

Article

Is There a Relationship between Increased Land-Use Intensity and the Rise in PM_{2.5} Pollution Levels in the Yangtze River Economic Belt, China (2000–2021)?

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Abstract: With the rapid urbanization and industrialization of the past few decades, environmental issues have become increasingly prominent, and air pollution in the form of PM_{2.5} has become a major concern in China. The Chinese government has recognized the severity of these environmental challenges and has placed great emphasis on protecting the environment while promoting economic growth. This study utilizes remote sensing technology to analyze the spatio-temporal evolution characteristics of the decoupling between land-use intensity and PM_{2.5} in the Yangtze River Economic Belt (YREB) using 2000–2021 series of PM_{2.5} and land-use-change data, with the Mean Center Change analysis and the Tapio Decoupling Model. This study attempts to analyze the causes of change from the perspectives of economic development stage and policy execution. The study found that the average PM_{2.5} level decreased by 11.77 µg/m³ during this period, with high levels concentrated in urban areas and low levels found in less developed regions. The central trajectory of the land-use intensity shifted southeast, indicating a consistent trend in urbanization and industrialization in that direction. Meanwhile, the average land-use intensity value increased by 0.19, with the highest values concentrated in urban areas. A total of 71.12% of the regions in the YREB exhibited strong negative decoupling or negative decoupling between land-use intensity and PM_{2.5} levels, suggesting rapid urbanization and industrialization with a decrease in PM_{2.5} levels. These findings provide insight into the dynamic relationship between economic development, urbanization, and PM_{2.5} in China's Yangtze River Economic Belt.

Keywords: land-use intensity; PM_{2.5}; mean center change; Tapio Decoupling Model; Yangtze River Economic Belt



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1. Introduction

From the beginning of China's reform and opening-up policy in 1978, China has undergone rapid urbanization and industrialization, which has led to significant economic growth and development. However, it has also resulted in severe environmental problems, such as air, soil and water pollution [1–3], land degradation [4], biodiversity loss [5], heavy metal contamination [6], and climate change [7], particularly in the form of air pollution. One of the key pollutants is PM_{2.5}, which consists of fine particulate matter with diameters of 2.5 µm or less [8,9]. PM_{2.5} refers to fine particulate matter that is less than or equal to 2.5 µm in diameter. Its components include sulfates, nitrates, carbon, organic compounds, and metals, all of which can have negative effects on human health, particularly on the respiratory and cardiovascular systems [10]. In summary, studying trends in PM_{2.5} levels is important for protecting public health, evaluating environmental policies, and sustainable development.

China is currently considered to be one of the most heavily polluted areas in the world in terms of PM_{2.5} pollution. Approximately 40% of the global total of premature deaths caused by prolonged exposure to polluted air occur in China, where over 1.3 million people

die prematurely each year [11]. The regions in China with the higher concentrations of $PM_{2.5}$ were primarily located in the central, eastern, and other areas, such as Beijing–Tianjin–Hebei Region, the Huang-Huai-Hai Plain, Lower Yangtze River Delta Plain, Sichuan Basin, and Taklimakan Desert, and there was a noticeable trend in the concentrations shifting towards the east [12–15]. Previous studies on the sources of $PM_{2.5}$ have found that vehicle exhausts [16,17], industrial processes [18,19], and coal/biomass combustions [20,21] are the main sources. Additionally, previous studies have found that meteorological factors [22] influenced the regional $PM_{2.5}$ pollution levels, such as humidity [23], temperature [24], wind speed [25], surface pressure [26], atmospheric circulation [27], wind direction [28], and air movement patterns [29,30].

Land-use change has significant impacts on various inter-regional aspects such as material cycles, energy flows, climates, and biodiversities. This is primarily because it alters the quantity, structure, and type of land use, resulting in changes to vegetation, soil properties, nutrient cycling, and water availability [31–34]. Quick urbanization and industrialization have resulted in changes in land-use structures and functions, where a significant amount of farmland and forest land have been developed into artificial surfaces, with an increase in residential and industrial land-use types [35,36]. This is especially true in the core economic regions such as the Beijing–Tianjin–Hebei region, Yangtze River Delta, Pearl River Delta, and Chengdu–Chongqing areas [37,38]. The pattern of regional land use is directly affected by urbanization and industrialization, which, in turn, has an indirect impact on the level of $PM_{2.5}$ pollution [39,40]. Different land-use types will directly affect the distribution of $PM_{2.5}$ in different degrees [41,42]. For example, the construction of factories, houses, roads, and stores has been shown to increase air pollution levels, whereas the presence of lakes, wetlands, and green spaces can reduce such levels, according to studies [43–45]. Changes in the landscape can affect climate change and thus regional $PM_{2.5}$ levels [46]. The common research methods for studying land use include land-use quantity change, land-use pattern change, land-use dynamic degree, transfer matrix, and land-use intensity [47–50].

Most of the existing studies on the influence of land-use change on $PM_{2.5}$ focus on the influence of land-use type, land-use quantity, and land-use pattern on $PM_{2.5}$. However, these studies lack the decoupling analysis of more sensitive land-use intensity [51] on $PM_{2.5}$, especially the panel analysis of high-precision data over a long period of time. The decoupling analysis method can be used to analyze the response relationship between two or more elements and can effectively reveal the extent of the impact of land-use change on $PM_{2.5}$. In this study, based on $PM_{2.5}$ and land-use-change data, we investigate the level of decoupling between more sensitive land-use intensity and $PM_{2.5}$ in the YREB during 2000–2021. Hoping to inform the sustainable development of the YREB, hoping to inform the sustainable development of the YREB.

2. Materials and Methods

2.1. Study Area

The YREB spans three regions in eastern, Central and Western China, which is one of the “three strategies” implemented by the central government. The YREB ($97^{\circ}21'–123^{\circ}10'$ E, $21^{\circ}08'–35^{\circ}20'$ N) includes 11 provinces and cities, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou, with a total area of about 2,052,300 km² (Figure 1). The three core urban agglomerations, namely, the Chengdu–Chongqing Urban Agglomerations (CCUA), the Mid-Yangtze River Urban Agglomerations (MYRUA), and the Yangtze River Delta Urban Agglomerations (YRDUA) are linked by Yangtze River waterway (Figure 1). The gross domestic product (GDP) of YREB increased notably over the same period (2000–2021), from 4.05 trillion to 53.20 trillion CNY, and the resident population (year-end) increased from 5.52 billion to 6.06 billion people. The Development Plan Outline of the YREB aims to utilize the golden waterway of the Yangtze River and the core roles of Shanghai, Wuhan, and Chongqing, along with other major cities along the river, to construct a green development axis along the Yangtze

River. The CUA, the MYUA, and the YRUA will leverage the radiating effects of their central cities to drive economic development and innovation in the surrounding regions. The YREB is one of the regions with the most rapid economic growth and is very crucial to China's modernization process from a strategic standpoint. The rapid economic growth of the region is accompanied by increases in environmental pollution, land-use imbalances, and other problems, especially in urban agglomerations [12–15]. Therefore, the YREB, a major national strategic development area, is used as the study area, and the study of the response of PM_{2.5} pollution to land-use change is beneficial to promoting regional sustainable development.

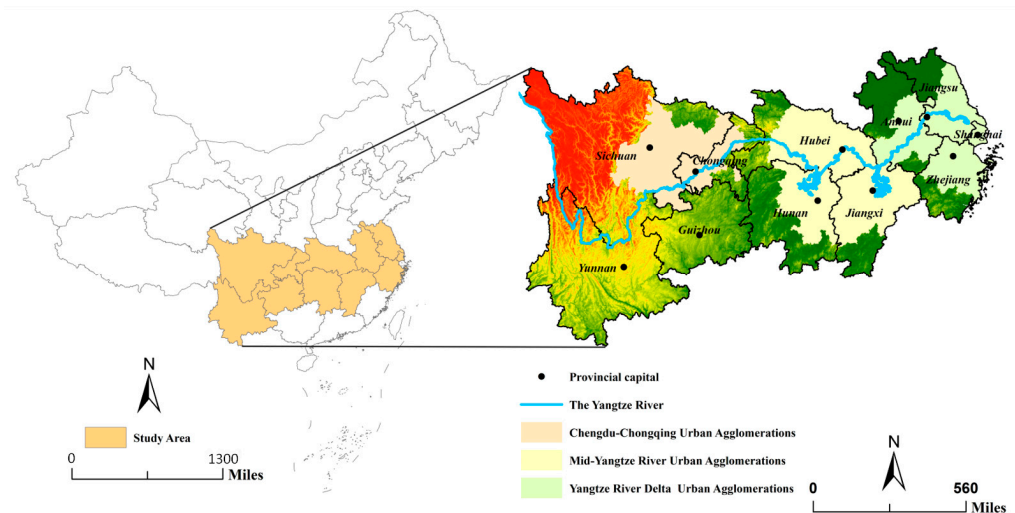


Figure 1. Location of the study area.

2.2. Data Sources

PM_{2.5} data were downloaded from <https://weijing-rs.github.io/product.html> (accessed 6 January 2023), with a cell size of 1000 m × 1000 m, and the time span was from 2000 to 2021 [52,53]. Land-use/cover maps data included nine land-use/cover types as follows, cropland, forest, shrub, grassland, water, snow/ice, barren, impervious, and wetland, with a cell size of 30 m × 30 m, downloaded from <https://zenodo.org/record/5816591#.Y-si3H2BxPZ> (accessed on 6 January 2023), and the time span was from 2000 to 2021 [54]. The scope of this paper's research was centered on the county level, specifically in measuring PM_{2.5} as an average value and calculating land-use data at the same level.

2.3. Methods

2.3.1. Land-Use Intensity (LUI)

Land-use intensity (LUI) encompassed the extent of human activity and development taking place in a specific land area [51]. It gauged the level of utilization and intensity with which the land was used for different endeavors, including agriculture, urbanization, industry, and conservation [55,56]. The concept of land-use intensity takes into account factors such as population density, infrastructure development, resource extraction, and ecological impact [57,58]. Li, Wu, Gong, and Li [51] assigned the score as more sensitive based on the assignment of Zhuang and Liu [55], who assigned a score of 10 to built-up land and a score of 7 to cropland. Due to the difference in the classification of land-use types, we assigned a score of 10 to impervious, a score of 7 to cropland, and a score of 0 to other land-use types based on the study of Li, Wu, Gong, and Li [51]. The equation is as follows:

$$LUI = \sum_{i=1}^n \frac{S_i}{\sum_{i=1}^n S_i} \times D_i \quad (1)$$

where *LUI* is the LUI of a region; *S_i* is the area of land-use type *i*; *D_i* is the score of land-use type *i*.

2.3.2. Mean Center Change

The mean center change is a spatial analysis technique used to investigate changes in the central location of a set of geographic features over time [59]. The method involves calculating the mean center of a set of features at two or more points in time and then comparing the resulting mean centers to determine how they have shifted. It is commonly used in fields such as urban planning, environmental science, and sociology to study changes in the spatial distribution of various phenomena [60,61]. It can assist us in this study in gaining understanding of the changing patterns of PM_{2.5} and LUI. Please refer to Arc Gis 10.8 software for the details of the mean center change tool.

2.3.3. The Tapio Decoupling Model

The Tapio method, also known as the Tapio Decoupling Model, is a statistical technique widely utilized across multiple domains such as agriculture, transportation, energy, construction, and carbon emissions [62,63]. This model was created by Tapio in 2005, and it classifies decoupling into three different states and eight levels of decoupling (Table 1) [64]. This study utilized the Tapio Decoupling Model to explore the correlation between LUI and PM_{2.5} through a decoupling analysis. The equation is as follows:

$$DI_{t1-t2} = \frac{\% \Delta LUI}{\% \Delta MPM_{2.5}} = \frac{(LUI_{t2} - LUI_{t1}) / LUI_{t1}}{(MPM_{2.5,t2} - MPM_{2.5,t1}) / MPM_{2.5,t1}} \quad (2)$$

where DI_{t1-t2} is the decoupling index; LUI_{t1} and LUI_{t2} are the LUI in years $t1$ and $t2$; $MPM_{2.5,t1}$ and $MPM_{2.5,t2}$ are the mean PM_{2.5} at county level in years $t1$ and $t2$.

Table 1. Evaluation of decoupling level between LUI and PM_{2.5}.

Decoupling Status		%ΔLUI	%ΔMPM _{2.5}	DI _{t1-t2}
Decoupling	Strong decoupling	—	+	DI < 0
	Weak decoupling	+	+	0 ≤ DI < 0.8
	Expansion negative decoupling	+	+	DI ≥ 1.2
Negative Decoupling	Strong negative decoupling	+	—	DI < 0
	Weak negative decoupling	—	—	0 ≤ DI < 0.8
	Recessive decoupling	—	—	DI ≥ 1.2
Connection	Expansion connection	+	+	0.8 ≤ DI ≤ 1.2
	Recessive connection	—	—	0.8 ≤ DI ≤ 1.2

Note: “—” means reduced LUI or PM_{2.5}, and “+” means increased.

3. Results

3.1. Spatial and Temporal Change Characteristics of PM_{2.5}

3.1.1. PM_{2.5} Time Change Trend

Figure 2 shows the trend in PM_{2.5} values at the county level in the YREB, including the maximum, minimum, median, mean, and range of 25–75% during 2000–2021. The trends in PM_{2.5} maximum, minimum, median, mean, and range of 25–75% exhibited fluctuations over the period of 2000–2021. Specifically, there was a gradual increase from 2000 to 2007, followed by an insignificant change during 2007–2012. However, from 2013 to 2021, there was a significant reduction in the aforementioned parameters. During the entire period of 2000–2021, the trends in PM_{2.5} maximum, minimum, median, mean, and range of 25–75% displayed a downward trajectory. As can be seen from Figure 2, the mean value of PM_{2.5} decreased by 11.77 µg/m³ from 39.91 µg/m³ to 28.14 µg/m³ during the entire period of 2000–2021. This suggested an overall improvement in air quality in the given location during this period. However, the changes in PM_{2.5} levels were not consistent throughout the entire period. In the initial period of 2000–2007, the mean value of PM_{2.5} increased from 39.91 µg/m³ to 54.97 µg/m³ by 14.79 µg/m³. This was followed by a decrease from 54.97 µg/m³ to 51.97 µg/m³ by 3 µg/m³ during 2007–2010. Subsequently, there was a further decrease in the mean value of PM_{2.5} from 54.60 to 51.66 by 2.94 µg/m³ during

2011–2012. The most significant decrease in $PM_{2.5}$ was observed during 2013–2021, when the mean value decreased from $57.37 \mu\text{g}/\text{m}^3$ to $28.14 \mu\text{g}/\text{m}^3$ by $29.23 \mu\text{g}/\text{m}^3$. The trend in decreasing range in the minimum to maximum values of $PM_{2.5}$ after 2013. The trends in $PM_{2.5}$ maximum, minimum, and range of 25–75% exhibited significant reductions after 2013. This suggested that efforts to reduce particulate matter emissions had been successful in mitigating air pollution levels, especially after the Eighteenth National Congress of the CPC. The most significant decrease in $PM_{2.5}$ levels during 2013–2021 could have been attributed to a combination of factors, including emphasis on green economy development, stricter ecological protection quality regulations, increased use of clean energy sources, and technological advancements in emission reduction measures.

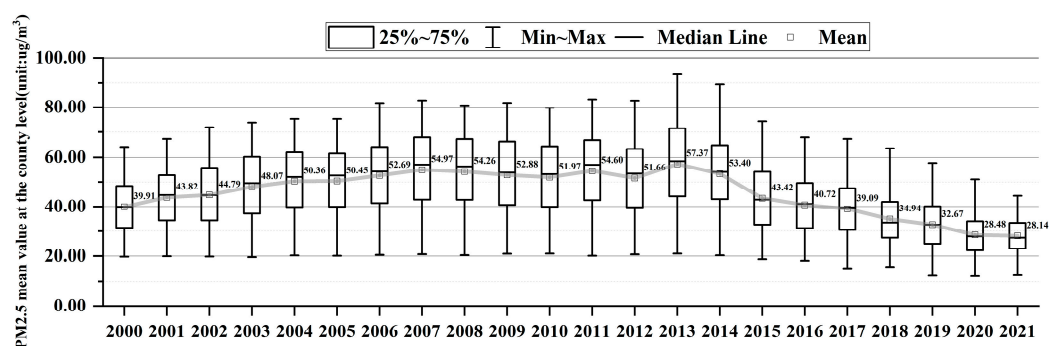


Figure 2. The Box-plot of $PM_{2.5}$ time change trend in YREB.

Figure 3 displays the maximum, minimum, median, mean, and range of 25–75% of $PM_{2.5}$ values at the county level in CCUA, MYRUA, and YRDUA from 2000–2021, providing a simple visual comparison of these trends between the three core urban agglomerations.

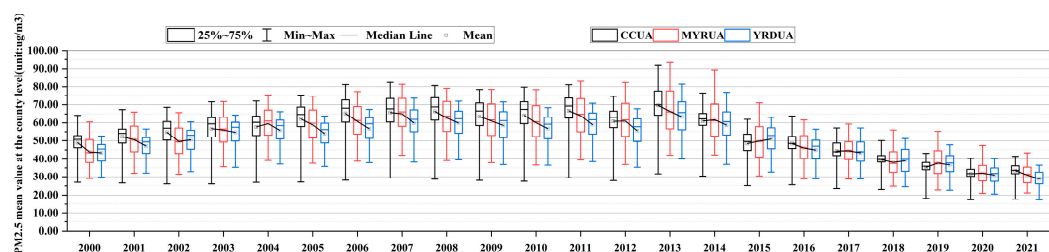


Figure 3. The Box-plot of $PM_{2.5}$ time change trend in CCUA, MYRUA, and YRDUA.

From 2000–2013, through a comprehensive examination of the mean, maximum, and 25–75% range of $PM_{2.5}$ values (Figure 3), it was observed that the CCUA had higher $PM_{2.5}$ levels compared to the other two urban agglomerations, except for the years 2004 and 2012. Specifically, in the majority of districts and counties within the CCUA, $PM_{2.5}$ levels were higher than those in the majority of districts and counties within the MYRUA and YRDUA. With the exception of 2002, the $PM_{2.5}$ levels in three-quarters of the urban agglomerations in the MYRUA area were higher than those in three-quarters of the YRDUA region. In other words, the higher levels of $PM_{2.5}$ pollution in most of the MYRUA region compared to most of the YRDUA region, except for 2002, suggested that air quality was generally worse in the former region during this time period. By comparing the range of minimum–maximum of $PM_{2.5}$ values among the three urban agglomerations, it could be observed that the $PM_{2.5}$ levels were more concentrated in the YRDUA when compared to the CCUA and the MYRUA; the MYRUA ranked second in the range of minimum–maximum of $PM_{2.5}$ values, followed by the CCUA, which showed a more dispersed pattern. By comparing the minimum and maximum of $PM_{2.5}$ value variations among the three urban agglomerations, it could be observed that the CCUA experienced higher levels of $PM_{2.5}$ pollution than the MYRUA and YRDUA, but the minimum $PM_{2.5}$ levels in the CCUA were consistently lower

than those in the other two city groups, with the exception of 2009, 2011, 2012, and 2013. The maximum $PM_{2.5}$ levels in the MYRUA were generally higher than those in the YRDUA; however, the lowest $PM_{2.5}$ levels in the MYRUA and YRDUA alternated with each other.

From 2014–2021, there were notable reductions in the mean, maximum, and minimum levels of $PM_{2.5}$, as well as the 25–75% range, across the three core urban agglomerations within the YREB, indicating a marked improvement in air quality (Figure 3). The analysis of $PM_{2.5}$ mean change levels among the three urban agglomerations indicated that the CCUA had generally lower $PM_{2.5}$ levels than the MYRUA in most years between 2014 and 2021, except for the years 2016, 2018, and 2021. In contrast, the CCUA had higher $PM_{2.5}$ levels than the YRDUA in most years between 2014 and 2021, except for the years 2015 and 2019. Moreover, the MYRUA generally had higher $PM_{2.5}$ levels than the YRDUA in most years between 2014 and 2021, except for the years 2015 and 2018. This suggested that the $PM_{2.5}$ levels varied significantly between the different urban agglomerations, which could have been due to differences in geographic location, climate, and human activities, among other factors. By analyzing the maximum and minimum values of $PM_{2.5}$ pollution in three urban agglomerations, it was found that the MYRUA had significantly higher maximum levels of $PM_{2.5}$ pollution compared to the CCUA and the YRDUA, but the minimum pollution level of $PM_{2.5}$ in the CCUA was significantly lower than that in the MYRUA and the YRDUA, with an exception in 2016. By comparing the range of 25–75% of $PM_{2.5}$ values among the three urban agglomerations, it could be observed that the $PM_{2.5}$ levels were more concentrated in the CCUA when compared to the YRDUA and the MYRUA; the YRDUA ranked second in the range of 25–75% of the $PM_{2.5}$ values, followed by the MYRUA, which showed a more dispersed pattern.

3.1.2. Spatial Distribution Characteristics of $PM_{2.5}$

The spatial distribution of average $PM_{2.5}$ during the research period of 2000–2021 is shown in Figure 4 (due to the page limitation, only pictures from the past 9 years are displayed). The high value of $PM_{2.5}$ is mainly distributed in the three major urban agglomerations, which also include the whole area of Jiangsu and Anhui. These areas are economically developed areas of the YREB. In contrast, low $PM_{2.5}$ values are mainly distributed the Yunnan, Guizhou, and western Sichuan plateau areas with low population densities and relatively unconventional economic developments.

The CCUA is characterized by a dense concentration of industrial activities, encompassing various heavy industries such as steel, cement, chemical manufacturing, and coal-fired power plants. These industries emit large amounts of pollutants, including $PM_{2.5}$, into the air, contributing to the high levels of pollution in the regions. Furthermore, the topography of the CCUA, enclosed by mountains, can impede the dispersion of pollution, resulting in its accumulation within the region. Similarly, the MYRUA, including Wuhan, Changsha, and Nanchang, among others, is also home to numerous industries, transportation hubs, and a large population. The region is one of the most densely populated areas in China and is home to many large industrial centers, which are major sources of $PM_{2.5}$ emissions. The MYRUA has a high density of vehicles on the road, and these vehicles emit pollutants such as nitrogen oxides, sulfur oxides, and particulate matter. In addition, the MYRUA's geography, with mountains to the south and west, can trap pollutants and prevent them from dispersing, leading to high levels of pollution. The YRDUA is highly industrialized and densely populated, which has contributed to the high levels of $PM_{2.5}$ pollution in the area. One major factor is the large number of factories and power plants in the area. These facilities emit pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter, which contribute to the formation of $PM_{2.5}$. The above indicates that the $PM_{2.5}$ distribution pattern roughly aligns with the population and economic distribution pattern, except for natural conditions, suggesting a strong influence of human socio-economic activities on the concentration of $PM_{2.5}$.

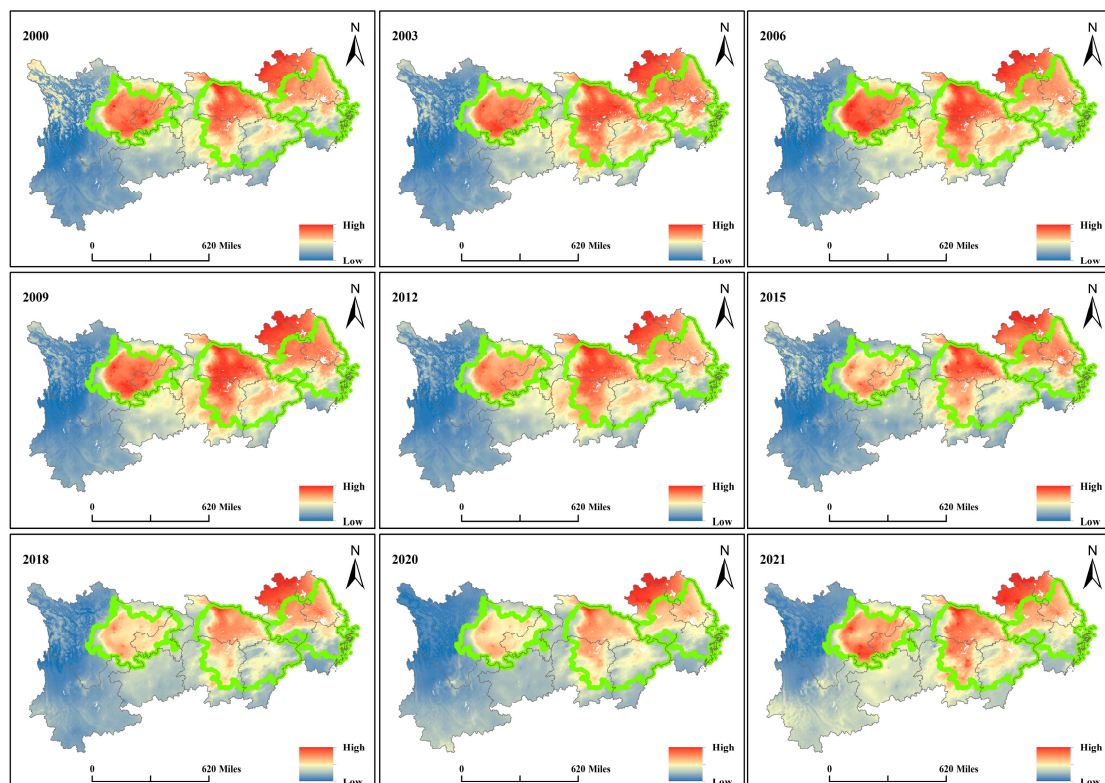


Figure 4. Spatial distribution map of $PM_{2.5}$ mean value at the county level during 2000–2021. Note: the green boundary line indicates the boundary of the urban agglomerations.

To address the problem of $PM_{2.5}$ pollution in the YREB, the Chinese government has implemented a range of measures, including emphasis on green economy development, stricter ecological protection quality regulations, stricter emissions standards for vehicles and factories, promoting the use of clean energy sources, and investing in public transportation infrastructure. The government has also imposed temporary measures such as factory closures and traffic restrictions during times of high pollution. Despite the most significant decrease in $PM_{2.5}$ levels after 2013, there are still challenges to reducing $PM_{2.5}$ pollution in the region. For example, the implementation and enforcement of emissions standards can be challenging, and there is also a need to address the issue of pollution from small and medium-sized enterprises, which may not have the resources to comply with regulations. Overall, addressing the problem of $PM_{2.5}$ pollution in the YREB will necessitate persistent commitment and long-term investment.

3.1.3. Mean Center Change in $PM_{2.5}$ and LUI

The technique of mean center change was utilized to detect the trend in spatial variation in $PM_{2.5}$ (Figure 5a) and LUI (Figure 5b). The change in the central track denoted a shift in the direction of $PM_{2.5}$ and LUI, indicating an increase in air pollution levels and varying degrees of modification in land-use patterns, ranging from severe to moderate.

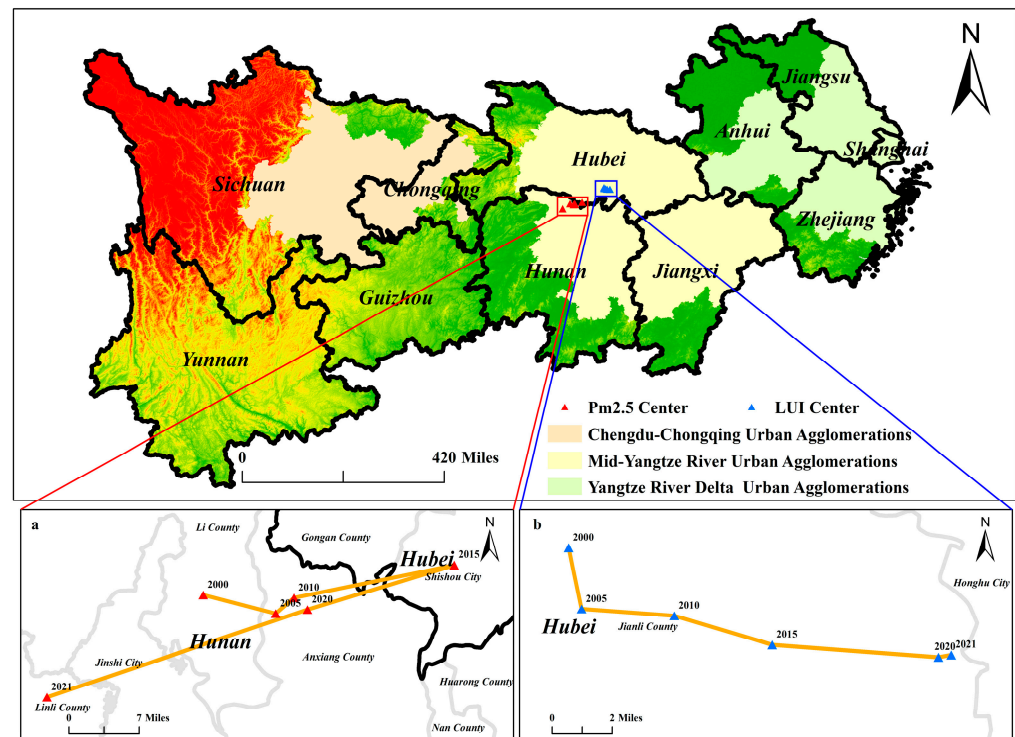


Figure 5. Center and spatial change central tracks of PM_{2.5} and LUI. Note: (a) represents the trend in spatial trajectories of PM_{2.5}, while (b) illustrates the trend in spatial trajectories of LUI.

The PM_{2.5} centers and central change track (Figure 5a) were located in Hunan and Hubei provinces, with specific locations including Li county in 2000, Anxiang county in 2005, 2010, and 2020, Linli county in 2021, and Shishou City in 2015. The movement of PM_{2.5} centers were reliable indicators of air quality changes, with reversals in direction suggesting improvements. In the region under study, the levels of air pollution have been subject to fluctuation over the years, and these changes have been reflected in the trajectory of the PM_{2.5} centers. Specifically, from 2000 to 2005, the PM_{2.5} centers moved in a southeastward direction, indicating a shift in pollution levels in that direction. From 2005 to 2015, the centers reversed their direction and moved northeastward, suggesting a corresponding change in the levels of air pollution in that region. Between 2015 and 2021, the PM_{2.5} centers shifted direction again, this time moving northwestward. The PM_{2.5} centers moved in a northwestward direction for the entire period, indicating that areas in this direction had high levels of air pollution. To better understand the magnitude of these changes, we could examine the size of the distance traveled by the PM_{2.5} centers. The largest distance traveled was during the period of 2020–2021, indicating a significant increase in pollution levels during that time in northwestern direction. The next largest distance traveled was from 2000 to 2021 in northwestern direction, followed by the period of 2010–2015 in northeast direction, and then 2015–2020 in northwestern direction. The smallest distances traveled were during the periods of 2000–2005 in southeast direction and 2005–2010 in northeast direction, suggesting that pollution levels were relatively stable during those times.

The LUI is a measure of how much land is used for human activities such as agriculture, urbanization, and industrialization. The displacement of LUI centers, which refers to the shift in the location of areas with high LUI, can serve as an effective gauge of the extent to which human activities have impacted an area. The LUI centers and central change tracks (Figure 5b) were located in Jianli County, Hubei Province in 2000, 2005, 2010, 2015, 2020, and 2021. The central spatial trajectory of the LUI shifted southeast in the time periods of 2000–2005, 2005–2010, 2010–2015, 2015–2020, 2020–2021, and 2000–2021. This indicated a consistent trend in human activities such as urbanization and industrialization

spreading towards the southeast over time. Furthermore, the magnitudes of the distances of the central LUI trajectories in different time periods were ranked as follows: 2000–2021, 2015–2020, 2010–2015, 2005–2010, 2000–2005, and 2020–2021. This ranking implies that the highest level of change in LUI occurred between 2000 and 2021, which could have been attributed to rapid economic development and urbanization in the region during this time period.

3.2. Spatial and Temporal Change Characteristics of LUI

3.2.1. LUI Time Change Trend

LUI refers to the degree to which land is developed or utilized for different purposes and is an important metric for assessing the impact of human activities on land-use patterns within a given region. This metric can be measured by the amount of land that is developed or used for a specific purpose, as well as the intensity of use per unit of land. The way in which land is utilized and allocated can have significant effects on the sustainability of an area, both environmentally and economically. Inefficient land-use structures, such as urban sprawl and the depletion of natural habitats and open spaces, can result in increased traffic congestion, air pollution, and a decreased quality of life for residents. On the other hand, an efficient land-use structure can promote sustainable development by encouraging mixed-use development, minimizing transportation emissions, and conserving natural resources. Assessing LUI is an important step in developing effective land-use policies that support sustainable development. We can calculate the LUI by using Equation (1).

Figure 6 shows the trend in LUI values at the county level in the YREB, including the maximum, minimum, median, mean, and range of 25–75% during 2000–2021. The mean value of the LUI increased from 3.73 to 3.92 by 0.19, suggesting that there was more construction and development of buildings and infrastructure, leading to a higher intensity of land use. This could have been attributed to various factors such as population growth, urbanization, and increased economic activity in the YREB. The minimum and maximum LUI values were observed within the range of 0 to 10, no significant changes were found in the entire range of values, but the range of 25–75% of the values increased significantly, and the mean value of the LUI was consistently above the median, indicating that there were some areas with very intense land use, such as cities or heavily industrialized regions, whereas most of the other areas had lower levels of LUI. This suggested that some areas within the zone had low levels of development and human activity, whereas others had much higher levels of development and activity. However, the fact that there were no significant changes in the range of values indicated that the level of economic development across the region was uneven, with some areas more developed than others. Areas with lower levels of development may have less access to resources and opportunities, whereas more developed areas may face challenges such as environmental degradation and resource depletion.

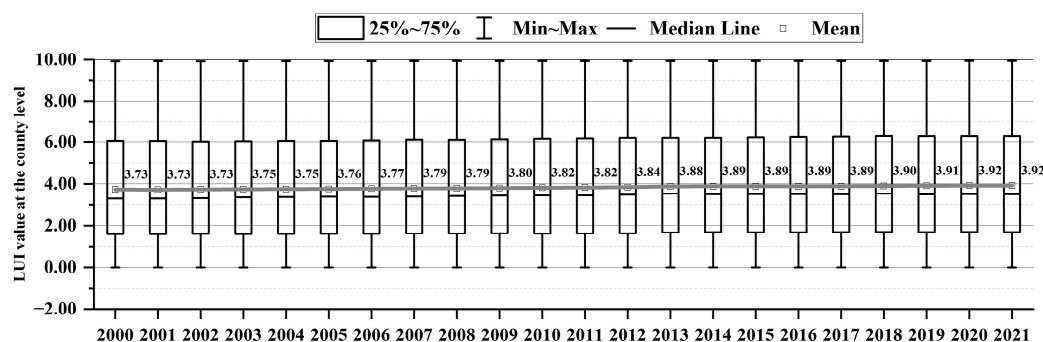


Figure 6. The Box-plot of LUI time change trend in YREB.

Figure 7 provides a clear and simple graphical comparison of the maximum, minimum, median, mean, and range of 25–75% of the LUI values at the county level for CCUA,

MYRUA, and YRDUA from 2000 to 2021, facilitating a straightforward comparison of the trends in these three main urban agglomerations.

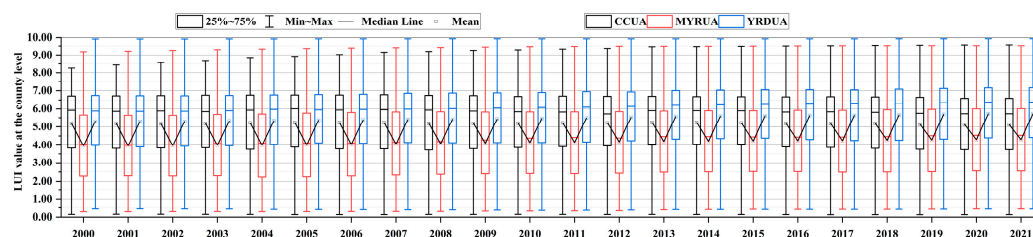


Figure 7. The Box-plot of LUI time change trend in CCUA, MYRUA, and YRDUA.

From 2000 to 2021, the mean value of the LUI in the YRDUA was greater than those in the urban agglomerations, and the CCUA was greater than that in the MYRUA. This meant that the LUI in the YRDUA was consistently high, indicating significant development of land for urban purposes such as residential and commercial areas, industrial parks, and infrastructure. The LUI in the CCUA was higher than that in the MYRUA, suggesting that the former underwent more rapid urbanization and development. However, both of these urban agglomerations had lower LUI values compared to the YRDUA. Within the three main urban agglomerations, the maximum LUI increased across the entire range. However, there were significant increases in the range of 25–75% in the MYRUA and YRDUA, particularly in the YRDUA. There was a significant increase in the LUI values in most regions of the MYRUA and YRDUA. This meant that certain areas of these urban agglomerations experienced marked increases in LUI values over time. The extent of this increase was most pronounced in YRDUA, indicating that this region may have been undergoing more rapid urbanization or development compared to the other regions studied. The median values of the LUI for both MYRUA and YRDUA were consistently higher than their respective mean values. In the MYRUA, the median LUI increased from 4.00 to 4.54, a difference of 0.54, the mean value of the LUI increased from 3.97 to 4.30 by 0.33, and the difference between the median and the mean of the LUI increased from 0.04 to 0.24 by 0.20. Similarly, the median LUI in the YRDUA increased from 5.89 to 6.39, a difference of 0.50, the mean value of the LUI increased from 5.30 to 5.73 by 0.43, and the difference between the median and the mean of the LUI increased from 0.59 to 0.61 by 0.66. The increase in median LUI values in both the MYRUA and YRDUA indicated a trend towards more intensive land-use practices in these regions. This trend may reflect an increasing demand for land resources, growing urbanization, and economic development in the area, and there was a growing disparity or unequal distribution in the level of economic development across the regions. The rise in LUI is a potential cause for concern as it can lead to environmental degradation, loss of natural habitats, and increased pressure on natural resources. The median value of the LUI in the CCUA decreased from 5.93 to 5.72, a decrease of 0.21, and the mean value of the LUI decreased from 5.17 to 5.11 by 0.16, and the difference between the median and the mean of the LUI decreased from 0.75 to 0.61 by 0.14. However, the maximum LUI increased across the entire range, indicating a more uneven regional economic development in this area compared to the other two urban agglomerations. This was related, as Sichuan Province has been focusing on the development of its capital city, Chengdu. To support the urbanization and industrialization of Chengdu, the government of Sichuan Province has invested in infrastructure development including building new highways, expanding public transportation, constructing new housing and commercial complexes, and promoting the development of high-tech industries such as electronics, information technology, and biotechnology. As a result, many people from nearby regions are drawn to Chengdu in search of a better quality of life. This siphoning effect has contributed to the city's population growth and economic development.

3.2.2. Spatial Distribution Characteristics of LUI

The spatial distribution of the LUI during the research period of 2000–2021 is shown in Figure 8 (due to the page limitation, only pictures from the past 9 years are displayed). Topographic differences play a crucial role in shaping land use and spatial distribution patterns. Significant spatial variations can be observed in the distribution of the LUI, where the eastern region displays high value of LUI, the central region exhibits moderate value of LUI, and the western region shows low value of LUI. The high value of LUI is primarily concentrated in three major urban agglomerations, as well as the entire regions of Jiangsu and Anhui. These areas are specifically located in the Chengdu Plain, Hanzhong Plain, Dongting Lake Plain, Poyang Lake Plain, and Yangtze River Delta Plain. These flat and fertile plains are abundant in water resources, making them some of the most important agricultural areas in China. In addition, these regions also house several of the country's major economic centers and cities. In contrast, low LUI values are mainly located in western Sichuan, Yunnan, Guizhou, western Hubei, and other areas with many mountain ranges, uneven terrains, and inconvenient transportation systems, such as the eight concentrated contiguous poverty areas in the Qinba Mountains, the Wumeng Mountains, the Wuling Mountains, the border areas in western Yunnan, the Yunnan–Guizhou–Qiangyan Stone Desertification Area, the Dabie Mountains, the Luoxiao Mountains, and the Tibetan areas in four provinces.

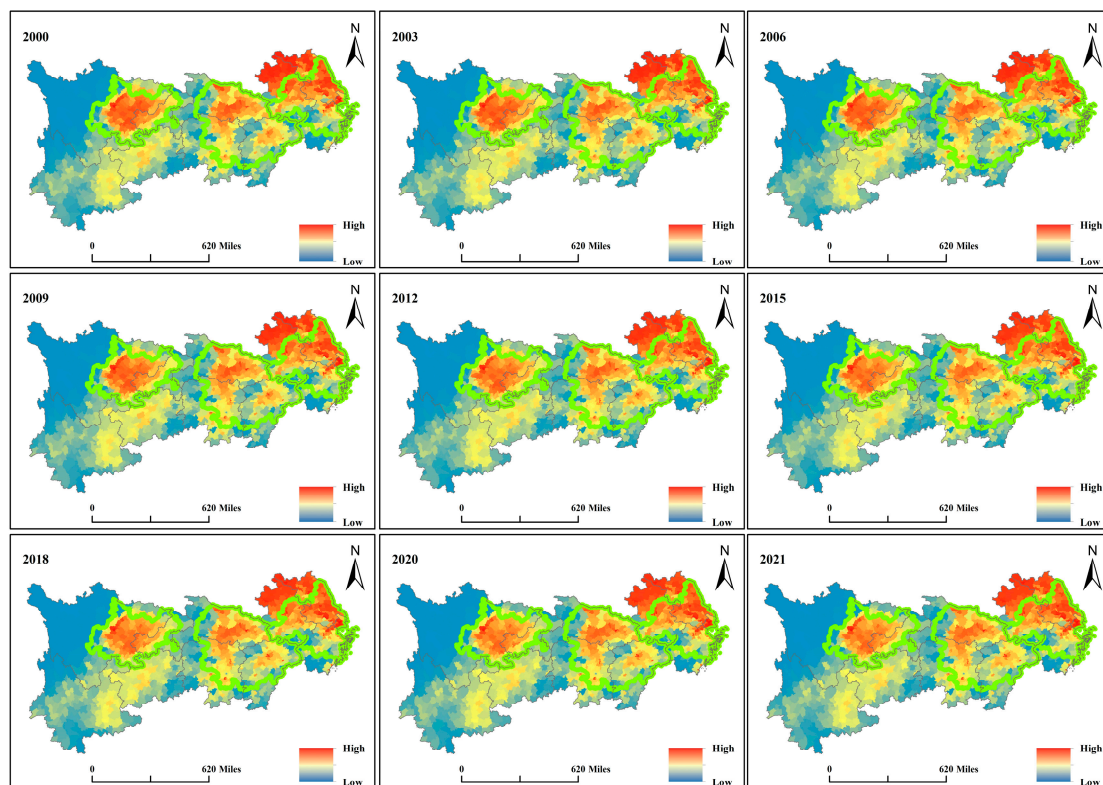


Figure 8. Spatial distribution map of LUI value at the county level during 2000–2021. Note: the green boundary line indicates the boundary of the urban agglomerations.

The spatial characteristics of LUI and economic development are closely related. In general, more developed regions tend to have higher levels of economic activity and a greater LUI. An imbalanced economic development within the YREB was recognized in Section 3.2.1. Figure 8 displays the areas where economic development is unbalanced.

Due to its strategic location at the mouth of the Yangtze River, the Yangtze River Delta boasts a complex network of waterways that includes smaller rivers, lakes, and canals, in addition to the Yangtze River itself. This expansive water system has played a vital role

in driving the region's economic development by facilitating the seamless movement of goods and people and providing easy access to the sea. Furthermore, the region serves as a critical transport hub, with numerous major ports, airports, and highways linking it to other parts of China and the world. As a result, the Yangtze River Delta has consistently been at the forefront of China's economic progress and development, particularly since the era of global trade, which primarily relies on maritime transportation. This region, which has a high level of land-use intensity, is one of the most economically dynamic regions in China.

The MYRUA comprises several major urban areas, including the Wuhan City Circle, Changzhutan Urban Agglomerations, and Poyang Lake Urban Agglomerations, which are the three main sub-regions. Wuhan, Changsha, and Nanchang are the central cities of this region and are important economic and cultural centers in their own right. The distribution of LUI indicates differences in the urban areas' developments, with Wuhan exhibiting higher levels of LUI compared to the other two sub-regions. While the Wuhan City Circle is the most dominant force in the region and is experiencing significant growth, the other two urban agglomerations also play an essential role in the overall development of the area. The Wuhan city circle is located at the intersection of several major transportation routes, including the Yangtze River, several major highways, and high-speed rail lines. This makes it a natural transportation hub for the region and has helped to drive its economic growth. In recent years, the Chinese government has implemented a number of policies and initiatives aimed at boosting economic growth in central China. As a result of these factors, the Wuhan city circle has seen rapid urbanization and industrialization in recent years.

The CCUA is situated in the upper reaches of the Yangtze River. The CCUA has been recognized by the Chinese government as a pivotal development zone, and, to reduce the economic disparities between the East, Central and West regions, significant investments have been made to promote its growth. The CCUA is a key economic hub in western China, and it plays an important role in the region's development. The relocation of numerous manufacturing industries from the lower areas of the YREB to the middle and upper regions has elevated the standard of industries in those areas while also reducing the regional disparity. Industrial restructuring and economic transformation and upgrading are occurring in the downstream region of the Yangtze River. The increased values of the LUI observed in CCUA suggest a hastened pace of urbanization and industrialization in these areas.

3.2.3. Decoupling Analysis of LUI and PM_{2.5}

Table 2 displays the decoupling analysis results of the LUI and PM_{2.5} for the period between 2000 and 2021. Figure 9 shows the spatial distribution map of the level of decoupling between LUI and PM_{2.5} during 2000–2021. The ranking of desired levels of decoupling between LUI and PM_{2.5} is as follows, starting from the highest to lowest: strong negative decoupling, weak negative decoupling, recessive decoupling, and recessive connection. On the other hand, the ranking of undesired levels of decoupling is as follows, starting from the highest to lowest: strong decoupling, weak decoupling, expansion negative decoupling, and expansion connection. These rankings are based on the rate of change in LUI and PM_{2.5}, taking into consideration their positive or negative natures, as well as their numerical magnitudes. This section divides the entire study period into three parts based on the trend in PM_{2.5} levels from 2000 to 2021: 2000–2007, 2007–2013, and 2013–2021.

From 2000 to 2021, the desired levels of decoupling between LUI and PM_{2.5} were classified into two types in most regions of YREB: strong negative decoupling and negative decoupling. These accounted for 71.12% and 24.86%, respectively, indicating rapid urbanization and industrialization in most regions, along with a significant decrease in PM_{2.5}. Over time, there were varying trends across different periods. Strong negative decoupling was primarily observed in the MYRUA, YRDUA, Chongqing's main city areas, and the majority of Yunnan Province. Conversely, weak negative decoupling was primarily

observed in most parts of Chongqing and Sichuan, as well as a few areas in the western region of Guizhou.

Table 2. Results from Tapio Decoupling Model during 2000–2021.

Decoupling Status	2000–2007	2007–2013	2013–2021	2000–2021
Strong decoupling	40.47%	23.18%	0.00%	0.00%
Weak decoupling	56.36%	31.31%	0.00%	0.00%
Expansion negative decoupling	0.84%	20.47%	0.00%	0.00%
Strong negative decoupling	0.56%	15.33%	67.01%	71.12%
Weak negative decoupling	0.09%	1.21%	32.62%	24.86%
Recessive decoupling	1.31%	2.52%	0.19%	1.50%
Expansion connection	0.37%	5.61%	0.00%	0.00%
Recessive connection	0.00%	0.37%	0.19%	2.52%

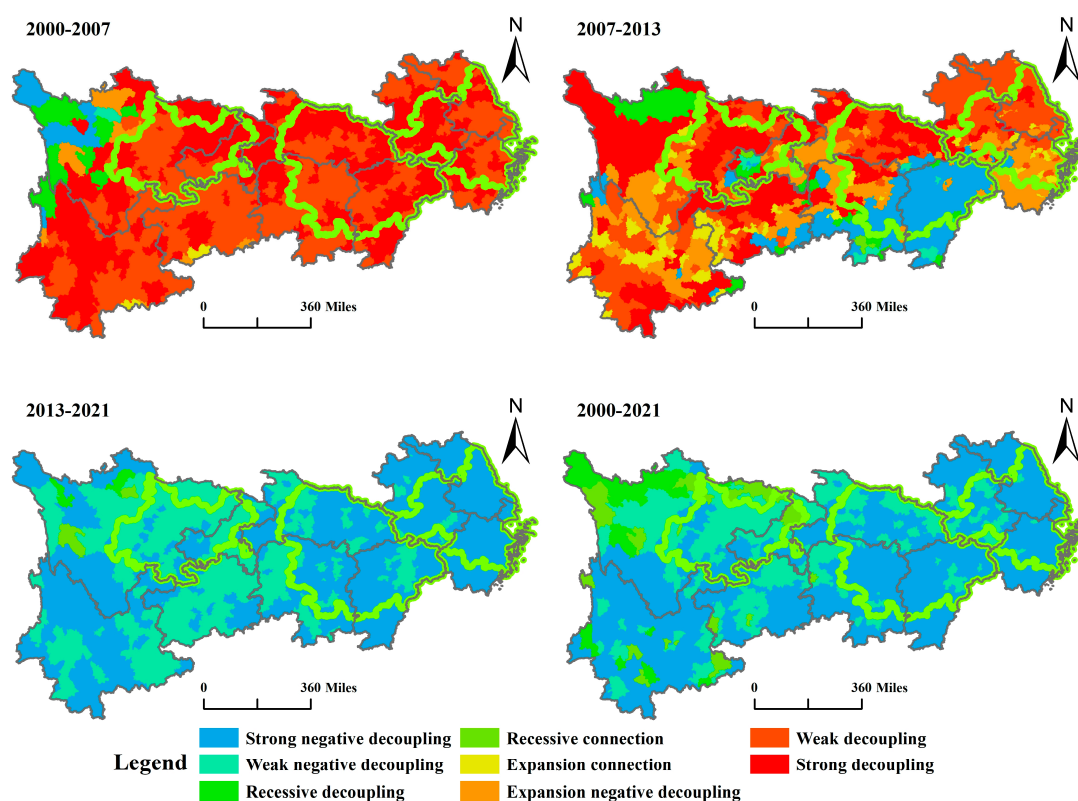


Figure 9. Spatial distribution map of the level of decoupling between LUI and $PM_{2.5}$ during 2000–2021. Note: the green boundary line indicates the boundary of the urban agglomerations.

During 2000–2007, most regions in YREB mainly exhibited two types of undesired decoupling between LUI and $PM_{2.5}$ levels: strong decoupling and weak decoupling. Strong decoupling was observed in 40.47% of the regions, where $PM_{2.5}$ levels increased as land-use intensity decreased. In contrast, weak decoupling was observed in 56.36% of the regions, where $PM_{2.5}$ levels increased as LUI increased. During this study period, there was a noticeable upward trend in $PM_{2.5}$ levels within the YREB. The regions of strong decoupling and weak decoupling were mainly distributed in most provinces of the YREB, except for a very small part of Sichuan Province and Yunnan Province. Throughout this study period, China underwent swift economic growth and urbanization, yet at a substantial expense to the environment. The manufacturing industry played a major role in driving China's rapid economic growth during this period; however, this resulted in elevated levels of air and water pollution. As factories ramped up production to meet the demands of global markets, they released pollutants such as sulfur dioxide, nitrogen oxide, and particulate matter into

the air and water. Additionally, China's energy consumption soared, largely dependent on coal, which is a major contributor to air pollution and greenhouse gas emissions.

During 2007–2013, the levels of decoupling between LUI and $PM_{2.5}$ were mainly classified into four types in most regions of YREB: weak decoupling, strong decoupling, expansion negative decoupling, and strong negative decoupling, indicating that $PM_{2.5}$ levels in the YREB increased with decreasing LUI in 23.18% of the regions, increasing with increasing LUI in 51.79%, and decreasing with increasing LUI in 15.33% of the regions. The areas with strong decoupling were primarily located in Hubei, Sichuan, Yunnan, and certain parts of Guizhou. On the other hand, regions with weak decoupling were mainly found in Jiangsu, Anhui, Hubei, and some parts of Yunnan. Expansion negative decoupling was observed primarily in Zhejiang, western Hubei, northern Hunan, parts of Yunnan, Guizhou, and Sichuan. Meanwhile, areas with strong negative decoupling were mainly concentrated in the southern parts of Hunan and Jiangxi provinces. During this study period, a significant downward trend was observed in the proportion of areas showing strong and weak decoupling in the YREB. Specifically, only 17.29% of areas exhibited strong decoupling, and 25.05% showed weak decoupling, indicating a reduction in the number of areas where $PM_{2.5}$ levels increased with changes in LUI, and it was observed that extended weak decoupling occurred in 15.33% of the areas, indicating that the rate of increase in land use surpassed those of $PM_{2.5}$ in those areas. While there is still a long way to go in reducing air pollution to safe levels, the decreasing trend in $PM_{2.5}$ levels with urbanization and industrialization is a positive sign that effective measures are being taken to address the issue. It is crucial to continue implementing and enforcing environmental policies and promoting sustainable practices to improve air quality and protect public health.

During 2013–2021, the desired levels of decoupling between LUI and $PM_{2.5}$ were mainly classified into two types in most regions of YREB: strong negative decoupling and weak negative decoupling. This indicated that $PM_{2.5}$ levels in the YREB decreased with increasing LUI in 67.01% of the regions, meaning that $PM_{2.5}$ levels decreased as human activities and developments increased in these areas. In contrast, in 32.62% of the regions, $PM_{2.5}$ levels decreased with decreasing LUI, indicating that $PM_{2.5}$ levels also decreased in these areas as human activities and developments decreased. During this study period, there was a noticeable downward trend in $PM_{2.5}$ levels within the YREB. The areas exhibiting strong negative decoupling were predominantly situated in MYRUA, YRDUA, Chongqing's main city areas, and parts of Yunnan Province. On the other hand, the areas with weak negative decoupling were mainly dispersed across most of the western regions, including Chongqing, Sichuan, and Guizhou. Overall, during this study period, the decrease in $PM_{2.5}$ levels with urbanization and industrialization in the YREB could be attributed to China's economic transformation and upgrading, where green development became the predominant theme, and environmental protection measures were intensified.

The decoupling relationship between LUI and $PM_{2.5}$ in the YREB over the years can provide insights into the air quality trends in the region. From 2000 to 2021, the $PM_{2.5}$ level in the YREB showed a fluctuating trend, with periods of increase, stabilization, and decrease. During the initial phase of urbanization and industrialization in the early 2000s, the $PM_{2.5}$ level in the region increased significantly due to the rapid expansion of urban areas and industrial activities. The increase in emissions from factories, power plants, transportation, and other sources contributed to the deterioration of air quality. However, in the mid-2000s, the $PM_{2.5}$ level in the YREB began to stabilize, despite continued urbanization and industrialization. This could have been attributed to the implementation of various measures to control air pollution, such as the promotion of clean energy, the closure of outdated factories, and the improvement of emission standards for vehicles and industries. In the last decade, the $PM_{2.5}$ level in the YREB showed a clear downward trend, indicating an overall improvement in air quality. This could have been attributed to the continued implementation of air pollution control measures, as well as the shift towards a more service-oriented economy and the adoption of cleaner technologies in industries. The

decoupling relationship between LUI and PM_{2.5} in the YREB also indicated that the region had achieved a certain degree of environmental sustainability.

4. Discussion

4.1. From the Perspective of Economic Development Stages

China has transitioned from rapid development to high-quality development. This shift aims to tackle issues such as regional imbalances, urban–rural disparities, environmental pollution, and urban sprawl. The government is implementing strategies to promote balanced regional development, reduce disparities, protect the environment, create more sustainable and livable cities, and achieve sustainable development. The goal is to achieve inclusive and equitable growth while improving the overall well-being of the population.

Since the beginning of China's reform and opening-up policy in 1978, China has become one of the world's fastest-growing economies and has attracted significant foreign investment. China has been able to leverage its market size, low labor costs, and growing infrastructure to become a key player in the global economy dominated by shipping and to undertake the transfer of Western industrial chains. As Western companies look for methods to reduce their production costs and expand their markets, many have turned to China as a manufacturing hub. China's labor costs are typically lower than those in the West, making it an attractive location for companies seeking to reduce their production costs. China has seized this opportunity to initiate urbanization and industrialization in a gradual manner. China's approach to urbanization and industrialization has led to impressive economic growth, but it has also resulted in significant environmental challenges such as air and water pollution, land degradation, biodiversity loss, and climate change. Certainly, there are discrepancies in income among different regions, between urban and rural areas, and among the rich and poor. The coastal provinces have experienced significant growth, whereas the western and central regions have lagged behind. In addition, urban areas have also seen greater economic growth than rural areas, resulting in a widening income gap. Undoubtedly, the YREB also faces these issues, and the findings presented in this paper indicate an increase in PM_{2.5} levels with urbanization and industrialization within China's YREB from 2000 to 2007. The Yangtze River is the world's busiest inland waterway and the golden waterway with the highest freight volume.

The Chinese government aims to foster the integrated development of the upper, middle, and lower reaches of the Yangtze River, as well as the high-quality development of the surrounding regions, by leveraging the Yangtze River Golden Waterway, which spans across the eastern, Western, and Central regions of China. The policy of transferring labor-intensive industries to the Central and Western regions of China involves relocating manufacturing activities from the more developed eastern coastal regions to the less developed regions in Central and Western China. This policy aims to promote balanced regional development and alleviate the pressure on resources and the environment in the eastern coastal regions. The Central and Western regions of China have abundant resources and lower labor costs, which can attract more investment and promote economic growth in these regions. At the same time, the development of the Yangtze River Delta urban cluster is a strategic plan to create a world-class modern urban agglomeration in the eastern coastal region of China. This urban cluster includes Shanghai and the surrounding provinces of Jiangsu, Zhejiang, and Anhui. The plan aims to integrate the resources of these regions to enhance their overall competitiveness and promote sustainable development. In the process of industrial chain transfer, ecological priority and green development are taken as the guiding principles. This means that environmental protection is given top priority, and the development of industries is guided by sustainable and green principles. The policy aims to prevent environmental pollution and degradation and promote the efficient use of resources. The government has put various measures in place to encourage and support the development of green industries and the adoption of environmentally friendly technologies. The paper's findings suggest that the Chinese government's efforts towards green development have been effective in controlling and reducing PM_{2.5} levels in the YREB.

This study shows that as urbanization and industrialization continue, PM_{2.5} levels first rise, then stabilize, and, finally, decline. This trend indicates that the government's policies and regulations have been successful in reducing pollution levels. Overall, the study's findings provide encouraging evidence that the Chinese government's green development strategies are having a positive impact on the environment. By continuing to prioritize sustainability and pollution reduction, China can work towards a cleaner, healthier future for its citizens.

4.2. From the Perspective of Policy Execution

The environmental protection laws in China include the Environmental Protection Law (Enacted in 1989), Air Pollution Prevention and Control Law (Enacted in 1987), Water Pollution Prevention and Control Law (Enacted in 1984), Environmental Impact Assessment Law (Enacted in 2002), Solid Waste Pollution Prevention and Control Law (Enacted in 1995), Wildlife Protection Law (Enacted in 1988), etc. In terms of their enactment dates, all of China's environmental protection laws were established earlier. However, the results of this study indicated that significant declines in PM_{2.5} levels were observed only after 2013. This paper analyzed the policy factors influencing the level of PM_{2.5} change in China with the help of the flexible execution perspective in policy execution theory in the context of China. Flexible execution included actual execution, selective execution, supplementary execution, and alternative execution [65,66]. In this paper, the main focus was on actual execution and selective execution.

The results of this paper provide evidence of a substantial shift in PM_{2.5} pollution levels within the YREB after 2013. Specifically, there was a gradual rise in PM_{2.5} pollution levels from 2000 to 2007, followed by a period of insignificant change from 2007 to 2012, as shown in Figure 2. Consequently, it was observed that local governments frequently prioritized their own self-interests and prioritized extensive developments at the expense of environmental protection from 2000 to 2007. This preference for extensive development over environmental protection could manifest in several ways. Local governments might prioritize industrial growth, urbanization, or infrastructure projects that contribute to economic expansion but disregard their environmental impact. This approach often involved relaxed regulations, insufficient enforcements of environmental standards, and a lack of emphasis on sustainable practices.

From 2007 to 2012, PM_{2.5} levels changed smoothly and exhibited a decreasing trend after 2013, indicating that local governments in the region were seriously executing policies to protect the environment and achieve sustainable economic development, such as implementing stringent emission standards, upgrading coal-fired power plants, promoting clean energy, enforcing vehicle emission controls, improving industrial pollution control, engaging in regional air quality cooperation, and raising public awareness and participation. The spatial distribution map of PM_{2.5} also reflects, to some extent, the selective execution strategies of local governments in the region when it came to selecting industries with high PM_{2.5} pollution levels (Figure 4).

Undoubtedly, the findings of this paper demonstrated the simultaneous presence of actual execution and selective execution. Additionally, it was observed that the PM_{2.5} centers shifted in a northwestern direction between 2000 and 2020, suggesting that regions in this particular direction experienced elevated levels of air pollution (Figure 5a). The results of this study revealed that certain local governments in the YREB opted for active execution in terms of PM_{2.5} pollution prevention and control. Conversely, other governments in the YREB prioritized the development of industries associated with high PM_{2.5} pollution, disregarding the environmental consequences.

5. Conclusions

This study employed remote-sensing inversion of PM_{2.5} data and land-use-change data in a long time series to analyze the spatio-temporal evolution characteristics of the decoupling between land-use intensity and PM_{2.5} in the YREB using Mean Center Change analysis and the Tapio Decoupling Model. The main conclusions were as follows:

- (1) During 2000–2021, the mean value of PM_{2.5} decreased by 11.77 µg/m³ from 39.91 µg/m³ to 28.14 µg/m³. The high values of PM_{2.5} were mainly distributed in the three major urban agglomerations, also including the whole areas of Jiangsu and Anhui. In contrast, low PM_{2.5} values were mainly distributed the Yunnan, Guizhou, and western Sichuan plateau areas with low population densities and relatively unconventional economic developments.
- (2) During 2000–2021, the PM_{2.5} centers moved in a northwestward direction, indicating that areas in this direction had high levels of air pollution. The central spatial trajectory of the LUI shifted southeast, indicating that a consistent trend in human activities such as urbanization and industrialization spread towards the southeast over time.
- (3) During 2000–2021, the mean value of the LUI increased from 3.73 to 3.92 by 0.19. The high values of the LUI were primarily concentrated in three major urban agglomerations, as well as the entire regions of Jiangsu and Anhui. In contrast, low LUI values were mainly located in western Sichuan, Yunnan, Guizhou, western Hubei, and other areas with many mountain ranges, uneven terrains, and inconvenient transportation systems.
- (4) During 2000–2021, the desired levels of decoupling between LUI and PM_{2.5} were classified into two types in most regions of YREB: strong negative decoupling and negative decoupling. These accounted for 71.12% and 24.86%, respectively, indicating rapid urbanization and industrialization in most regions, along with a significant decrease in PM_{2.5}.

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Data Availability Statement: PM_{2.5} data were downloaded from <https://weijing-rs.github.io/product.html> (accessed 6 January 2023), with a cell size of 1000 m × 1000 m, and the time span was from 2000 to 2021. Land-use/cover maps data included nine land-use/cover types as follows, cropland, forest, shrub, grassland, water, snow/ice, barren, impervious, and wetland, with a cell size of 30 m × 30 m, downloaded from <https://zenodo.org/record/5816591#.Y-si3HZBxPZ> (accessed on 6 January 2023), and the time span was from 2000 to 2021.

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