation Greenness

Based on the NDVI change trend map, areas with significant decline (p 0.05) accounted for 11.56% of Bangkok' s total area, while areas with significant increase accounted for 22.59% of the total area. Declining areas were mainly distributed within 10–20 km of the city center, while increasing areas were mainly distributed beyond 20 km from the city center. Buffer analysis results showed that vegetation greenness decline was most significant in the 10–20 km range, which had a significant negative correlation with AI. In areas within 10 km of the city center, urban expansion was the main factor causing vegetation reduction. Beyond 20 km, NDVI change trends showed no obvious relationship with AI, indicating that vegetation far from the city center has not yet been affected by urban expansion.

[Figure 6: see original paper] NDVI trends from 2000 to 2015 in Bangkok
[Figure 7: see original paper] Variations of NDVI slope, AI, and AGR along the distance to city center

3.4 Urban Expansion Heat Island Effect

The spatial distribution maps of heat islands in four periods and Bangkok' s land use/cover maps showed that in 1990, heat islands were mainly distributed in built-up areas and bare land areas in the east. In the other three periods, heat islands were mainly distributed in built-up areas, while non-heat islands were mainly distributed in water bodies and green spaces. Strong and extreme heat islands in the four periods were mainly distributed at Don Mueang International Airport in Bangkok' s northern suburbs, Bangkok Port in the south, and high-density built-up areas along both sides of the Chao Phraya River. Bangkok' s urban heat island distribution is spatially consistent with built-up land distribution.

The 1990 heat islands were also distributed in the northeast region because Bangkok' s northeast was dominated by bare land at that time. Bare land has high surface reflectance and surface temperature, thus creating heat island phenomena. The Thai government decided to increase agricultural investment, and by 2015, the large bare land areas in 1990 had become vegetated, resulting in significantly reduced heat island range and decreased heat island proportion index in 2015 compared to 1990. Meanwhile, strong heat island phenomena became more obvious in high-density built-up areas within the city.

From 1990 to 2015, Bangkok' s urban heat island range expanded and the heat island effect strengthened overall. The proportion index of weak heat islands showed a gradual upward trend consistent with the overall heat island proportion index, while strong and extreme heat islands showed a downward trend. This indicates that during the urbanization process, the overall urban heat island effect strengthened, but local variations became less obvious. Arifwidodo' s research findings are similar to this study' s results, both finding that Bangkok' s extreme heat islands are mainly distributed in high-density built-up areas, and Bangkok' s heat island intensity is higher than that of Shanghai, San Francisco, and other places. Land cover type and population density are the main factors affecting urban heat island.

[Figure 8: see original paper] Spatial distribution of urban heat island of Bangkok in four periods
[Figure 9: see original paper] Land cover maps in four periods in Bangkok
Ratio index of urban heat island for different classes

3.5 Driving Forces of Urban Expansion

Dynamic analysis of Bangkok' s built-up land expansion shows that built-up land expansion has obvious spatio-temporal differences. Bangkok' s built-up land has been in a continuous expansion stage, with the main reasons depending on Bangkok's natural geographical location, socio-economic conditions, and city layout.

Natural Geographical Location. Bangkok is located in the Chao Phraya River Delta region. The Chao Phraya River running through Bangkok divides the city into eastern and western parts. The west bank is now considered the old urban area with slow urban development, while the east has faster urbanization development. Numerous industrial parks and airports are located on the east bank. Bangkok's northeastern land is relatively vast and dominated by farmland. High-resolution Google Earth images and multi-temporal land use type spatial data from this study show that Bangkok's urban expansion has the characteristic of being distributed along main transportation arteries, especially evident in the central and eastern regions.

Socio-economic Conditions. To explore the driving role of socio-economic conditions on urban expansion, this study selected three socio-economic indicators (urban population, GDP, and per capita GDP) for correlation analysis with built-up land area. Bangkok' s urban population grew from 9.27 million to 11.529 million, an increase of 57.44%. Bangkok' s built-up land area and population are highly positively correlated (correlation coefficient = 0.97, p = 0.95), indicating that population growth promotes built-up land growth. According to Bangkok' s economy accounting for about 57.44% of Thailand' s total economy, we estimated Bangkok' s GDP and per capita GDP. Bangkok' s built-up land is positively correlated with both GDP and per capita GDP, with correlation coefficients of 0.96 (p = 0.92) and 0.95 (p = 0.90), respectively, indicating that economic growth is one of the driving forces of built-up land expansion.

City Layout. Bangkok's urban construction centers on the Grand Palace, with temples and government agencies closest to the center, followed by commercial circles outward, and residential areas in the outermost ring. The inner city circle has dense built-up land due to the distribution of famous tourist attractions like the Grand Palace and temples, as well as government agencies. Therefore, built-up land expansion in the city center has not been obvious in recent decades. Bangkok, known as the "Venice of the East," has well-developed water transportation. The construction of transportation lines including the Skytrain (operating since 1999), subway (since 2004), and Airport Rail Link (since 2010) has transformed Bangkok' s urban land use patterns and spatial structure. The spatial distribution characteristics of new patches from this study show that Bangkok' s urban expansion is distributed along main transportation arteries, particularly evident in the central and eastern regions.

Correlation between built-up land areas and driving force factors in Bangkok

[Figure 10: see original paper] Case of the influence of traffic on urban expansion

4. Conclusions and Discussion

Ports are the gateway for cities to open to the outside world and play a dominant role in urban development. While driving urban economic development, ports also bring negative ecological environmental impacts to cities. How to coordinate harmonious and sustainable development between port-city economy and ecological environment has become an important issue for urban planning. As an important node city on the China-Indochina Peninsula Economic Corridor and the 21st Century Maritime Silk Road, Bangkok has an irreplaceable international strategic position and transportation hub role. Bangkok Port, as Thailand' s largest port, has provided tremendous impetus to Bangkok' s urban development.

This study used multi-temporal Landsat and MODIS remote sensing data to investigate the ecological environmental effects of Bangkok' s urban expansion. The results show that since 1990, Bangkok' s built-up land area has continued to grow, experiencing a process of first rapid, then slow, and then rapid growth again. Urban expansion has mainly occurred in the northeast direction and along the urban fringe. The expansion patterns are dominated by edge-expansion and infilling. During the urbanization process, vegetation greenness has declined overall, with significant degradation areas coinciding with significant built-up land expansion areas. Heat island distribution is also spatially consistent with built-up land distribution, showing an overall strengthening trend.

Analysis shows that Bangkok' s socio-economic conditions, natural geographical conditions, and city layout all have important driving effects on urban expansion. Similar to China' s port cities, Bangkok' s built-up land expansion mainly occupies farmland. Urbanization increases food demand while causing pollution to some farmland, which has irreversible effects, thus intensifying the human-land contradiction. It is necessary to formulate overall land use plans, rationally use land and protect farmland, improve farmland quality, and maintain balance between urbanization and food supply.

Bangkok' s early urban development lacked rational planning, leading to problems such as excessive population 膨胀. In response, Bangkok has implemented a series of measures: establishing secondary towns, developing industries in sub-development areas, improving supporting facilities, and constructing transportation roads. Additionally, it has reduced air pollution from vehicle emissions by strictly controlling vehicle numbers and fuel quality, and reduced urban environmental pollution by transporting solid waste from the city center to old port landfills. Under these policies, multiple urban sub-centers have formed around Bangkok' s city center.

Today' s Bangkok has long broken through administrative boundaries, developing into a mega-urban agglomeration with "Bangkok central city - Bangkok metropolitan area - Bangkok urban circle"as the core. This urban agglomeration has strong radiation capacity and demonstrates enormous economic creativity and potential. Under the 21st Century Maritime Silk Road strategy, China' s coastal cities and ports are undergoing reforms in policy, economy, and technology. For example, Guangdong Province issued implementation plans to build a strategic transportation hub, and Ningbo formulated action outlines to actively build a Ningbo port economic circle. Strengthening the construction of port and hinterland clusters has become a main measure.

Compared with inland cities, coastal cities have superior geographical locations, but due to coastline constraints, land resources are extremely precious. In urban planning, Chinese cities could learn from Bangkok's development experience and lessons. While building port-centered industrial clusters, they should optimize urban land use structure, rationally layout transportation networks, enhance the radiation driving effect of ports on economic hinterlands and core cities on regional small cities, and create prosperous port clusters and urban agglomerations.

Bangkok' s urbanization has not only caused ecological environmental problems such as reduced urban vegetation greenness and increased surface temperature, but also brought social problems including insufficient infrastructure and high unemployment rates. The phenomenon of "false urbanization" should alert all developing countries. Based on Bangkok' s lessons of false urbanization and extremely high primacy, China' s port cities should fully emphasize synchronized development of urbanization and socio-economy, pay attention to the common development of core ports/cities and regional small ports/cities, and while improving the economic creation capacity and radiation driving effect of port clusters and urban agglomerations, avoid problems such as extremely high primacy and unbalanced regional development similar to Bangkok.

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Note: Figure translations are in progress. See original paper for figures.