Environmental regulation of PM2.5 in urban green vegetation and the influence of green technology progress based on remote sensing image

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Abstract
In the face of increasingly serious environmental problems, Chinese governments at all levels have issued a series of regulatory measures for energy conservation and emission reduction. The rational use of science and technology can not only improve environmental quality but also promote rapid economic development. In order to encourage and guide the development of green technology and drive the collaborative progress of preventive technology and processing technology, it is necessary to develop the green technology progress-oriented function of environmental regulation and explore the transmission mechanism. This paper analyzes the relationship between environmental regulation policy and green technology progress. The results show that environmental regulation policy is an effective way to promote the progress of green technology.; The regulation policy combination of environmental tax and environmental subsidy can effectively improve social welfare, which is embodied in the increase of output, the reduction of production cost, and the reduction of pollution caused by the coordinated progress of pollution prevention technology and pollution treatment technology. Through the means of spatial planning, we can provide the construction ideas with urban characteristics for the ecological city represented by vegetation coverage. We can improve the urban greening by inserting green in the cracks; we can also build various types of large-scale urban green belts by increasing urban farmland, so as to improve the construction of urban ecosystem.

Keywords Remote sensing image · Urban environment · Vegetation coverage · Green technology

Introduction
Environmental regulation can not only focus on pollution itself but ignore the development of economic guidance function of environmental regulation (Buchholz et al. 2010). The key to solve the problem of environmental pollution lies in technological progress, which is the policy guidance and focus of environmental regulation (Keeratikasikorn 2018). In accordance with the changing trend of environmental regulation, it should gradually change to market incentive policy and from post event governance to pre prevention, so that the short-term and long-term, mandatory and incentive, and local and holistic environmental regulation can be effectively taken into account (Chakraborty et al. 2017). The green technology progress-oriented environmental regulation policy can make the enterprise production process and pollution control well combined, take the promotion of pollution prevention technology progress and pollution treatment technology progress as the guiding goal, and form a joint force to promote enterprise emission reduction and enhance the green competitiveness of enterprises (Lee 2014; Fan and Liu 2018). From the development trend of international environmental protection science and technology, western countries should pay more attention to the dual control of source collection and end treatment than China (Agarwal et al. 2002). China has caught up with the achievements of western industrialization in the past few decades, which will inevitably cause a series of ecological and environmental problems. The root cause is that the extensive and inefficient growth mode has not been transformed into intensive, efficient, and green growth mode (Bei et al. 2017).
If we take technical measures from the root and integrate green technology into the industry, we can fundamentally eliminate the ecological problems such as environmental pollution (Kassomenos et al. 2003). According to the provisions of the national development plan, to build an ecological civilization city, we must rely on science and technology to break through the bottleneck of resources and environment (Al-Dousari and Pye 2005). Science and technology should focus on environmental protection, support scientific innovation, vigorously promote innovation of sustainable development, control and monitor early warning technology, improve the process of green development, and strengthen the technical system of pollution prevention and control, so as to improve the urban ecological environment Tim wa. Therefore, the state should attach great importance to the role of technological progress in industrial upgrading and environmental governance.

**Research status of environmental regulation and green technology progress**

As for the impact of environmental regulation on the progress of green technology, foreign scholars have systematically studied the relationship between the two from the theoretical aspect, and the “following cost theory” and “Porter hypothesis” of neoclassical school are the most popular. The neoclassical school thinks that the production technology of enterprises is difficult to change in the short term (Al-Hemoud et al. 2018). The implementation of environmental regulation will internalize the externality of the environment into the production cost of enterprises, resulting in “crowding out effect,” and have a negative impact on the progress of green technology. Gray JC, Branlund R, Kriitrom B, and others supported the above theory. New Keynesianism has made some expansion on the basis of Porter’s hypothesis and thinks that in order to achieve the goal of green technology progress by encouraging enterprises to invest in innovation, it is necessary to use environmental regulation policies to avoid enterprises’ high aspirations in decision-making (Haiduc et al. 2007).

Based on the above theories, Chinese scholars have carried out concrete empirical research. This paper studies the relationship between the level of environmental regulation and the innovation ability of China’s manufacturing industry and finds that the impact of environmental regulation level on the innovation ability of China’s manufacturing industry mainly depends on the pollution degree of the manufacturing industry. Based on the panel data of 271 cities in China, Xu Jihong found that environmental regulation can bring positive impact on technological innovation, but the impact is regional. Some scholars have studied the adaptability of environmental regulation in the progress of green technology (Fleming et al. 2012). Lu Ming and Feng Hao found that too high level of environmental regulation will lead to the transfer of polluting enterprises, resulting in “bottom to bottom competition.” Only appropriate environmental regulation policies can promote the progress of green technology (Ashrafi and Hoshyaripour 2010). In the mathematical model, Yao Xiaojian found that the comparison between the cost of environmental regulation and the compensation effect of new technology has a direct impact on the progress of green technology, because when the cost of environmental regulation is less than the compensation effect of new technology, enterprises will carry out technological innovation. Lin Chunyan and Gong Xiaohui found that only when the environmental regulation reaches a certain intensity can it promote the local green technology progress, and the impact on the neighboring areas will be significant only within 400 km. Dong Zhiqing found that environmental regulation does not necessarily stimulate the local green technology progress, but shows an inverted “U” type relationship that first suppresses and then promotes. Based on the macro and micro perspective, Zhang Jie found that the impact of environmental regulation on green technology progress presents a “U” type relationship.

In short, scholars at home and abroad have actively explored the relationship between environmental regulation and green technology progress, thus providing a useful reference for the study of environmental regulation and green technology progress, but the relevant conclusions have not yet reached an agreement. Therefore, it is necessary to do further research. In addition, the measurement of green technology progress is mostly based on the decomposition of global Malmquist-Luenherger index (Yasmeen 2010; Rolph et al. 2017). However, the index uses a single co-production frontier to measure production efficiency without considering regional heterogeneity. Due to historical and geographical reasons, China’s economic development varies greatly in different regions. It is difficult to accurately analyze the efficiency and technological changes of each production unit in different regions by using a single co-production frontier. Therefore, green technology is decomposed by referring to the Metafront index of ODH regional technology differences the index of progress.

**Mechanism analysis of environmental regulation on green technology progress**

**Positive mechanism of environmental regulation on green technology progress**

The implementation of environmental regulation policy will increase the R & D investment of enterprises, thus increasing the production cost of enterprises. However, with the increase of environmental regulation, in the long run, enterprises will be encouraged to improve and innovate production process or
production technology to meet the standards of environmental regulation, which will not only reduce part or completely offset the extra production costs but also promote the progress of green technology of enterprises (Stein et al. 2015). In addition, the implementation of environmental regulations will affect the decision-making of enterprises. Specifically, the increase of environmental regulation intensity will increase the entry threshold of pollution-intensive enterprises. On the one hand, it limits the expansion of pollution-intensive industries and reduces the pollution emissions in economic activities; on the other hand, market entry barriers formed by environmental regulations will make the production factors that should flow into pollution-intensive industries turn to other low pollution technology intensive industries, which can greatly improve the utilization efficiency of resources.

Negative mechanism of environmental regulation on green technology progress

According to the view of neoclassical school, in order to meet the regulatory standards, enterprises need to purchase new sewage equipment, pay environmental taxes, purchase emission rights, etc., which will inevitably increase production costs and squeeze the funds for new technology research and development, which is not conducive to the progress of green technology of enterprises. In addition, the implementation of environmental regulation reduces the competitive pressure of enterprises. In addition, the implementation of environmental regulations will affect the decision-making of enterprises. Specifically, the increase of environmental regulation intensity will increase the entry threshold of potential pollution-intensive enterprises, thus weakening the innovation power of existing pollution-intensive enterprises, which will not be conducive to the progress of green technology of enterprises. Shimadera et al. (2013) proposed that the pressure of China’s environmental regulation, in order to reduce the cost of pollution control, enterprises will transfer their factories to other areas, which will reduce the proportion of national economy, which is obviously not conducive to the development of science and technology and economy in China. Through the analysis of the above mechanism, it is found that the ultimate impact of environmental regulation on green technology progress is not simply a linear promotion or inhibition problem, but a game of positive and negative effects.

Materials and methods

Data source and preprocessing

This paper mainly uses remote sensing data to collect the images of August 23, 1989, August 12, 1999, July 1, 2010, and September 6, 2017. Then according to the needs of the study, the cultivated land, woodland, grassland and water area were classified. The sources of land use data are land use data of 1989, which are classified by SVM method, and the overall classification accuracy is about 86%; the land use data of 2000, 2010, and 2017 are all from the Chinese Academy of Sciences; and the evaluation accuracy can reach more than 85%, which has been widely used in the regional and urban spatial pattern change experiments. Since there were no MODIS data with the same date as TM data in 1989 and 1999, only MODIS land surface temperature products with the same date as Landsat data in 2010 and 2017 were downloaded in this study. In ENVI 5.0, the atmospheric correction, geometric correction, image reduction, and other expected processing are completed, and the root mean square error of geometric correction should be controlled within 0.5. Landsat5, Landsat7, and Landsat8 image data with good quality were selected for research (Table 1, Fig. 1).

Calculation formula of vegetation coverage

The regional spatial distribution model of vegetation coverage is a combination of linear model and square model. These two regional spatial distribution models are both pixel bisection spatial distribution models of NDVI:

$$FR_{GI} = \frac{NDVI_{I} - NDVI_{O}}{NDVI_{O} - NDVI_{I}}$$

$$FR_{CR} = \left(\frac{NDVI_{I} - NDVI_{O}}{NDVI_{O} - NDVI_{I}}\right)^2$$

where \(FR_{GI}\) is the regional spatial distribution model, abbreviated as CR, and NDVI is the normalized vegetation regional index. The research results of domestic and foreign scholars show that the Fr of GI model is overestimated in low vegetation coverage area; Cr model overcomes the overestimation problem of GI model in low vegetation coverage area, but it lacks Fr underestimate problem in high vegetation coverage area. Therefore, in order to overcome the error that CR model will evaluate GI model as vegetation information in the process of square operation, this paper combines the two models, namely GC model:

$$GC = \begin{cases} CR_{GI} \geq O \\ GI_{GI} < O \end{cases}$$

Verification of vegetation coverage data

In order to verify the accuracy of vegetation coverage, the vegetation coverage data is obtained from the 1:500 scale topographic map, and the vegetation coverage topographic map is taken as the verification data. According to the corresponding spatial resolution of remote sensing image on 1:500 topographic map, the grid
The vegetation coverage of grid is analyzed, and the vegetation coverage matrix and the evaluation map of vegetation coverage image are constructed (Fig. 2).

It can be seen from Table 2 that with the gradual increase of the spatial resolution, the area of the full coverage area is constantly shrinking. When the full coverage area disappears, the spatial resolution just reaches the maximum value; when

![Fig. 1 Overall process of data processing](image)

**Table 1** Classification accuracy evaluation of land cover types

| Year | Features       | Vegetation | Accuracy /% | Classification accuracy% |
|------|----------------|------------|-------------|--------------------------|
| 1989 | Vegetation     | 103        | 14          | 88.03                    |
|      | Nonvegetation  | 8          | 25          | 75.76                    |
| 2000 | Vegetation     | 92         | 7           | 92.93                    |
|      | Nonvegetation  | 4          | 47          | 92.16                    |
| 2009 | Vegetation     | 82         | 6           | 93.18                    |
|      | Nonvegetation  | 7          | 55          | 88.71                    |
| 2019 | Vegetation     | 71         | 4           | 94.67                    |
|      | Nonvegetation  | 3          | 72          | 96                       |

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the minimum and maximum value of vegetation coverage gradually shrink, the areas of low coverage area and medium high coverage area gradually expand. In the process of micro coverage and high coverage area from small to large, its area is also increasing, until it reaches the maximum value, it begins to decrease gradually. Therefore, it can be seen that the scale effect seriously affects the area change of vegetation coverage.

Vegetation coverage evaluation index based on remote sensing

System deviation

The system deviation is the overall difference between the estimated vegetation coverage image and the reference image. The smaller the value, the smaller the difference degree. The ideal value is 0.

\[
SD = \frac{1}{MN} \sum_{r=1}^{M} \sum_{c=1}^{N} \left| Fr(r,c) - Fr(r,c) \right|
\]  

Root mean square error

Root mean square error (RMSE) reflects the difference between the estimated image and the reference image.

\[
RMSE = \sqrt{\frac{1}{M} \sum_{r=1}^{M} \sum_{c=1}^{N} \left( Fr(r,c) - Fr(r,c) \right)^2 / MN}
\]  

Table 2  Statistical table of vegetation coverage classification at different spatial resolutions

| Section | 1m     | Area (m²) | 4m     | Area (m²) | 10m    | Area (m²) | 15m    | Area (m²) | 30m    | Area (m²) |
|---------|--------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|-----------|
| 0       | 258 124| 258 124   | 12 490 | 199 840   | 1 275  | 127 500   | 418    | 94 050    | 69     | 62 100    |
| (0.0,0.1)| 6 148  | 6 148     | 1 683  | 26 928    | 544    | 54 400    | 277    | 62 325    | 60     | 54 000    |
| [0.1,0.3)| 7 384  | 7 384     | 1 772  | 28 352    | 553    | 55 300    | 288    | 64 800    | 100    | 90 000    |
| [0.3,0.5)| 6 617  | 6 617     | 1 639  | 26 224    | 488    | 48 800    | 326    | 73 350    | 124    | 111 600   |
| [0.5,0.7)| 6 706  | 6 706     | 1 454  | 23 264    | 481    | 48 100    | 259    | 58 275    | 80     | 72 000    |
| [0.7,1.0)| 13 749 | 13 749    | 3 001  | 48 016    | 768    | 76 800    | 363    | 81 675    | 67     | 60 300    |
| 1       | 151 272| 151 272   | 6 011  | 96 176    | 391    | 39 100    | 69     | 15 525    | 0      | 0         |
vegetation coverage area from the Third Ring Road to the sixth ring road was the largest; on September 8, 2019, the vegetation coverage area within the third ring road was the largest (Table 3).

**Analysis of the development and change of urban land cover types**

Comparing the area change process of urban land cover types from 1989 to 2019, the results are shown in Table 4 and Fig. 3. The vegetation coverage in the sixth ring road is only 42.87%, of which 33.55% of the vegetation coverage is converted to other land coverage, and the land coverage unchanged is only 17.36% (Figs. 4, 5, 6, 7, 8, 9, and 10). The area covered by the vegetation unchanged from the second ring to the third ring is only 5.45%, and the fifth ring to the sixth ring is 52.57%. Among the areas where the land cover was changed, the second to third ring roads lost 9.98% of the land area, the third to fourth ring roads lost 25.98% of the land area, and the fourth to fifth ring roads lost 36.32%. The 5th to 6th ring road lost 36.23% of the land area. The conversion of other land cover within the fourth ring road to vegetation cover has improved significantly. For example, the area within the second ring road accounts for 10.68%, the area from the second ring road to the third ring road accounts for 14.85%, and the area from the third ring road to the fourth ring road accounts for 10.68% and 13.65%. From Table 4, it can be seen that most of the land area in the second ring road is the unchanged area of other land cover; the area of other land from the second ring to the third ring converted into vegetation is more than the area converted from vegetation cover to other land cover. From the third ring to the fourth ring, the unaltered area of other land covers in the ring accounted for 50.72%, while 25.59% of the land area was converted from vegetation cover to other land cover. The proportion of vegetation from the fifth ring to the sixth ring was converted to other land cover. Among them, the fifth to sixth ring is 36.55%, and the reserved vegetation coverage area is very limited, accounting for only 52.85%.

| Position                  | August 16, 1989 | September 16, 2000 | September 8, 2009 | September 4, 2019 |
|---------------------------|-----------------|--------------------|-------------------|-------------------|
|                           | Area (km²)      | Coverage (%)       | Area (km²)        | Coverage (%)      |
| Within the second ring    | 4.22            | 6.74               | 7.30              | 11.67             |
| Second ring to third ring | 15.09           | 15.69              | 15.62             | 16.24             |
| Third ring to fourth ring | 51.70           | 36.01              | 36.05             | 25.11             |
| Fourth ring to fifth ring | 239.66          | 65.69              | 185.68            | 50.90             |
| 5th to 6th ring           | 1431.77         | 89.40              | 1240.09           | 77.43             |
| Total                     | 1742.44         | 76.80              | 1484.74           | 65.45             |
while the area from the third ring to the fifth ring is shrinking, indicating that human activities have moved out. The conversion from other land cover to vegetation cover has almost increased from the second ring to the third ring and the fourth ring to the sixth ring. Only the third ring to the fourth ring does not change significantly. This shows that most areas of the city are improving greening, but the green area is very limited. The area of the overall land cover within the sixth ring road has not changed significantly compared with the previous period, and it has shrunk from the city center; but compared with the continuous increase outside the third ring road in 1984–1995, the area within the third ring road continues to decrease, especially from the third ring road to the unchanging area of the fifth ring. Land cover has increased a lot, indicating that human-made development and construction activities have seriously interfered with the urban layout.

**Changes in urban vegetation coverage at the beginning of the twenty-first century**

It can be seen from Table 7 that from 1995 to 2004, the total vegetation coverage within the sixth ring road decreased by

| Position                  | The vegetation coverage has not changed | Conversion of vegetation to other land cover | Conversion of other land cover to vegetation | Other land cover remains unchanged |
|---------------------------|----------------------------------------|---------------------------------------------|---------------------------------------------|----------------------------------|
|                           | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) |
| Within the second ring    | 3.17       | 5.07            | 1.05       | 1.68            | 6.32       | 10.68           | 52.05    | 83.19            |
| Second ring to third ring | 5.68       | 5.45            | 9.41       | 9.98            | 13.58      | 14.85           | 67.53    | 70.22            |
| Third ring to fourth ring | 14.97      | 10.43           | 36.74      | 25.98           | 19.17      | 13.65           | 72.64    | 50.72            |
| Fourth ring to fifth ring | 105.07     | 28.80           | 134.60     | 36.32           | 33.72      | 9.24            | 91.21    | 28.90            |
| 5th to 6th ring           | 846.35     | 52.57           | 585.42     | 36.23           | 57.05      | 3.56            | 111.80   | 6.98             |
| Total                     | 975.24     | 42.87           | 767.22     | 33.55           | 129.84     | 5.72            | 395.23   | 17.42            |
10.16%, leaving only 37.84% of the vegetation coverage, although the conversion of other land coverage into vegetation coverage increased by 3.12%. However, the remaining area of other land coverage also increased by 7.23%, indicating that the total vegetation coverage area within the sixth ring road is still shrinking. The loss of vegetation coverage from the fourth ring to the sixth ring road is more serious, with the largest loss being about 12. 10% of the vegetation coverage from the fifth ring to the sixth ring road. Compared with the previous period, when the area covered by vegetation was transformed into the area covered by other land, the loss of vegetation coverage in the third ring road was more than the loss of vegetation coverage in the third ring to the sixth ring, indicating the urbanization in the third ring road. The process of urbanization is much faster than the urbanization process outside the third ring road, but the degree of greening inside the third ring road is not as good as that outside the third ring road, and the loss of vegetation coverage within the third ring road cannot be compensated. Other unchanged conditions of land coverage show that the city continues to expand outward from the city center,
but the expansion trend from the third ring to the fifth ring is slow. In the past 10 years, the area covered by vegetation within the second ring road has continued to expand, and the area covered by vegetation within the second ring road to the third ring road has increased slightly during this period. The change trend of land cover area from the third ring to the sixth ring is similar. The area where vegetation cover remains unchanged and the area where other land cover is converted into vegetation are gradually slowing down, but the area where other land cover remains unchanged is gradually expanding, especially from the fourth ring to the unaltered area of other land covering the fifth ring road is over 48.12%, and the unaltered area of other land covering the fifth ring to the sixth ring road is over 25.71%.

Spatial correlation analysis of corporate green technological progress

Moran’I index is usually used to test whether the variables are spatially correlated, and the formula is as follows:

Fig. 6 Changes in vegetation coverage within the sixth ring road in a certain place from 1984 to 2019
Fig. 7 Changes in urban vegetation cover in the 1990s
Fig. 8 Urban vegetation cover changes at the turn of the century especially from the fourth ring to the unaltered area of other land covering the fifth ring road is over 48.12%, and the unaltered area of other land covering the fifth ring to the sixth ring road is over 25.71%.
Fig. 9 Changes in urban vegetation cover at the beginning of the twenty-first century
In the formula, \( n \) represents 280 prefecture-level cities, \( W_{ij} \) is the spatial weight matrix, and \( X \) and \( Y \) are the variable value and the variable mean value, respectively. The results are divided into three possibilities. If it is greater than 0, there is a positive spatial correlation; if it is less than 0, it means that there is a negative spatial correlation; if it is equal to 0, there is no spatial correlation. Table 8 records the Moran' I spatial index of green technology progress. The green technology progress index is below 1% except in 2006, which is a positive spatial correlation. This shows that we need to use spatial measurement methods to regress the model analysis.

**Discussion**

**Comparison of vegetation cover changes and related research**

Based on remote sensing image data, the changes in urban vegetation cover over the past 30 years have been studied and analyzed. The results found that the increase in the area covered by vegetation within the fourth ring road is very consistent with the results of the study, which shows that human production and life have seriously affected the area covered by urban vegetation, affecting the urban ecological environment and the degree of urban greening, so we need to improve the city. To improve the greening of the ecological environment, it is necessary to use science and technology to carefully plan the vegetation coverage area and to rationally plan human production and life to reduce the impact of human activities on the urban ecological environment.

![Fig. 10 Analysis of Moran’ I index of green technology progress](image-url)

**Table 5** Changes in urban vegetation coverage in the 1990s

| Position            | The vegetation coverage has not changed | Conversion of vegetation to other land cover | Conversion of other land cover to vegetation | Other land cover remains unchanged |
|---------------------|----------------------------------------|--------------------------------------------|---------------------------------------------|----------------------------------|
|                     | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) |
| Within the second ring | 3.37  | 5.39          | 0.85      | 2.75          | 3.93      | 6.28          | 54.44      | 77.56          |
| Second ring to third ring | 6.02  | 6.26          | 9.07      | 8.23          | 9.60      | 9.98          | 71.50      | 64.23          |
| Third ring to fourth ring | 21.54 | 15.00         | 30.17     | 23.26         | 14.49     | 11.23         | 77.32      | 63.75          |
| Fourth ring to fifth ring | 153.62 | 42.11         | 86.04     | 24.76         | 31.91     | 8.75          | 93.02      | 25.50          |
| 5th to 6th ring      | 1188.21 | 78.63         | 243.56    | 15.21         | 51.30     | 3.20          | 117.55     | 7.34           |
| Total               | 1372.76 | 65.23         | 369.69    | 18.52         | 111.23    | 5.23          | 413.83     | 18.24          |
Analysis of the driving forces of vegetation cover changes

Changes in vegetation coverage caused by policy guidance

Due to urban expansion and population growth, the urban ecological environment has been damaged to a certain extent. In order to improve the urban ecological environment and other issues, the municipal party committee and municipal government of this place have started an artificial forestation project in the plain area since 2013. The positive effect of this project is immeasurable, and more importantly, it has increased the area of urban greening and the vitality of the city. As of 2015, the city has successfully afforested more than 650 million trees and constructed 11,023 forest landscapes, and its forest coverage area has increased by 10.32%.

The impact of urbanization process on vegetation coverage

After 1988, the process of urbanization in this area has been accelerating, and the proportion of land use in this area has been increasing. According to research, from 1988 to 1997, the built-up area of the area increased to 38.42 km²/a. In 1990, in response to the Asian Games, the fourth and fifth ring roads were built; from 1997 to 2006, the city promulgated land resources. The protection policy has slowed down the process of urban land use; from 2005 to 2012, affected by the 2008 Olympic Games in the area, the land area expanded at a rate of 65.39 km²/a. Before 2000, the urbanization of this city was mainly concentrated in Haidian, Chaoyang, Fengtai, and other areas. However, with the advancement of urbanization, urban construction continues to expand outward, resulting in the continuous reduction of the vegetation coverage of the fifth ring to the sixth ring. However, with the advancement of urbanization, urban construction continues to expand outward, resulting in the continuous reduction of the vegetation coverage of the fifth ring to the sixth ring, which is very consistent with the research results. It can be seen from this that urban development must start with optimizing the internal land structure of the city and coordinate the development of the three major spaces of production, life, and ecology. Urban construction land should focus on revitalizing the stock. The construction land should not be expanded uncontrollably. The

| Table 6 | Changes in urban vegetation cover at the turn of the century |
| --- | --- |
| Position | The vegetation coverage has not changed | Conversion of vegetation to other land cover | Conversion of other land cover to vegetation | Other land cover remains unchanged |
| | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) |
| Within the second ring | 5.61 | 8.97 | 1.69 | 2.70 | 4.53 | 7.24 | 50.76 | 81.13 |
| Second ring to third ring | 10.07 | 10.47 | 5.55 | 5.77 | 10.32 | 10.73 | 70.26 | 73.06 |
| Third ring to fourth Ring | 15.99 | 11.14 | 20.06 | 13.97 | 14.47 | 10.08 | 93.05 | 64.81 |
| Fourth ring to fifth ring | 108.97 | 29.87 | 76.71 | 21.03 | 33.19 | 9.10 | 146.00 | 46.72 |
| 5th to 6th ring | 918.53 | 57.35 | 321.56 | 20.08 | 102.48 | 6.40 | 258.95 | 16.17 |
| Total | 1059.17 | 46.81 | 425.57 | 18.76 | 164.99 | 7.27 | 619.02 | 27.56 |

| Table 7 | Changes in urban vegetation coverage at the beginning of the twenty-first century |
| --- | --- |
| Position | The vegetation coverage has not changed | Conversion of vegetation to other land cover | Conversion of other land cover to vegetation | Other land cover remains unchanged |
| | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) | Area (km²) | Percentage (%) |
| Within the second ring | 6.41 | 10.24 | 3.73 | 5.96 | 3.08 | 4.92 | 49.37 | 78.90 |
| Second ring to third ring | 11.56 | 12.02 | 8.84 | 9.19 | 7.70 | 8.01 | 68.11 | 70.82 |
| Third ring to fourth ring | 18.11 | 12.61 | 12.36 | 8.61 | 16.05 | 11.18 | 97.07 | 67.61 |
| Fourth ring to fifth ring | 92.80 | 25.44 | 49.36 | 13.53 | 46.11 | 12.64 | 176.60 | 48.78 |
| 5th to 6th ring | 724.73 | 45.25 | 296.29 | 18.50 | 179.09 | 11.18 | 401.42 | 25.71 |
| Total | 853.61 | 37.84 | 370.58 | 16.33 | 252.03 | 11.11 | 792.57 | 34.94 |
development intensity should be set scientifically according to the natural conditions of the region. While urban construction, the urban ecological environment should also be taken into account.

**Green technology progress-oriented environmental regulation strategy**

According to the previous analysis, the effects of different environmental regulatory policies on technological progress under different conditions present differences or uncertainties. Here we mainly discuss the policy effect on environmental regulation from the perspective of green technology progress and choose a policy application strategy with strong universality.

From the perspective of pollution prevention technology progress, the policy effects of environmental taxes and environmental subsidies are more complex and uncertain. This may be due to the relative progress in pollution prevention technology (productive technology progress), and the progress in pollution treatment technology is not an industrial pursuit of enterprises primary tendency of technological progress. When the government implements normal environmental subsidies, if the scale of enterprise pollution treatment R&D is small and environmental R&D funds are sufficient, the positive effect of environmental subsidy pollution treatment technology progress is obvious, but the increase in environmental taxes will increase corporate costs and is not conducive to pollution treatment technology progress. Even so, the environmental tax policy still has a certain degree of technical protection; that is, certain pollution treatment technologies can be maintained or renewed when the increase in environmental tax has adverse technical effects. Only when the scale of enterprise pollution treatment R&D is very small, the effect of environmental tax policy has great uncertainty. Therefore, in this situation, the government can try to apply environmental subsidies to the environmental protection industry and guide companies through environmental tax policies to outsource pollution treatment to third-party governance; if the company has sufficient R&D funds for pollution treatment, environmental taxes and environmental subsidy policies can optimize pollution treatment. The allocation of R&D funds has a positive effect on the progress of pollution treatment technology. Environmental subsidy policies can cooperate with environmental tax policies, so that the R&D expenditure saved by optimizing the allocation of funds will not be reduced excessively, thus playing a good supplementary role. When the government implements excessive environmental subsidies, if the enterprise pollution treatment R&D scale is small, the environmental tax policy effect is better, and the environmental subsidy effect will be more uncertain; if the enterprise pollution treatment R&D scale is large, the environmental tax policy will not have a positive effect on the progress of pollution treatment technology. If the company has bad motives to defraud environmental subsidies, if the scale of enterprise pollution treatment R&D is very small, the environmental tax policy will not have a positive effect on the progress of pollution treatment technology. If the company has bad motives to defraud environmental subsidies in the name of expanding pollution treatment R&D, then the company must have a reasonable explanation for the effect of the defrauded environmental subsidies. Therefore, environmental subsidies are only available to the company. The pollution treatment R&D will only promote the progress of pollution treatment technology when the scale of pollution treatment is very large. Therefore, in this case, the government should cancel the excess subsidy, use the excess environmental subsidy for environmental protection industry, and use the environmental tax policy to outsource the pollution treatment process. Tripartite governance fosters the environmental protection “third-party governance” market.

### Table 8 2003–2016 Moran’ I index of green technology progress

| Year | I   | Z   | E(I) | sd(I) |
|------|-----|-----|------|-------|
| 2003 | 0.016*** | 3.830 | −0.004 | 0.005 |
| 2004 | 0.018*** | 4.147 | −0.004 | 0.005 |
| 2005 | 0.010*** | 2.520 | −0.004 | 0.005 |
| 2006 | 0.002    | 1.042 | −0.004 | 0.005 |
| 2007 | 0.024*** | 5.171 | −0.004 | 0.005 |
| 2008 | 0.013*** | 3.180 | −0.004 | 0.005 |
| 2009 | 0.019*** | 4.377 | −0.004 | 0.005 |
| 2010 | 0.009*** | 2.473 | −0.004 | 0.005 |
| 2011 | 0.020*** | 4.551 | −0.004 | 0.005 |
| 2012 | 0.039*** | 8.111 | −0.004 | 0.005 |
| 2013 | 0.039*** | 8.191 | −0.004 | 0.005 |
| 2014 | 0.039*** | 8.076 | −0.004 | 0.005 |
| 2015 | 0.071*** | 14.181| −0.004 | 0.005 |
| 2016 | 0.090*** | 17.752| −0.004 | 0.005 |
In summary, there is a universal application strategy for the policy portfolio of environmental regulation oriented to green technological progress: while the government implements a gradually strict environmental tax policy, it also implements normal environmental subsidies and uses excess subsidies for support environmentally friendly “third-party governance” market. Such a market-based policy combination has a positive effect of technological progress, which can not only promote the progress of pollution control technology of industrial enterprises, but also promote the progress of independent pollution control technology of industrial enterprises. At the same time, it expands the effect of “third party governance”, promotes the development of environmental protection industry, and improves the overall level of environmental protection technology.

Conclusion

Through the establishment of a game model to analyze the relationship between environmental regulations and green technology progress, the results confirmed that environmental regulation policies are an effective way to promote green technology progress; environmental subsidies have a certain positive impact on the technology of environmental regulation policies; environmental taxes and the regulatory policy combination of environmental subsidies can effectively improve social welfare, which is specifically reflected in the increase in output, the reduction of production costs, and the reduction of pollution through the coordinated progress of pollution prevention and pollution treatment technologies. Therefore, the government should gradually establish and improve the green financing market, implement the corporate environmental R&D statistical accounting system, strengthen financial investment in green technology research and development, encourage and guide the public to actively participate in the development of green science and technology, and use the progress of green technology to improve the construction of urban ecological environment.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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