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Simulation of the Impact of Urban Forest Scale on PM_{2.5} and PM₁₀ based on System Dynamics

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Abstract: In the context of ecological civil construction in China, afforestation is highly valued. Planting trees can improve air quality in China's large cities. However, there is a lack of scientific analysis quantifying the impact urban forest scale has on the air quality, and what scale is advisable. The problem still exists of subjective decision-making in afforestation. Similar studies have rarely analyzed the long-term effect research of urban forests on air improvement. Using as an example, the city of Wuhan, this paper identifies the regularity between particulate matter concentration and adsorption of sample leaves, and establishes a system dynamics model of "economy, energy and atmospheric environment." By combining this regularity with the model, the long-term impact of forest scale on particulate matter and atmospheric environment was simulated. The results show that if the forest coverage rate reaches at least 30%, the annual average concentrations of inhalable particulate matter (PM₁₀) and fine particulate matter (PM_{2.5}) can both reach the Grade I limit of national Ambient Air Quality Standard by 2050. The current forest cover is 22.9% of the administrative area. Increasing the forest cover by 600 km² would increase this percentage to 30% of the total area. In the long run (by the year 2050), however, we showed that this increase would only reduce the annual concentration of PM_{2.5} and PM₁₀ by 1–2%. Therefore, about 90% of the concentration reduction would still rely on the traditional emission reduction measures. More other ecological functions of forests should be considered in afforestation plan.

Keywords: particulate matter; forest cover; system dynamics; Wuhan

1. Introduction

Particulate matter (PM), including the inhalable particulate matter (PM₁₀) and fine particulate matter (PM_{2.5}), is harmful to human health [1]. In particular, PM_{2.5} has a greater negative impact on human health. PM_{2.5} can float in the atmosphere for a long time and spread on a large scale via atmospheric circulation [2]. Moreover, the large specific surface area of PM_{2.5} allows it to easily adsorb heavy metals and toxic organic compounds, enter the human respiratory system, penetrate into the alveoli via blood, and subsequently, cause various illnesses, such as cardiovascular disease, respiratory disease, lung cancer or other diseases [3–5]. For every 10 µg/m³ increasing in PM_{2.5}, the death rate from cardiovascular disease and lung cancer increases by 6–8% [6]. Afforestation can play an important role in mitigation of PM pollution [7–9], aside from reducing emissions at the source [10]. China is now vigorously promoting the construction of an ecological civilization, where afforestation is highly

valued. In recent years, the municipal government of Wuhan city has invested 2 billion Chinese Yuan (CNY) which equals to 282 million USD in afforestation every year to extensively carry out planting activities and project construction [11]. But after communicating with the staff of Wuhan Garden and Forestry Bureau, we found that the afforestation process has problems with subjective decision-making.

In regard to the influence of trees or forests on PM, different kinds of studies have been conducted. One type of research focuses on physical processes, exploring the adsorption process and effect of vegetation on PM [7]. This type of research includes the net particle accumulation of different tree species [12,13], effects of leaf surface structures or surface morphological features on PM adsorption [5,14], main influencing factors of PM retention of different trees in different wind environments [9], PM removal processes of leaves of different tree species under different rainfall patterns [15], etc. Another type of research simulates and calculates the amount of PM removal within a certain area and the forest's environmental health value [16]. The aspects of both include PM retention by roadside trees and optimization strategies for tree-planting patterns [17,18], PM adsorption capability of urban tree cover [19–21], impacts of spatial heterogeneity of trees on air pollution [22], the impact of tree cover on PM_{2.5} and its health value evaluation [4,23–25]. The related studies cover many aspects of trees and PM removal from different objectives.

However, from the view of eco-environmental planning (ecological environmental planning is usually stressed to carry out necessary simulations and propose development strategies or solutions according to the current situation), there is a lack of comprehensive dynamic simulations and solutions. Few studies have taken into consideration the long-term state changes and impacts of forests on PM in the context of sustainable development [26]. This is a dynamic and interdisciplinary system, which requires the establishment of a quantitative systematic dynamic model of "society, economy and environment" to avoid PM generation, change its concentration and establish a pollution reduction mechanism.

Several examples demonstrate that system dynamics (SD) is suitable to simulate such a comprehensive system. A SD model was proposed in order to estimate the behavior of parameters affecting air pollution in Tehran, including two subsystems: urban transportation and air polluting industries [27]. Xing et al. built an economy–resource–environment system by SD and evaluated its coordination level of immense significance for sustainable urban development [28]. A sustainable use model of water resources was split into five subsystems: economy, population, water supply and demand, land resources, and water pollution and management [29]. Moreover, we previously established the dynamic transformation relationship between the annual average concentration of PM and its precursor emissions, and simulated the interaction between the economic, energy and atmospheric environment [30]. It can simulate the changes of various variables; calculate the time when PM₁₀ and PM_{2.5} concentrations reach the standard; facilitate macro prediction and analysis; and improve the research efficiency [31]. It is an ideal "laboratory" for complex systems [32,33].

Therefore, in this paper, we try to answer the following questions through modelling and analysis: when the air quality can reach an acceptable standard in the process of urban development, how great is the effect of urban forests on improving urban air quality; what impact does having no trees, or more trees, have on air quality; and what scale of forest is recommended? As an example of Wuhan city, we identify the regularity between PM concentration and adsorption of sample leaves, and establish the SD model of "economy, energy and atmospheric environment." By combining this regularity with the SD model, the 2016–2050 impacts of forest scale on PM and atmospheric environment under different scenarios are simulated based on the current sustainable development trend. The paper aimed to find a long-term effect of forests on air quality, propose a better scale of forest cover and provide a suggestion for an urban greening plan.

2. Methods

2.1. Study Area and Data

Wuhan city, the capital of Hubei province, is at the intersection of Yangtze River and Han River in central eastern China, with a total administrative area of 8569 km² (Figure 1) and a population of 11.08 million, as of 2018. Wuhan has a prominent strategic position and is expected to become a national center city in the future. However, the current air quality in Wuhan is still poor. The annual average PM_{2.5} concentration is 49 µg/m³ in 2018, almost 50% higher than the Grade II limit of national Ambient Air Quality Standard (35 µg/m³) (GB3095-2012), which is worse than most cities in China [34]. To build a healthy, green and livable city is the long-term goal of Wuhan's future development [35].

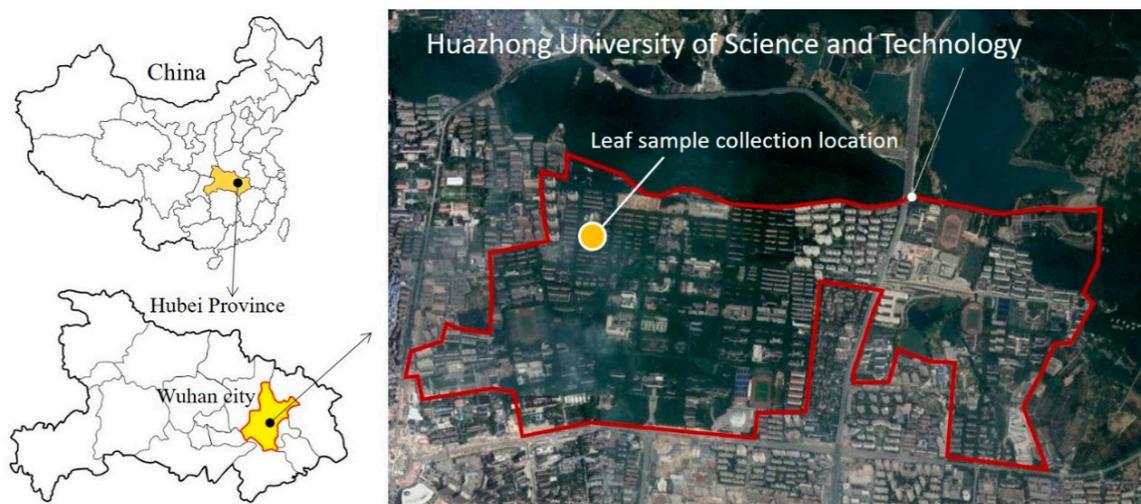


Figure 1. Leaf sample collection location.

The data to be used in the research (in 2016) include:

1. Socio-economic data: GDP (primary, secondary and tertiary production) and energy consumption (coal, oil products, gas and non-fossil energy consumption);
2. Atmospheric environment data: PM₁₀, PM_{2.5} annual concentration; SO₂, NO_x, VOCs, NH₃, PM₁₀ and PM_{2.5} emissions; and atmospheric chemical compositions of PM₁₀ and PM_{2.5};
3. Development goals: social, economic, energy, environment, garden, industry, agriculture, urban development and other 13th Five-year Plan goals; Wuhan 2049 Vision;
4. Urban forest-related data: forest coverage area, coverage rate, PM₁₀ and PM_{2.5} adsorption per unit area of forest.

2.2. Statistic Regularity between PM Concentration and Adsorption by Leaves

2.2.1. Leaf Sample Collection

Leaf sample collection is aimed at analyzing the relationship between PM concentration and adsorption on leaves per unit time, which is the key to setting the variables and supporting the subsequent simulation in SD.

Evergreen leaves have a better PM adsorption than fallen leaves [25]. According to a survey of plant diversity in Wuhan city [36], two kinds of evergreen broad-leaved trees (*Cinnamomum Camphor* and *Magnolia Grandiflora*), which are the most popular trees and convenient to collect, were selected as the research subjects. Elements such as weather, location, time, duration and tree species were taken into account in sample collection.

Location and Time of Sampling

We chose non-street trees in Huazhong University of Science and Technology (Figure 1). The trees were far away from the influence of road dust, which can better reflect the PM adsorption capability of leaves in the overall pollution background during a period of 20 days from 11–30 May 2019.

Leaf Quantity Collection

About 20 *Cinnamomum Camphor* leaves (2–3 branchlets) were collected each time, and every 10 leaves were taken as one sample, a total of two samples. Four leaves of *Magnolia Grandiflora* were collected, and two leaves were taken as a sample, a total of two samples. The leaves were gently placed into a plastic bag for storage. The amount of leaves can meet the requirements of the experiment.

Measure of Leaf's Floated PM

The PM was observed to be “floated PM” or “deposited PM” on the leaves. A floated PM means that the PM that is attached to the leaf surface and is easy to wash off with water. In contrast, the deposited PM has attached to the leaf surface for a long time and could not be easily washed away. As deposition is a time-related and complex process, it is hard to know how long the deposited particles were attached for, but we tried to analyze the time the floated ones were.

The floated PM was filtered by filter paper during gently washing the dust on the leaves. Then, the filter paper was dried and weighed with electronic analysis balance (precision 0.1 mg). The weight difference between filter paper after drying (W_1 is the weight of filter paper and PM) and filter paper before filtering (W_0 is the filter paper self-weight) is the PM adsorption ($W_1 - W_0$).

2.2.2. A Comparison of PM Concentration and Adsorption by Leaves

PM₁₀ and PM_{2.5} adsorption were estimated at 50% and 95% of the measurement of floated PM respectively [37–39]. Thus, analysis between PM concentrations and their adsorptions was conducted correspondingly.

Correlation between PM Concentration and Leaf PM Adsorption

The higher the concentration, the higher the PM adsorption on leaves [13,14]. But concentration is a time-dependent value, and the accumulated duration time of floated PM is vague [15]. Therefore, we assumed that the duration time was 1 day, 2 days or 3 days respectively, and analyzed the correlation between background concentration of different time and the amount of floated PM to identify for how long the floated PM on the leaf accumulates.

Estimation on the Amount of PM Adsorbed by Green Leaves Per Unit Area

The Equation (1) was adopted to estimate the hourly PM adsorption per unit area of tree cover. The reason why the hourly PM retention should be determined is that the concentration is measured once per hour, and the daily or yearly value is the 24-h or 365-day average value, which is a mean instantaneous value. Thus, the retention, no matter if it is a day, a few days or longer, is a time-related and cumulative amount, and the two (‘concentration and adsorption’) should scale correspondingly with time duration.

$$M_{PM} = \frac{W_{PM} \times n \times H}{D} \quad (1)$$

where W is PM adsorption by sample leaves (g), M is the amount of PM adsorption per unit area ($\text{g m}^{-2} \text{h}^{-1}$), H is the effective height of tree's foliage quantity (m), n is a multiple of sample leaf quantity per cubic meter (m^{-3}) and D is the duration of PM retention by sample (h).

Linear Correspondence of PM₁₀ and PM_{2.5} Concentration and Adsorption

With PM₁₀ or PM_{2.5} concentration as the independent variable (X) and the corresponding adsorption per unit area of green leaves as the dependent variable (Y), the scattered diagram of ‘concentration–adsorption’ was drawn (Equation (2)). Then, calculated the regression coefficient to establish the equation and test the regression equation.

$$Y = aX + b \quad (2)$$

The expected result in this part was that the PM₁₀ and PM_{2.5} adsorption would decrease with the decrease of background concentration, and the fitted regression curve would reflect the statistical feature. If an apparent exception appeared, possible problems in sample processing were examined and data with significant differences were excluded.

2.3. SD Model and Scenarios

2.3.1. System Analysis

Many factors, like industrial production, energy consumption and environmental governance, will have impacts on atmospheric environment and PM concentration. The system boundary of the SD model involves urban energy consumption, industrial production, the atmospheric environment and forest scale.

Economic Subsystem

Under the city’s development background, economic condition is the driving factor of the model. Industrial structure and emission per unit of polluting GDP determine the initial atmospheric emission status in the model. According to the social and economic development plan, the primary, secondary and tertiary production and their growth rate will be set. Over time, the industrial structure has been continuously optimized with the proportion of the secondary decreasing and the tertiary increasing. The emission per unit GDP, air pollutants and PM concentration will have been continuously reduced.

Energy Subsystem

Energy consumption determines emission level. With the optimization of the energy structure, the proportion of clean energy use will increase to reduce emissions from the source and reduce PM concentration.

Environmental Subsystem

Discharged pollutants are reduced through a series of end-treatment measures, including controlling various pollutant emissions, improving the management system and legal system, strengthening the supervision, etc. Additionally, large areas of tree cover can intercept and absorb PM. The basic systematic causal relationship is illustrated in Figure 2.

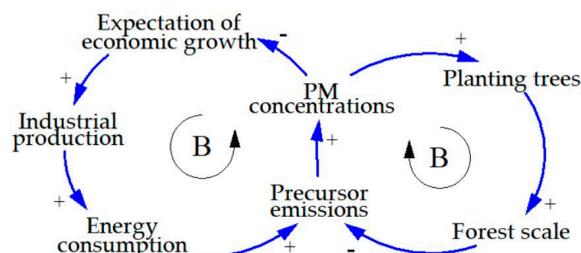


Figure 2. Systematic causal diagram. B represents balance, which has a negative feedback loop. “+” is reinforcement and “-” is balance.

2.3.2. Variables and SD Flows

From the perspective of variable function of SD model, it has five categories: state, rate, auxiliary, constant and control variables. Figure 3 is the simplified SD flow diagram of economic, energy and the environmental (including urban forest) systems, which generalizes the basic feedback relationship of all variables in the model. State variables include: three industrial productions, pollutant discharged volumes, PM₁₀ and PM_{2.5} concentrations and energy consumptions. Main control variables include: industrial growth rates, energy growth rates, emission control factors, contribution rates of various precursors of PM₁₀ and PM_{2.5}, etc. Their values were set comprehensively with the relevant plan objectives. A rate variable can change the state variable stock. Auxiliary variables are also very important. They connect other variables in the model and change under the influence of other variables. A constant is a stable objective quantity, or a quantity that does not change in a simulation. In the model operation, all variables and values will feedback dynamically (for variables, see Appendix B, Table A3). Key auxiliary variables, in value, are changed under other variable changes. They are the important nodes that connect subsystems in series. Key nodes and the corresponding equation numbers in the model are illustrated in Figure 3.

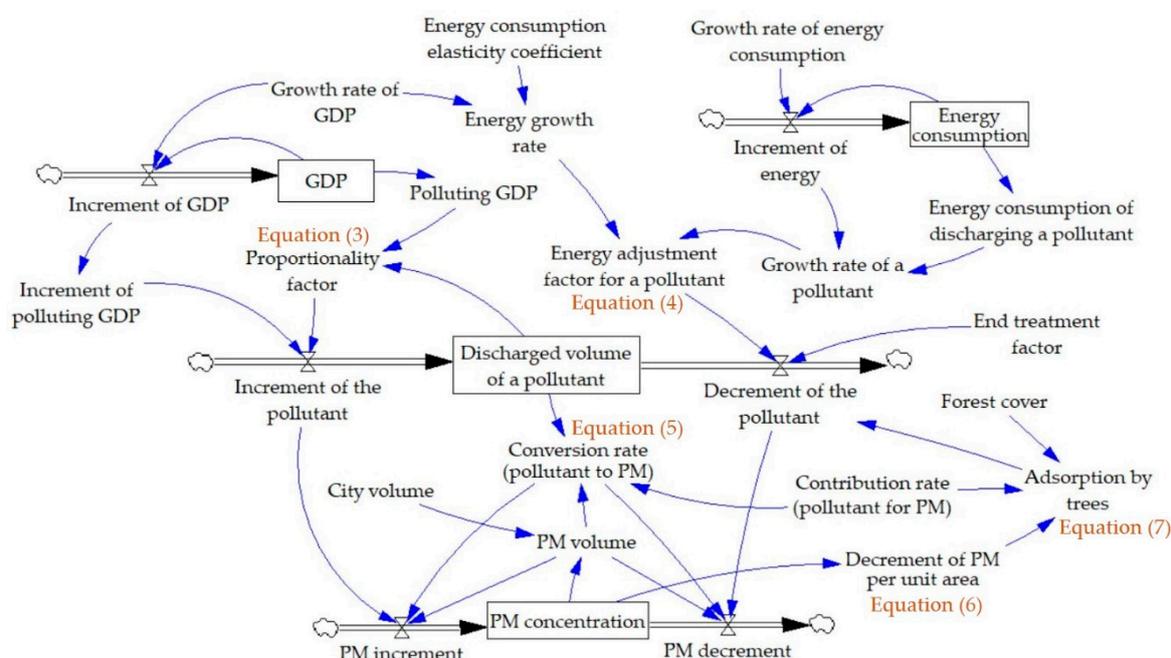


Figure 3. Simplified system dynamics (SD) flow diagram. It generalizes the actual complex model which can be seen in Appendix B. In this figure, the “Discharged volume” includes six air pollutants; i.e., SO₂, NO_x, VOCs, NH₃, primary PM_{2.5} and primary PM₁₀. “Energy consumption” has four resources; i.e., coal, gas, petroleum and non-fossil energy. “GDP” is composed of the primary, secondary and tertiary production. Additionally, PM concentration includes PM_{2.5} and PM₁₀ concentrations. They are classified as internal and external sources of PM concentrations.

Proportionality Factor

The proportionality factor is a specific air pollutant discharged volume per billion CNY of GDP. Its function is to convert the increment of GDP to the increment of a discharged volume quantitatively in a SD model dynamic simulation. The mathematical expression is shown as Equation (3), where *i* refers to a pollutant. Polluting GDP refers to the part of GDP producing emissions.

$$\text{Proportionality Factor}(i) = \frac{\text{Discharged volume}(i)}{\text{Polluting GDP}} \quad (3)$$

Energy Adjustment Factor

The energy adjustment factor is a ratio of the energy use after adjusting the energy structure and before adjusting it to the base year. The mathematical expression is shown as Equation (4), where, i stands for a specific air pollutant; ε is the energy consumption elasticity coefficient; and $r(GDP)$ is the growth rate of GDP.

$$\text{Energy adjustment factor}(i) = 1 - \frac{1 + r(i)}{1 + \varepsilon \times r(GDP)} \quad (4)$$

Conversion Rate

The conversion rate refers to the ratio of the contributed component derived from the annual discharged volume of a specific air pollutant to PM_{10} or $PM_{2.5}$ volume and this discharged volume itself. In the SD model, this variable is a very important auxiliary one that constructs a link between the annual discharged volume and the annual PM_{10} or $PM_{2.5}$ concentration in the quantitative relationship. The conversion rate is based on statistical data and does not have any actual physical and chemical significance, and it is only in the service for the SD model. The mathematical expression is shown as Equation (5), where, i is a pollutant and PM Volume is the mass of PM_{10} or $PM_{2.5}$ existing over the city in the average state. Contribution rate indicates a pollutant to PM_{10} or $PM_{2.5}$ determined by chemical composition.

$$\text{Conversion rate}(i) = \frac{\text{PM Volume} \times \text{Contribution rate}(i)}{\text{Discharged volume}(i)} \quad (5)$$

Adsorption by Trees

In SD model, six precursor air pollutants should be considered. According to the regularity in Section 2.2, we set a variable named Decrement per unit area of PM_{10} or $PM_{2.5}$, which represents the reduction of unit area in different PM concentrations (Equation (6)). Then, Equation (7) is for the adsorption levels of different pollutants. The a is the same coefficient in Equation (2), and i stands for a pollutant.

$$\text{Decrement per unit area} = a \times \text{Concentration} \quad (6)$$

$$\text{Adsorption}(i) = \text{Forest cover} \times \text{Contribution rate}(i) \times \text{Decrement per unit area} \quad (7)$$

2.3.3. Differentiation of Internal and External Sources of PM Concentration

The study target of the model was the whole area of Wuhan city. Industrial, energy structure optimization and environmental-end treatment were all urban internal actions. As PM pollution is not only from internal sources, external influence should not be ignored. We tried to solve the problem according to the research by Xue [40], by indicating the ratio of internal and external sources of $PM_{2.5}$ of all provinces and key city cases in China. Wuhan contributed 60% as internal sources and 40% was from external sources. The ratio of PM_{10} is 70% from internal and 30% from external sources. Therefore, the average annual concentration of PM can be decomposed in the model. The internal PM concentration can be predicted in the city according to Wuhan development goals, and the external can be predicted according to the national macro goals, such as the national 13th Five-year Environmental Plan. The sum of the two concentrations is the average annual concentration of PM. In addition, the influence by tree quantity and quality on the concentration from external sources will also be reflected in the model.

2.3.4. Model Tests

Model test included a syntax check, model check, unit check, reality check and sensitivity analysis. The emphasis is on the reality check and sensitivity testing, which determine the availability of the model.

1. Reality check. Wuhan's earliest available data about PM_{2.5} is from 2012, so GDP and PM₁₀ were used in the model test for verification (because PM_{2.5} and PM₁₀ are significantly correlated). The initial values of GDP and PM₁₀ in the SD model were the data in 2001. The growth rate of industrial GDP, the growth rate of energy consumption and the end treatment factor of emission reduction were all based on the historical growth and reasonable estimation. The tested trend of GDP and PM₁₀ concentration from 2001 to 2015 was simulated and then checked with the real value.
2. Sensitivity analysis. This refers to an uncertainty analysis that the degree of change in certain factors impact on one or a set of key indicators from the view of quantitative analysis. The industrial structure adjustment can influence on the simulation of the whole model, which can reflect the sensitivity of the model to a large extent. Therefore, we selected the coefficients of 'polluting GDP' in the economic subsystem, that is, α_2 and α_3 for sensitivity test, and adjusted one parameter at a time in a certain reasonable range. By the way, α_1 corresponds to agriculture, whose scale and influence are too small to analyze.

2.3.5. Scenarios Settings

Three scenarios were set up for the simulation: "non-forests, current forests and increased forests" with coverage rates of 0%, 22.88% and 30% respectively. The pollution emissions; social and economic development; air conditions; and PM adsorption by trees was simulated from 2016 to 2050 under the current sustainable development trend. Through the scenario simulations we tried to predict the time that the air quality of PM can reach the standard and how much effect of different forests on PM reduction will be.

3. Results

3.1. Regularity Between PM Concentration and Adsorption by Leaves

As already stated, leaves were collected during a period of 20 days from May 11 to May 30 in 2019, with the exception of the rainy days on 12, 15, 25, 26 and 30. The PM₁₀ and PM_{2.5} adsorptions by two kinds of trees were estimated at 95% and 50% of the sample weight measured, and the adsorption of the overall sample was estimated at the mean adsorption of the two kinds of leaves.

Based on Equation (1), the PM adsorption per unit area (M-PM) can be calculated by sample weight (W-PM). (1) *Cinnamomum camphor*. The newly planted trees were young and small. The tree height was 5 m (up to the quality standard of third types of arbor trees) [41]; the effective height of tree canopy was 3 m; and the leaf quantity per cubic meter was 10 times that of the sample. (2) *Magnolia grandiflora*. Tree height was 5 m; the effective height of the canopy was 3 m; and the leaf quantity per cubic meter was 15 times that of the sample. Therefore, M-PM can be calculated (Appendix A, Tables A1 and A2). For example, the sample adsorption weight of PM_{2.5} in *Cinnamomum camphor* leaves was 0.0023 g. Since it was the cumulative amount of one day, 0.0023 g was divided by 24 h, which corresponds to the unit time of PM_{2.5} concentration monitoring. Then, according to the volume of leaves, the sample size was multiplied by 30 to get 0.0029 g/m², which represents the PM_{2.5} capacity of *Cinnamomum camphor* leaves with canopy cover per unit area (1 m²) per unit time (1 h).

From Tables A1 and A2, the correlations between the average PM₁₀ of the overall sample (M-PM₁₀) and the PM₁₀ concentrations over the last 3 days, the last 2 days and the given day were 0.7284, 0.7422 and 0.7769 respectively. Similarly, the correlations of PM_{2.5} were 0.6914, 0.7338 and 0.7951. The adsorption of overall samples showed strong positive correlations with PM₁₀ and PM_{2.5}

concentrations on the given day, indicating that the higher probability of floated PM on the leaf surface was accumulated on one day (within 24 h), and the longer or shorter the time, the lower the correlation was.

On this basis, the linear correspondences of the ‘concentration–adsorption’ of PM₁₀ and PM_{2.5} can be obtained according to Equation (2) (Figure 4). (1) The linear correspondence between PM₁₀ concentration and adsorption on *Cinnamomum camphor* leaf was $Y = 0.00004X$, and that between PM₁₀ concentration and *Magnolia grandiflora* was $Y = 0.0001X$. The linear regression between PM₁₀ concentration and the overall level per unit area was $Y = 0.00009X$ (Figure 4a–c). (2) the regularities between PM_{2.5} concentration and *Cinnamomum camphor*, *Magnolia grandiflora* and the overall level were $Y = 0.00004X$, $Y = 0.0002X$ and $Y = 0.0001X$ (Figure 4e–f).

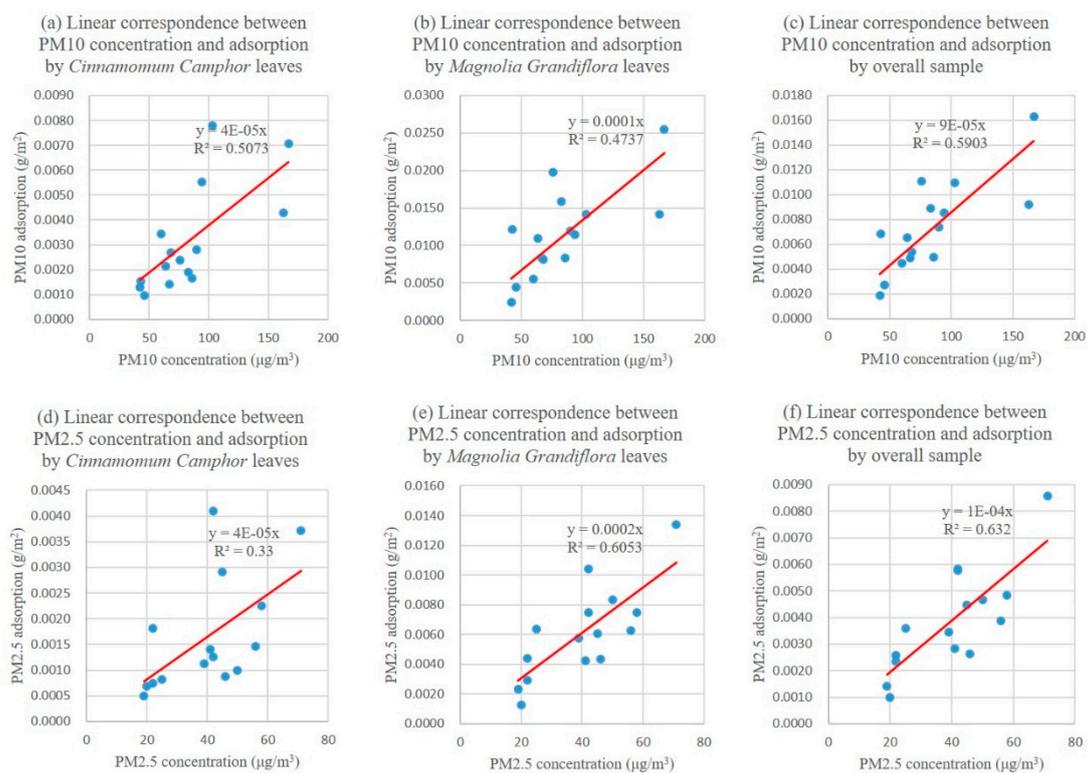


Figure 4. Regularities between inhalable particulate matter (PM₁₀) and fine particulate matter (PM_{2.5}) concentrations and adsorption by leaves.

3.2. SD Model Tests

3.2.1. Reality Check

The test results show (Figure 5) that the maximum error between the real and simulated GDP was -10.1% , the minimum error was 0.5% , the average error rate was -1.4% and the correlation coefficient $r = 0.99$. The maximum error of PM₁₀ concentration was -20.2% , the minimum error was -0.8% , the average error rate was -2.5% and the correlation coefficient $r = 0.75$. The forecast accuracy and correlation of GDP and PM₁₀ were good, and the result of model reality check was reasonable.

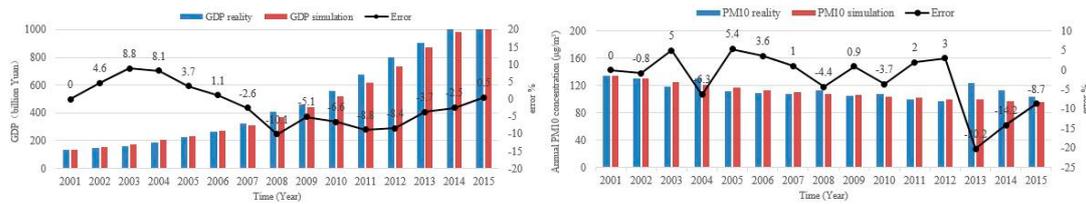


Figure 5. Reality check (GDP and PM₁₀ concentration).

3.2.2. Sensitivity Analysis

The weight coefficient of polluting GDP ($\alpha_2 = 0.8$ in Basic Group) was adjusted to 0.9 and 0.7 respectively in test Group 1 and Group 2, with the change ranges of 12.5% and -12.5% . In Group 1, the predicted PM_{2.5} concentration changes were -0.6% in 2030 and -1.5% at the end of 2050 compared to Basic Group. In Group 2 it changed 0.6% and 2.0 % correspondingly. In the other test, the value of α_3 ($\alpha_3 = 0.1$ in Basic Group) was adjusted to 0.15 and 0.2 in test Group 1 and Group 2, increasing the range of 50% and 100%. In Group 1, the predicted PM_{2.5} concentration changed 2.0% and 7.1% in 2030 and 2050 compared to the Basic Group. In Group 2, it changed 4.1% and 13.2% correspondingly (Table 1).

Table 1. Sensitivity analysis results.

Group	α_2 in Polluting GDP				α_3 in Polluting GDP			
	Coefficient Value	Change (%)	PM _{2.5} (µg/m ³) Change in 2030	PM _{2.5} (µg/m ³) Change in 2050	Coefficient Value	Change (%)	PM _{2.5} (µg/m ³) Change in 2030	PM _{2.5} (µg/m ³) Change in 2050
Basic	0.8	0%	34.2	19.6	0.1	0	34.2	19.6
Test 1	0.9	12.5%	34.0 (-0.6%)	19.3 (-1.5%)	0.15	50%	34.9 (2.0%)	21.0 (7.1%)
Test 2	0.7	-12.5%	34.4 (0.6%)	20.0 (2.0%)	0.2	100%	35.6 (4.1%)	22.2 (13.2%)

From the sensitivity analysis results (Table 1), the change rate of the predicted PM_{2.5} result was far less than the adjustment range of the coefficient for a simulation period of 15 to 35 years. Therefore, the stability of the complex system is good.

3.3. SD Model Prediction and Analysis

- S1: Non trees. If there are no trees, the PM₁₀ concentration is simulated to be 47.47 µg/m³ in 2035 and 35.45 µg/m³ in 2050. The average annual concentration of PM_{2.5} will reach 33.25 µg/m³ in 2035 and 25.58 µg/m³ in 2050. In this scenario, both PM₁₀ and PM_{2.5} will reach the Grade II limit of national Ambient Air Quality Standard (GB3095-2012) by 2035, but PM_{2.5} will not reach Grade I by 2050.
- S2: Current forests. The urban forest area will not change in the future, and the annual PM₁₀ concentration will reach 36.38 µg/m³ in 2035 and 22.91 µg/m³ in 2050. The average annual concentration of PM_{2.5} will reach 25.25 µg/m³ in 2035 and 15.91 µg/m³ in 2050. Under the effect of current trees, PM₁₀ could reach the Grade I limit by 2035, but PM_{2.5} could closely achieve it by 2050.
- S3: Increased forests. An additional 600 km² of forests was added; the average annual PM₁₀ concentration will reach 34.87 µg/m³ by 2035 and 21.80 µg/m³ by 2050. The average PM_{2.5} concentration will reach 23.98 µg/m³ in 2035 and 14.75 µg/m³ in 2050. Under the effect of additional trees, PM_{2.5} could reach the Grade I by 2050.

By 2035, the PM₁₀ concentration in S2 will be 11.09 µg/m³ lower than that in S1, and 10.66% better in the air quality. S3 will be 1.51 µg/m³ lower than that in S2 and be better 1.45%. By 2050, PM₁₀ concentration in S2 will be 12.54 µg/m³ lower than that in S1, and be better 12.06%. S3 will be 1.11 µg/m³ lower than that in S2, and be better 1.07%. Similarly, in 2035, the PM_{2.5} concentration in S2 will be lower by 8.00 µg/m³ than in S1, and the corresponding air quality improves by 11.43%. It will be

lower by $1.27 \mu\text{g}/\text{m}^3$ in S3 than that in S2, and the improvement is 1.81%. By 2050, $\text{PM}_{2.5}$ concentration in S2 will drop more by $9.67 \mu\text{g}/\text{m}^3$ than S1 and improved by 13.81%. It will be lower by $1.16 \mu\text{g}/\text{m}^3$ in S3 than that in S2, and improved by 1.66%.

In S2, the PM concentration in the city is decreased, and the yearly PM absorption of forest per unit area is also decreasing. In the years of 2016–2020, the average urban forest can remove the pollution emissions of SO_2 , NO_x , VOCs, NH_3 , primary $\text{PM}_{2.5}$ and primary PM_{10} in amounts: 2.83, 2.31, 4.43, 1.45, 1.58 and 2.93 tons, respectively. By 2050, their removal amounts will be 0.24, 1.01, 1.58, 0.77, 0.17 and 0.24 tons. In S3, the average annual reduction of the six pollutants before 2020 is 3.05, 2.53, 4.85, 1.60, 1.70 and 3.15 tons, respectively, and by 2050, the reduction is 0.31, 1.27, 1.99, 0.97, 0.21 and 0.31 tons, respectively. Therefore, S3 is a better state of urban development. By 2050, both PM_{10} and $\text{PM}_{2.5}$ can reach the Grade I limit, and the forest scale is recommended to reach at least 2570 km^2 .

However, it should be noted that the effect of added forests on the improvement of PM concentration is actually small, only about 1–2%, about 90% of which comes from the source control. The results revealed that the overall effect of trees on air quality is limited. Much of the improvement in air quality depends on emission reductions, not on the trees (Figure 6).

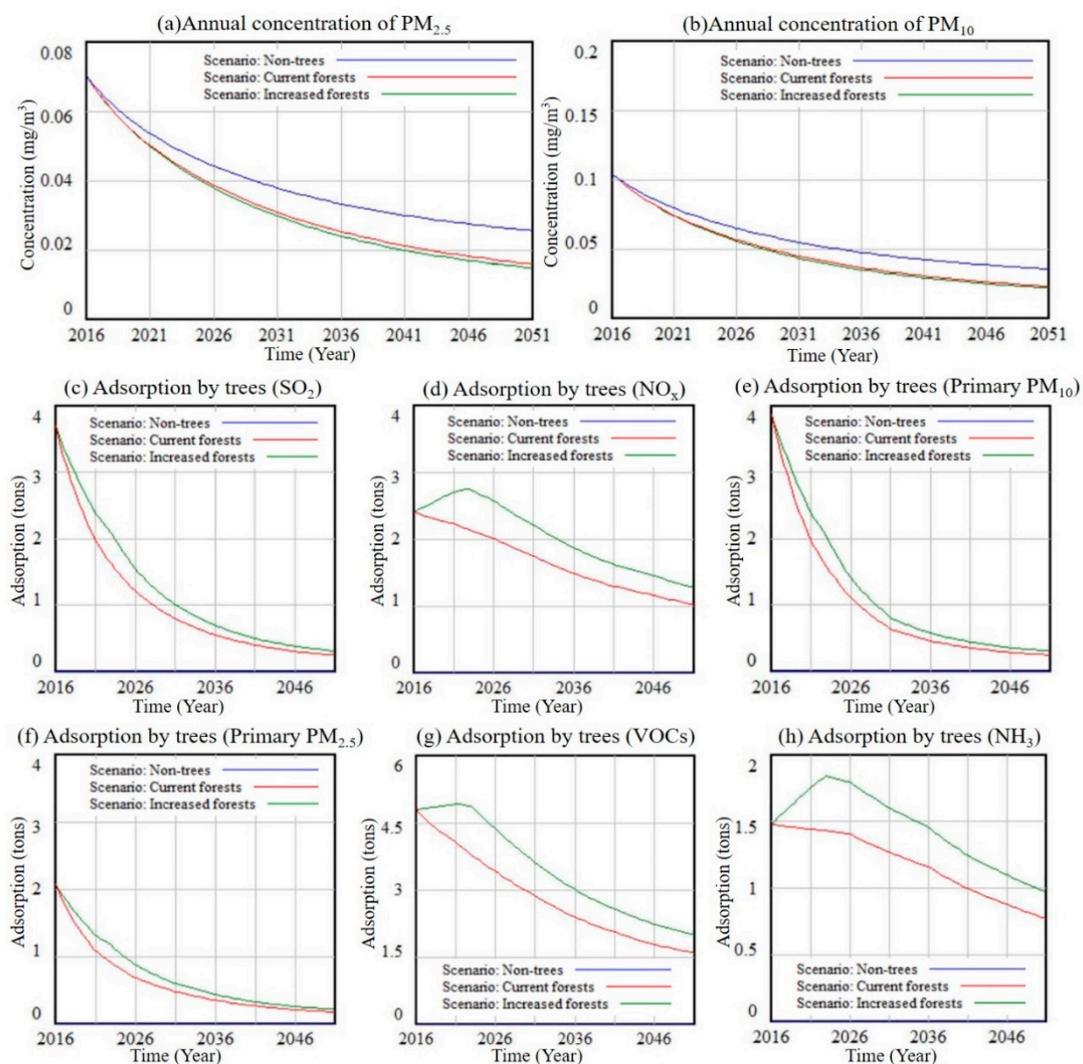


Figure 6. Environmental effects of three forest scales on particulate matters and air pollutants. (a) Annual concentration of $\text{PM}_{2.5}$; (b) Annual concentration of PM_{10} ; (c) Adsorption by trees (SO_2); (d) Adsorption by trees (NO_x); (e) Adsorption by trees (Primary PM_{10}); (f) Adsorption by trees (Primary $\text{PM}_{2.5}$); (g) Adsorption by trees (VOCs); (h) Adsorption by trees (NH_3).

4. Discussion

4.1. Uncertainty Analysis

Due to the complexity of the system and the long period of time from 2016 to 2050, there are inevitable estimation errors when setting the parameters of control variables. The basic rule for setting these parameters is based on current planning with a sustainable development trend. There are two kinds of key settings of variables that need to be properly discussed.

Decrement per unit area. This refers to the PM adsorption by trees per unit area. The physical process of adsorption is complex. Different regions, time, climatic conditions, vegetation species, etc., may lead to value of the variable changing observably. What samples to collect and how to measure the PM adsorption on leaf are worth discussing.

Tree species in Wuhan, are 53% deciduous trees, and the scale of sycamore trees is second only to *Cinnamomum camphor* trees [36]. However, deciduous trees usually shed their leaves in the heavily polluted autumn and winter and lose the good effects of PM retention. We also found that the leaf surface of sycamore trees would adhere to a large number of villi instead of PM, which has been confirmed in the literature [42]. Therefore, we did not consider sycamores in the leaf selection. Among the common evergreen trees, we only selected the two most common trees for experimental analysis. Inevitably, from the time, batches, tree species, collecting location and other aspects, the sample of two species is limited; the results will have errors. At the same time, due to the limited samples, the statistical relationships of 'concentration–adsorption' of PM₁₀ and PM_{2.5} are worth an in-depth study.

The methods for measuring PM include the weighing method, scanning electron microscopy (SEM), particle size analysis, etc. [42]. Studies show that [43–45], the weighing method is a widely used method but may lead to a low-accuracy result. The SEM image is very clear, but the sample size selected is small, and it comes with a high cost and slow scanning speed. If the laser particle size analyzer is used, the water-soluble substances on the leaf surface particles will be washed away, causing errors in the results. In addition, SEMs and particle size analyzers interpret the adsorption capacity of leaf from the number of particles and it is difficult to determine how long the PM takes to attach. Using the weighing method can evaluate the trend and meet the needs of the research with low cost.

Parameter settings of control variables. The control variables included: industrial growth rate, energy growth rate, end-treatment factor and contribution rate of a pollutant to PM. These values of control variables were determined at the current stage by referring to the corresponding 13th Five-year Plan, while the parameters after 2020 could only be estimated. As China enters a transition stage, cities will transform from development to protection, the energy structure will be more green and economic growth will inevitably slow down. Therefore, it is expected that the pollution and intensity of end treatment will gradually decrease, and the overall environmental condition of city will be gradually improved. Additionally, Wuhan has made great efforts to reduce SO₂ emission in recent years, and it has already reached the standard. It is more difficult to control NO_x, VOCs and NH₃ that have a wide range of sources. Primary PM₁₀ and PM_{2.5} could be contained by measurements of controlling road and construction dust. Therefore, the contribution rates of SO₂, primary PM₁₀ and PM_{2.5} will drop, and the rates of NO_x, VOCs and NH₃ will rise correspondingly (specific parameter settings are available in Appendix C).

Regarding the understanding of the floated PM and deposited PM, some scholars also proposed the very similar concept, called surface PM and the in-wax PM [44,45]. But from only their descriptions in articles, it is difficult to evaluate whether the connotations are same as ours.

4.2. Innovation and Policy Implications

This study was essentially a dynamic analysis of the human–earth system reflecting the relationship and influence of urban forest scale on PM. The important innovation was to establish the integrated model based on the SD that put multi-variables together, such as particle concentration, forest impact,

emissions, social and economic factors. It simplifies the complex physicochemical processes of atmospheric transmission and diffusion with annual average values as the main modeling data, connects the quantitative conversion relationship between each subsystem and can be used to predict the state of each variable in the model. There are two kinds of key variable nodes in the model reflecting the dynamic connection. The first is the relationship between different PM concentrations and adsorption by forests, and the second is the variable of transformation from pollutant to particle concentration. The original method could be used to study the capacity and carrying capacity of atmospheric environment [30]. Forest scale is also one natural variable attributed expression of environmental carrying capacity. The SD-based method can simulate the impact of forest on air quality in the context of urban development. In terms of the research object and method, the highly related studies have not been seen yet.

At present, the Chinese government vigorously promotes ecological civil construction and green development strategies with the priority of ecological protection along the Yangtze river. The scale of afforestation and forest coverage rate will be further improved. But the scientific, systematic analysis and planning are insufficient to know how many trees should be planted and where to plant them. This study compensates for this defect by simulating the impact of different forest scales on an urban atmospheric environment in the context of comprehensive consideration of social factors. The prediction results can provide a reference for afforestation and support for the future planning.

A previous study we conducted, "GIS-Based Urban Afforestation Spatial Pattern and a Strategy for PM_{2.5} Removal," explored the impact of different distributions of newly added forests in Wuhan on PM_{2.5} and proposed suggestions [46]. One conclusion was that it is of limited significance to consider the forest distribution in city's whole administrative region with the same scale of afforestation. Therefore, the reference for this study is that the forest extent plays the main role in mitigating PM, regardless of the influence of the spatial heterogeneity of new forests.

4.3. Prospect

In view of the deficiencies mentioned above, subsequently, (1) sample collection should be increased in terms of vegetation types, batches and duration to enhance the accuracy and reliability of statistical analysis of samples [12]. (2) In addition, in the long run, once trees are planted, they are generally not replanted. Therefore, tree planting should also consider the multiple functional elements of their ecological services. This is also the research content that is expected to be further carried out in the study of forest distribution. Meerow and Newell have published an article on this subject [47]. We will constantly improve the scientific nature of forest planning.

5. Conclusions

In the context of ecological civil construction in China, afforestation is highly valued, but its planning is subjective. There is a lack of scientific analysis on what scale of urban forest should be considered to plant and how it may affect on air quality. As a case study of Wuhan, this paper modeled a 'social-economic-environmental' system based on SD to simulate the long-period impact of different urban forest scales on atmospheric environmental quality from 2016 to 2050 under a certain sustainable development trend, and we came to the following findings.

1. The amount of PM retained on leaves is proportional to the concentration, and floated and deposited PM is found on the leaves. Floated PM can be washed off, and the deposited PM is adsorbed solidly to the leaf. Furthermore, through correlation analysis, there is a high positive correlation between the floated PM₁₀, the PM_{2.5} and the corresponding average concentration on one day. Therefore, the linear correspondences of 'concentration (X)–adsorption (Y)' are conducted, that is $Y = 0.00009X$ for PM₁₀ and $Y = 0.0001X$ for PM_{2.5} according to the overall samples respectively. This provides support for the SD modeling of PM₁₀ and PM_{2.5} capacity by leaf under the change of concentration.

- Using SD is an effective way to model the dynamic human–earth system, when combined with the statistical regularity of PM adsorption by forests, in order to predict the impact of different forest scales on urban air quality. The simulation results showed if there were no trees in the city, the annual average concentration of PM₁₀ would be 10–12 µg/m³ higher than the current situation, and the annual average concentration of PM_{2.5} would be 8–10 µg/m³ higher. In the overall improvement of particle concentration, the contribution of trees accounted for was about 10%. At least 30% forest cover will help PM concentrations reach the Grade I limit of air quality standard by 2050.
- Urban forests can reduce particle pollution, and more trees are better. However, it should be recognized that 30% of the forest cover will only reduce the particulate matter concentration by 1%–2% in the long run compared with the current cover rate of 22.9% (an increased 600 km² of forest). Around 90% of the particulate matter reduction is still based on traditional measures to reduce emissions from the source. Besides, the forest’s service of air improvement and environmental purification, plus ecological services, including leisure tourism, soil and water conservation, flood storage and other functions, should be involved in the afforestation plan.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Particulate Matter Adsorption by Sample Leaves after Different Durations

Table A1. PM₁₀ adsorption by sample leaves after different durations of PM₁₀ concentration.

Time	PM ₁₀ concentration (µg/m ³)			<i>Cinnamomum Camphor</i>		<i>Magnolia Grandiflora</i>		Overall Sample	
	3day	2day	1day	W-PM10	M-PM10	W-PM10	M-PM10	W-PM10	M-PM10
May 11	75	80	94	0.0044	0.0055	0.0061	0.0115	0.0053	0.0085
May 13	125.3	141	163	0.0034	0.0043	0.0076	0.0142	0.0055	0.0092
May 14	149.6	165	167	0.0057	0.0071	0.0136	0.0255	0.0096	0.0163
May 16	89	50	68	0.0021	0.0027	0.0043	0.0081	0.0032	0.0054
May 17	58.6	72	76	0.0019	0.0024	0.0105	0.0198	0.0062	0.0111
May 18	69.3	70	64	0.0017	0.0021	0.0058	0.0110	0.0038	0.0065
May 19	61	53.5	43	0.0012	0.0015	0.0065	0.0121	0.0038	0.0068
May 20	58	55	67	0.0011	0.0014	0.0045	0.0084	0.0028	0.0049
May 21	71	85	103	0.0062	0.0078	0.0076	0.0142	0.0069	0.0110
May 22	86.6	96.5	90	0.0022	0.0028	0.0064	0.0119	0.0043	0.0074
May 23	93	88	86	0.0013	0.0017	0.0044	0.0083	0.0029	0.0050
May 24	86.3	48	83	0.0015	0.0019	0.0085	0.0159	0.0050	0.0089
May 27	33	47	42	0.0010	0.0013	0.0013	0.0024	0.0012	0.0019
May 28	35	44	46	0.0008	0.0010	0.0024	0.0045	0.0016	0.0027
May 29	49.3	53	60	0.0028	0.0034	0.0029	0.0055	0.0028	0.0045

Table A2. PM_{2.5} adsorption by sample leaves after different duration of PM_{2.5} concentration.

Time	PM _{2.5} Concentration (µg/m ³)			<i>Cinnamomum Camphor</i>		<i>Magnolia Grandiflora</i>		Overall sample	
	3 Day	2 Day	1 Day	W-PM2.5	M-PM2.5	W-PM2.5	M-PM2.5	W-PM2.5	M-PM2.5
May 11	42	48	45	0.0023	0.0029	0.0032	0.0060	0.0028	0.0045
May 13	55.6	61	58	0.0018	0.0023	0.0040	0.0075	0.0029	0.0048
May 14	64.3	64.5	71	0.0030	0.0037	0.0071	0.0134	0.0051	0.0086
May 16	46	33.5	41	0.0011	0.0014	0.0023	0.0043	0.0017	0.0028
May 17	36.3	41.5	42	0.0010	0.0012	0.0055	0.0104	0.0033	0.0058
May 18	40.6	40.5	39	0.0009	0.0011	0.0031	0.0058	0.0020	0.0034
May 19	35.3	32	25	0.0007	0.0008	0.0034	0.0064	0.0020	0.0036
May 20	28.3	23.5	22	0.0006	0.0007	0.0023	0.0044	0.0015	0.0026
May 21	29.6	32	42	0.0033	0.0041	0.0040	0.0075	0.0036	0.0058
May 22	40	49	56	0.0012	0.0015	0.0034	0.0063	0.0023	0.0039
May 23	48	51	46	0.0007	0.0009	0.0023	0.0044	0.0015	0.0026
May 24	50.6	48	50	0.0008	0.0010	0.0045	0.0083	0.0026	0.0047
May 27	19.6	16	20	0.0005	0.0007	0.0007	0.0013	0.0006	0.0010
May 28	17	19.5	19	0.0004	0.0005	0.0013	0.0023	0.0008	0.0014
May 29	20.3	20.5	22	0.0014	0.0018	0.0016	0.0029	0.0015	0.0023

Appendix B

Variables and SD Flows Diagram

Table A3. Classification of all variables in the SD model.

Subsystems	State Variables	Rate Variables	Auxiliary Variables	Constant Variables	Control Variables
Atmospheric Environment	Discharged volume of VOCs, SO ₂ , NO _x , NH ₃ , PPM _{2.5} , PPM ₁₀ ; Internal and external concentration of PM _{2.5} and PM ₁₀	Increment of VOCs, NO _x , SO ₂ , NH ₃ , PPM _{2.5} , PPM ₁₀ ; Decrement of VOCs, SO ₂ , NO _x , NH ₃ , PPM _{2.5} , PPM ₁₀ , PM _{2.5} , PM ₁₀	<Time>, Proportionality factor of SO ₂ , NO _x , VOCs, NH ₃ , PPM ₁₀ , PPM _{2.5} ; Conversion rate SO ₂ -PM _{2.5} , NO _x -PM _{2.5} , VOCs-PM _{2.5} , NH ₃ -PM _{2.5} , PPM ₁₀ , PPM _{2.5} , PM _{2.5} volume; Conversion rate SO ₂ -PM ₁₀ , NO _x -PM ₁₀ , VOCs-PM ₁₀ , NH ₃ -PM ₁₀ , City volume under boundary layer; Decrement of SO ₂ , NO _x , VOCs, NH ₃ , PPM _{2.5} , PPM ₁₀ ; Adsorption by trees (SO ₂ , NO _x , VOCs, NH ₃ , PPM _{2.5} , PPM ₁₀)	City area, Height of Boundary Layer; Forest cover	Emission reduction factor of SO ₂ , NO _x , VOCs, NH ₃ , PPM ₁₀ , PPM _{2.5} ; Contribution rate SO ₂ , NO _x , VOCs, NH ₃ , PPM _{2.5} for PM _{2.5} ; Contribution rate SO ₂ , NO _x , VOCs, NH ₃ , PPM ₁₀ for PM ₁₀
Energy	Annual consumption of coal, natural gas, petroleum, non-fossil energy	Increment of coal, natural gas, petroleum, new energy	<Time>, Energy growth rate, Energy adjustment factor of SO ₂ , NO _x , PPM _{2.5} , PPM ₁₀ , VOCs; Growth rate of NO _x , particulate matter, Energy consumption of discharging NO _x , discharging PM	Energy Consumption Elasticity Coefficient	Growth rate of coal, natural gas, petroleum, non-fossil energy
Economy	GDP of primary, secondary, tertiary industry	Increment of primary, secondary, tertiary industry	<Time>, GDP, Polluting GDP, Increment of polluting GDP, Growth rate of GDP	None	Growth rate of primary industry, secondary industry, tertiary industry

Note: PPM_{2.5} is primary PM_{2.5} and PPM₁₀ is primary PM₁₀ for short.

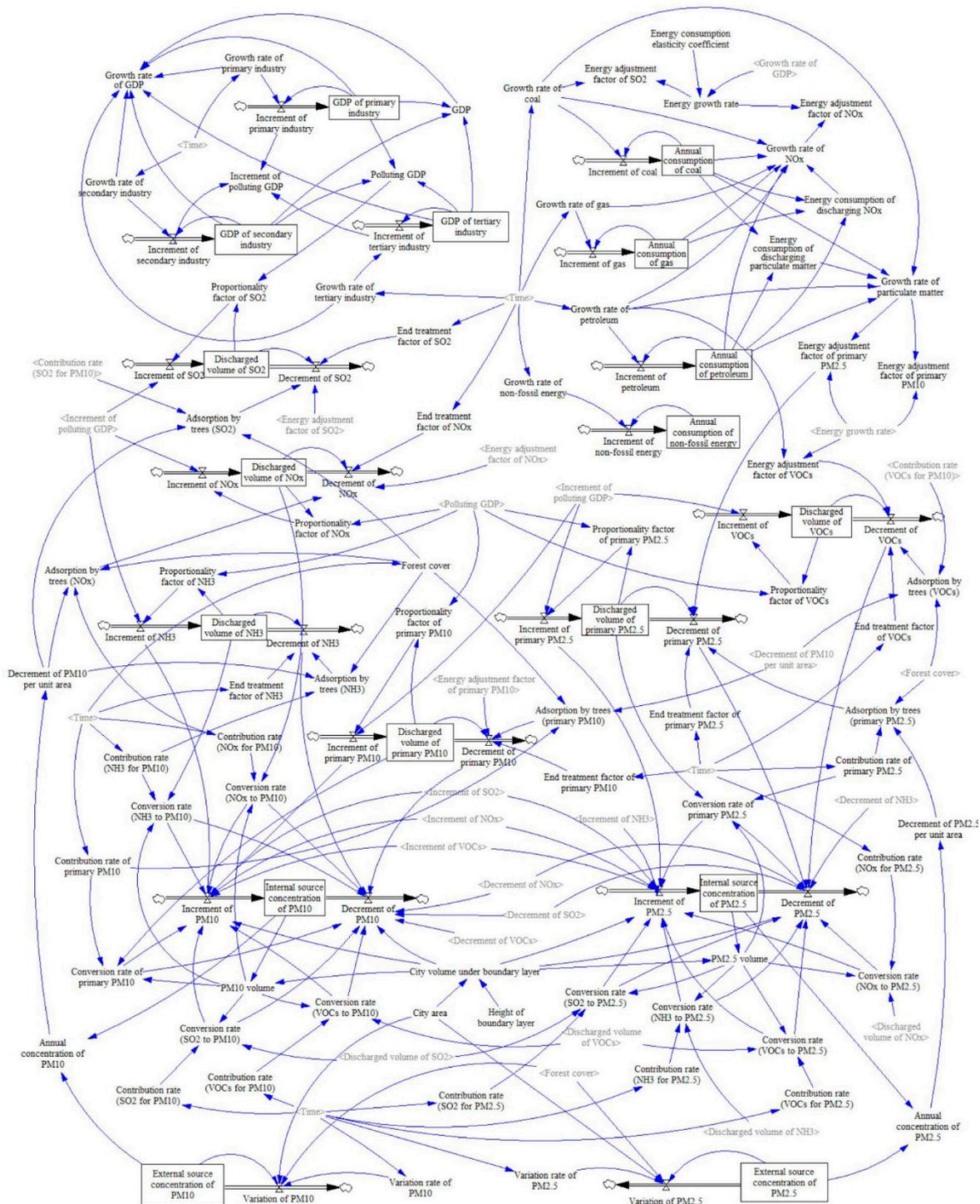


Figure A1. SD flow diagram.

Appendix C

Parameter settings of variables in SD model

(001)"Adsorption by trees (NH3)" = Forest cover * Decrement of PM10 per unit area * "Contribution rate (NH3 for PM10)," units: tons.

(002)"Adsorption by trees (NOx)" = Forest cover * Decrement of PM10 per unit area * "Contribution rate (NOx for PM10)," units: tons.

- (003) "Adsorption by trees (primary PM10)" = Forest cover * Decrement of PM10 per unit area * Contribution rate of primary PM10, units: tons.
- (004) "Adsorption by trees (primary PM2.5)" = Forest cover * "Decrement of PM2.5 per unit area" * "Contribution rate of primary PM2.5," units: tons.
- (005) "Adsorption by trees (SO2)" = Forest cover * Decrement of PM10 per unit area * "Contribution rate (SO2 for PM10)," units: tons.
- (006) "Adsorption by trees (VOCs)" = Forest cover * Decrement of PM10 per unit area * "Contribution rate (VOCs for PM10)," units: tons.
- (007) Annual concentration of PM10 = External source concentration of PM10 + Internal source concentration of PM10, units: mg/m³.
- (008) "Annual concentration of PM2.5" = "External source concentration of PM2.5" + "Internal source concentration of PM2.5," units: mg/m³.
- (009) Annual consumption of coal = INTEG (Increment of coal,24.3), units: million tons.
- (010) Annual consumption of gas = INTEG (Increment of gas, 2.71), units: million tons.
- (011) "Annual consumption of non-fossil energy" = INTEG ("Increment of non-fossil energy,"5.59), units: million tons.
- (012) Annual consumption of petroleum = INTEG (Increment of petroleum, 14.44), units: million tons
- (013) City area = 8569, units: km².
- (014) City volume under boundary layer = City area * Height of boundary layer, units: m³.
- (015) "Contribution rate (NH3 for PM10)" = WITH LOOKUP (Time, [(2016,0) (2051,1)], (2016,0.08), (2021,0.11), (2026,0.14), (2031,0.16), (2036,0.18), (2041,0.185), (2046,0.19), (2051,0.19)), units: Dmnl.
- (016) "Contribution rate (NH3 for PM2.5)" = WITH LOOKUP (Time, [(2016,0)-(2051,0.3)], (2016,0.1), (2021,0.135), (2026,0.16), (2031,0.17), (2036,0.175), (2041,0.18), (2046,0.183), (2051,0.185)), units: Dmnl.
- (017) "Contribution rate (NOx for PM10)" = WITH LOOKUP (Time, [(2016,0)-(2051,1)], (2016,0.13), (2021,0.17), (2026,0.2), (2031,0.22), (2036,0.23), (2041,0.24), (2046,0.25), (2051,0.25)), units: Dmnl.
- (018) "Contribution rate (NOx for PM2.5)" = WITH LOOKUP (Time, [(2016,0)-(2051,0.5)], (2016,0.15), (2021,0.18), (2026,0.2), (2031,0.22), (2036,0.23), (2041,0.24), (2046,0.245), (2051,0.25)), units: Dmnl.
- (019) "Contribution rate (SO2 for PM10)" = WITH LOOKUP (Time, [(2016,0)-(2051,0.3)], (2016,0.2), (2021,0.15), (2026,0.12), (2031,0.1), (2036,0.085), (2041,0.073), (2046,0.065), (2051,0.06)), units: Dmnl.
- (020) "Contribution rate (SO2 for PM2.5)" = WITH LOOKUP (Time, [(2016,0)-(2051,0.5)], (2016,0.21), (2021,0.16), (2026,0.12), (2031,0.1), (2036,0.08), (2041,0.07), (2046,0.06), (2051,0.058)), units: Dmnl.
- (021) "Contribution rate (VOCs for PM10)" = WITH LOOKUP (Time, [(2016,0)-(2051,0.5)], (2016,0.26), (2021,0.31), (2026,0.34), (2031,0.36), (2036,0.37), (2041,0.38), (2046,0.385), (2051,0.39)), units: Dmnl.
- (022) "Contribution rate (VOCs for PM2.5)" = WITH LOOKUP (Time, [(2016,0)-(2051,0.5)], (2016,0.3), (2021,0.33), (2026,0.35), (2031,0.36), (2036,0.37), (2041,0.375), (2046,0.378), (2051,0.38)), units: Dmnl.
- (023) Contribution rate of primary PM10 = WITH LOOKUP (Time, [(2016,0)-(2051,1)], (2016,0.21), (2021,0.15), (2026,0.11), (2031,0.08), (2036,0.07), (2041,0.065), (2046,0.06), (2051,0.06)), units: Dmnl.
- (024) "Contribution rate of primary PM2.5" = WITH LOOKUP (Time, [(2016,0)-(2051,0.2)], (2016,0.15), (2021,0.11), (2026,0.09), (2031,0.078), (2036,0.07), (2041,0.063), (2046,0.058), (2051,0.055)), units: Dmnl.
- (025) "Conversion rate (NH3 to PM10)" = PM10 volume * "Contribution rate (NH3 for PM10)"/Discharged volume of NH3, units: Dmnl.

- (026) "Conversion rate (NH₃ to PM_{2.5})" = "PM_{2.5} volume" * "Contribution rate (NH₃ for PM_{2.5})/Discharged volume of NH₃, units: Dmnl.
- (027) "Conversion rate (NO_x to PM₁₀)" = PM₁₀ volume * "Contribution rate (NO_x for PM₁₀)/Discharged volume of NO_x, units: Dmnl.
- (028) "Conversion rate (NO_x to PM_{2.5})" = "PM_{2.5} volume" * "Contribution rate (NO_x for PM_{2.5})/Discharged volume of NO_x, units: Dmnl.
- (029) "Conversion rate (SO₂ to PM₁₀)" = PM₁₀ volume * "Contribution rate (SO₂ for PM₁₀)/Discharged volume of SO₂, units: Dmnl.
- (030) "Conversion rate (SO₂ to PM_{2.5})" = "PM_{2.5} volume" * "Contribution rate (SO₂ for PM_{2.5})/Discharged volume of SO₂, units: Dmnl.
- (031) "Conversion rate (VOCs to PM₁₀)" = PM₁₀ volume * "Contribution rate (VOCs for PM₁₀)/Discharged volume of VOCs, units: Dmnl.
- (032) "Conversion rate (VOCs to PM_{2.5})" = "PM_{2.5} volume" * "Contribution rate (VOCs for PM_{2.5})/Discharged volume of VOCs, units: Dmnl.
- (033) Conversion rate of primary PM₁₀ = PM₁₀ volume * Contribution rate of primary PM₁₀/Discharged volume of primary PM₁₀, units: Dmnl.
- (034) "Conversion rate of primary PM_{2.5}" = "PM_{2.5} volume" * "Contribution rate of primary PM_{2.5}"/Discharged volume of primary PM_{2.5}, units: Dmnl.
- (035) Decrement of NH₃ = Discharged volume of NH₃ * End treatment factor of NH₃ + "Adsorption by trees (NH₃)," units: tons/year.
- (036) Decrement of NO_x = Discharged volume of NO_x * (End treatment factor of NO_x + Energy adjustment factor of NO_x) + "Adsorption by trees (NO_x)," units: tons/year.
- (037) Decrement of PM₁₀ = Decrement of NH₃ * "Conversion rate (NH₃ to PM₁₀)" * 1e + 009/City volume under boundary layer + Decrement of NO_x * "Conversion rate (NO_x to PM₁₀)" * 1e + 009/City volume under boundary layer + Decrement of primary PM₁₀ * Conversion rate of primary PM₁₀ * 1e + 009/City volume under boundary layer + Decrement of SO₂ * "Conversion rate (SO₂ to PM₁₀)" * 1e + 009/City volume under boundary layer + Decrement of VOCs * "Conversion rate (VOCs to PM₁₀)" * 1e + 009/City volume under boundary layer, units: year * mg/m³.
- (038) Decrement of PM₁₀ per unit area = 0.09 * Annual concentration of PM₁₀, units: tons/km².
- (039) "Decrement of PM_{2.5} per unit area" = 0.1 * "Annual concentration of PM_{2.5}," units: tons/km².
- (040) "Decrement of PM_{2.5}" = Decrement of NH₃ * "Conversion rate (NH₃ to PM_{2.5})" * 1e + 009/City volume under boundary layer + Decrement of NO_x * "Conversion rate (NO_x to PM_{2.5})" * 1e + 009/City volume under boundary layer + "Decrement of primary PM_{2.5}" * "Conversion rate of primary PM_{2.5}" * 1e + 009/City volume under boundary layer + Decrement of SO₂ * "Conversion rate (SO₂ to PM_{2.5})" * 1e + 009/City volume under boundary layer + Decrement of VOCs * "Conversion rate (VOCs to PM_{2.5})" * 1e + 009/City volume under boundary layer, units: year * mg/m³.
- (041) Decrement of primary PM₁₀ = Discharged volume of primary PM₁₀ * (End treatment factor of primary PM₁₀ + Energy adjustment factor of primary PM₁₀) + "Adsorption by trees (primary PM₁₀)," units: tons/year.
- (042) "Decrement of primary PM_{2.5}" = "Discharged volume of primary PM_{2.5}" * ("End treatment factor of primary PM_{2.5}" + "Energy adjustment factor of primary PM_{2.5}") + "Adsorption by trees (primary PM_{2.5})," units: tons/year
- (043) Decrement of SO₂ = Discharged volume of SO₂ * (End treatment factor of SO₂ + Energy adjustment factor of SO₂) + "Adsorption by trees (SO₂)," units: tons/year.
- (044) Decrement of VOCs = Discharged volume of VOCs * (End treatment factor of VOCs + Energy adjustment factor of VOCs) + "Adsorption by trees (VOCs)," units: tons/year.
- (045) Discharged volume of NH₃ = INTEG (Increment of NH₃-Decrement of NH₃,16496), units: tons.
- (046) Discharged volume of NO_x = INTEG (Increment of NO_x-Decrement of NO_x,181486), units: tons.
- (047) Discharged volume of primary PM₁₀ = INTEG (Increment of primary PM₁₀-Decrement of primary PM₁₀, 171630), units: tons.

- (048) "Discharged volume of primary PM2.5" = INTEG ("Increment of primary PM2.5"- "Decrement of primary PM2.5,"77251), units: tons.
- (049) Discharged volume of SO₂ = INTEG (Increment of SO₂-Decrement of SO₂,109604), units: tons.
- (050) Discharged volume of VOCs = INTEG (Increment of VOCs-Decrement of VOCs,208558), units: tons.
- (051) End treatment factor of NH₃ = WITH LOOKUP (Time, ([(2016,0)-(2051,0.1)], (2016,0.09), (2021,0.075), (2026,0.065), (2031,0.055), (2036,0.045), (2041,0.038), (2046,0.033), (2051,0.03))), units: 1/year.
- (052) End treatment factor of NO_x = WITH LOOKUP (Time, ([(2016,0)-(2051,0.2)], (2016,0.15), (2021,0.11), (2026,0.085), (2031,0.065), (2036,0.05), (2041,0.04), (2046,0.035), (2051,0.03))), units: 1/year.
- (053) End treatment factor of primary PM₁₀ = WITH LOOKUP (Time, ([(2016,0)-(2051,0.1)], (2016,0.08), (2021,0.05), (2026,0.036), (2031,0.028), (2036,0.022), (2041,0.018), (2046,0.015), (2051,0.012))), units: 1/year.
- (054) "End treatment factor of primary PM2.5" = WITH LOOKUP (Time, ([(2016,0)-(2051,0.1)], (2016,0.08), (2021,0.05), (2026,0.036), (2031,0.028), (2036,0.022), (2041,0.018), (2046,0.015), (2051,0.012))), units: 1/year.
- (055) End treatment factor of SO₂ = WITH LOOKUP (Time, ([(2016,0)-(2051,0.2)], (2016,0.15), (2021,0.09), (2026,0.06), (2031,0.04), (2036,0.03), (2041,0.022), (2046,0.015), (2051,0.012))), units: 1/year.
- (056) End treatment factor of VOCs = WITH LOOKUP (Time, ([(2016,0)-(2051,0.2)], (2016,0.14), (2021,0.1), (2026,0.075), (2031,0.06), (2036,0.05), (2041,0.04), (2046,0.035), (2051,0.03))), units: 1/year.
- (057) Energy adjustment factor of NO_x = $1 - (1 + \text{Growth rate of NO}_x) / (1 + \text{Energy growth rate})$, units: Dmnl.
- (058) Energy adjustment factor of primary PM₁₀ = $1 - (1 + \text{Growth rate of particulate matter}) / (1 + \text{Energy growth rate})$, units: Dmnl.
- (059) "Energy adjustment factor of primary PM2.5" = $1 - (1 + \text{Growth rate of particulate matter}) / (1 + \text{Energy growth rate})$, units: Dmnl.
- (060) Energy adjustment factor of SO₂ = $1 - (1 + \text{Growth rate of coal}) / (1 + \text{Energy growth rate})$, units: Dmnl.
- (061) Energy adjustment factor of VOCs = $1 - (1 + \text{Growth rate of petroleum}) / (1 + \text{Energy growth rate})$, units: Dmnl.
- (062) Energy consumption elasticity coefficient = 0.5, units: Dmnl.
- (063) Energy consumption of discharging NO_x = Annual consumption of coal + Annual consumption of gas + Annual consumption of petroleum, units: million tons.
- (064) Energy consumption of discharging particulate matter = Annual consumption of coal + Annual consumption of petroleum, units: million tons.
- (065) Energy growth rate = Energy consumption elasticity coefficient * Growth rate of GDP, units: 1/year.
- (066) External source concentration of PM₁₀ = INTEG (-Variation of PM₁₀,0.03), units: mg/m³.
- (067) "External source concentration of PM2.5" = INTEG (-"Variation of PM2.5,"0.025), units: mg/m³.
- (068) FINAL TIME = 2051, units: year, The final time for the simulation.
- (069) Forest cover = WITH LOOKUP (Time, ([(2016,0)-(2051,4000)], (2016,1970), (2021,2400), (2023,2570), (2051,2600))), units: km².
- (070) GDP = GDP of primary industry + GDP of secondary industry + GDP of tertiary industry, units: billion CNY.
- (071) GDP of primary industry = INTEG (Increment of primary industry,35.9), units: billion CNY.
- (072) GDP of secondary industry = INTEG (Increment of secondary industry,498.1), units: billion CNY.
- (073) GDP of tertiary industry = INTEG (Increment of tertiary industry,556.4), units: billion CNY

- (074) Growth rate of coal = WITH LOOKUP (Time, $[(2016,-0.1)-(2051,0.1)], (2016,-0.035), (2021,-0.02), (2026,-0.01), (2031,-0.005), (2036,-0.003), (2041,-0.003), (2046,-0.002), (2051,-0.001)]$), units: 1/year.
- (075) Growth rate of gas = WITH LOOKUP (Time, $[(2016,0)-(2051,0.3)], (2016,0.18), (2021,0.15), (2026,0.09), (2031,0.06), (2036,0.04), (2041,0.025), (2046,0.015), (2051,0.01)]$), units: 1/year.
- (076) Growth rate of GDP = Growth rate of primary industry * GDP of primary industry/GDP + Growth rate of secondary industry * GDP of secondary industry/GDP + Growth rate of tertiary industry * GDP of tertiary industry/GDP, units: 1/year
- (077) "Growth rate of non-fossil energy" = WITH LOOKUP (Time, $[(2016,0)-(2051,0.1)], (2016,0.09), (2021,0.095), (2026,0.075), (2031,0.06), (2036,0.05), (2041,0.045), (2046,0.04), (2051,0.037)]$), units: 1/year.
- (078) Growth rate of NO_x = Growth rate of gas * Annual consumption of gas/Energy consumption of discharging NO_x + Growth rate of coal * Annual consumption of coal/Energy consumption of discharging NO_x + Growth rate of petroleum * Annual consumption of petroleum/Energy consumption of discharging NO_x, units: 1/year
- (079) Growth rate of particulate matter = Growth rate of coal * Annual consumption of coal/Energy consumption of discharging particulate matter + Growth rate of petroleum * Annual consumption of petroleum/Energy consumption of discharging particulate matter, units: 1/year.
- (080) Growth rate of petroleum = WITH LOOKUP (Time, $[(2016,-0.1)-(2051,0.1)], (2016,0.02), (2021,0.01), (2026,0), (2031,-0.01), (2036,-0.013), (2041,-0.01), (2046,-0.005), (2051,-0.003)]$), units: 1/year.
- (081) Growth rate of primary industry = WITH LOOKUP (Time, $[(2016,0)-(2051,0.1)], (2016,0.035), (2021,0.028), (2026,0.025), (2031,0.022), (2036,0.02), (2041,0.017), (2046,0.013), (2051,0.01)]$), units: 1/year.
- (082) Growth rate of secondary industry = WITH LOOKUP (Time, $[(2016,0)-(2051,0.1)], (2016,0.095), (2021,0.06), (2026,0.04), (2031,0.03), (2036,0.025), (2041,0.019), (2046,0.015), (2051,0.012)]$), units: 1/year.
- (083) Growth rate of tertiary industry = WITH LOOKUP (Time, $[(2016,0)-(2051,0.2)], (2016,0.13), (2021,0.1), (2026,0.08), (2031,0.065), (2036,0.06), (2041,0.058), (2046,0.055), (2051,0.05)]$), units: 1/year.
- (084) Height of boundary layer = 1000, units: m.
- (085) Increment of coal = Annual consumption of coal * Growth rate of coal, units: million tons/year.
- (086) Increment of gas = Annual consumption of gas * Growth rate of gas, units: million tons/year.
- (087) Increment of NH₃ = Increment of polluting GDP * Proportionality factor of NH₃, units: tons/year.
- (088) "Increment of non-fossil energy" = "Annual consumption of non-fossil energy" * "Growth rate of non-fossil energy," units: million tons/year.
- (089) Increment of NO_x = Increment of polluting GDP * Proportionality factor of NO_x, units: tons/year.
- (090) Increment of petroleum = Annual consumption of petroleum * Growth rate of petroleum, units: million tons/year.
- (091) Increment of PM₁₀ = Increment of NH₃ * "Conversion rate (NH₃ to PM₁₀)" * 1e + 009/City volume under boundary layer + Increment of NO_x * "Conversion rate (NO_x to PM₁₀)" * 1e + 009/City volume under boundary layer + Increment of primary PM₁₀ * Conversion rate of primary PM₁₀ * 1e + 009/City volume under boundary layer + Increment of SO₂ * "Conversion rate (SO₂ to PM₁₀)" * 1e + 009/City volume under boundary layer + Increment of VOCs * "Conversion rate (VOCs to PM₁₀)" * 1e + 009/City volume under boundary layer, units: mg/m³ * year.
- (092) "Increment of PM_{2.5}" = Increment of NH₃ * "Conversion rate (NH₃ to PM_{2.5})" * 1e + 009/City volume under boundary layer + Increment of NO_x * "Conversion rate (NO_x to PM_{2.5})" * 1e + 009/City volume under boundary layer + "Increment of primary PM_{2.5}" * "Conversion rate of primary PM_{2.5}" * 1e + 009/City volume under boundary layer + Increment of SO₂ * "Conversion rate (SO₂ to PM_{2.5})" *

$1e + 009/\text{City volume under boundary layer} + \text{Increment of VOCs} * \text{"Conversion rate (VOCs to PM2.5)"}$
 $* 1e + 009/\text{City volume under boundary layer}$, units: year * mg/m³.

(093) Increment of polluting GDP = $0.1 * \text{Increment of primary industry} + 0.8 * \text{Increment of secondary industry} + 0.1 * \text{Increment of tertiary industry}$, units: billion CNY/year.

(094) Increment of primary industry = $\text{GDP of primary industry} * \text{Growth rate of primary industry}$, units: billion CNY/year.

(095) Increment of primary PM10 = $\text{Increment of polluting GDP} * \text{Proportionality factor of primary PM10}$, units: tons/year.

(096) "Increment of primary PM2.5" = $\text{Increment of polluting GDP} * \text{"Proportionality factor of primary PM2.5,"}$ units: tons/year.

(097) Increment of secondary industry = $\text{GDP of secondary industry} * \text{Growth rate of secondary industry}$, units: billion CNY/year.

(098) Increment of SO₂ = $\text{Increment of polluting GDP} * \text{Proportionality factor of SO}_2$, units: tons/year.

(099) Increment of tertiary industry = $\text{GDP of tertiary industry} * \text{Growth rate of tertiary industry}$, units: billion CNY/year.

(100) Increment of VOCs = $\text{Increment of polluting GDP} * \text{Proportionality factor of VOCs}$, units: tons/year.

(101) INITIAL TIME = 2016, units: year, the initial time for the simulation.

(102) Internal source concentration of PM10 = $\text{INTEG}(\text{Increment of PM10}-\text{Decrement of PM10}, 0.074)$, units: mg/m³.

(103) "Internal source concentration of PM2.5" = $\text{INTEG}(\text{"Increment of PM2.5"}-\text{"Decrement of PM2.5"}, 0.045)$, units: mg/m³.

(104) PM10 volume = $\text{Internal source concentration of PM10} * \text{City volume under boundary layer} * 1e-009$, units: tons.

(105) "PM2.5 volume" = $\text{"Internal source concentration of PM2.5"} * \text{City volume under boundary layer} * 1e-009$, units: tons.

(106) Polluting GDP = $0.1 * \text{GDP of primary industry} + 0.8 * \text{GDP of secondary industry} + 0.1 * \text{GDP of tertiary industry}$, units: billion CNY.

(107) Proportionality factor of NH₃ = $\text{Discharged volume of NH}_3/\text{Polluting GDP}$, units: tons/billion CNY.

(108) Proportionality factor of NO_x = $\text{Discharged volume of NO}_x/\text{Polluting GDP}$, units: tons/billion CNY.

(109) Proportionality factor of primary PM10 = $\text{Discharged volume of primary PM10}/\text{Polluting GDP}$, units: tons/billion CNY.

(110) "Proportionality factor of primary PM2.5" = $\text{"Discharged volume of primary PM2.5"}/\text{Polluting GDP}$, units: tons/billion CNY.

(111) Proportionality factor of SO₂ = $\text{Discharged volume of SO}_2/\text{Polluting GDP}$, units: tons/billion CNY.

(112) Proportionality factor of VOCs = $\text{Discharged volume of VOCs}/\text{Polluting GDP}$, units: tons/billion CNY.

(113) SAVEPER = TIME STEP, units: year [0,?], The frequency with which output is stored.

(114) TIME STEP = 0.5, units: year [0,?], The time step for the simulation.

(115) Variation of PM10 = $\text{External source concentration of PM10} * (\text{Variation rate of PM10} + 0.2 * \text{Forest cover}/\text{City area})$, units: mg * year/m³.

(116) "Variation of PM2.5" = $\text{"External source concentration of PM2.5"} * (\text{"Variation rate of PM2.5"} + 0.15 * \text{Forest cover}/\text{City area})$, units: mg * year/m³.

(117) Variation rate of PM10 = WITH LOOKUP (Time, $[(2016,0)-(2051,0.1)], (2016,0.045), (2021,0.03), (2026,0.022), (2031,0.017), (2036,0.014), (2041,0.011), (2046,0.009), (2051,0.008)]$), units: 1/year.

(118) "Variation rate of PM2.5" = WITH LOOKUP (Time, $[(2016,0)-(2051,0.1)], (2016,0.042), (2021,0.028), (2026,0.02), (2031,0.015), (2036,0.012), (2041,0.01), (2046,0.009), (2051,0.008)]$), units: 1/year.

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