

Eucalyptus Productivity Increase in China Comes From Newly Afforested Plantations

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Posted Date: September 29th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-81375/v1>

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***Eucalyptus* productivity increase in China comes from newly afforested plantations**

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Abstract: *Eucalyptus* trees are a major fast-growing species in southern China. The ecological problems associated with constantly developing new *Eucalyptus* plantations have been the focus of extensive debate. In this study, we used spatial analysis and geostatistical methods along with four continuous national forest resource inventories and meteorological data to analyze dynamic changes in the distribution of *Eucalyptus* plantations in China. The productivity levels of *Eucalyptus* plantations were compared at different time periods by measuring annual mean productivity in permanent sample plots to provide baseline data related to the scientific management of *Eucalyptus* plantations. Results showed that the area of *Eucalyptus* plantations increased constantly in China from 1998 to 2013, expanding from 60.7×10^4 hm² in 1998 to more than 445.5×10^4 hm² in 2013. The productivity of *Eucalyptus* plantations was positively correlated with temperature and rainfall, but negatively correlated with elevation. However, these changes did not necessarily indicate an improvement in the management quality of *Eucalyptus* plantations, because they were mainly

caused by an increased in the proportion of newly reclaimed areas for *Eucalyptus* afforestation and the constantly decreasing area of original *Eucalyptus* plantations, to which sufficient attention must be given.

Keywords: *Eucalyptus*, forest productivity, forest resource inventory, geographic distribution, China

1. Background

Eucalyptus is characterized by rapid growth, high yield, stress resistance, barren tolerance, good stem form, and extensive use. In many countries of the world, *Eucalyptus* is promoted for large-scale afforestation and is one of the four fast-growing genera used for afforestation in the world ^[1]. The total area of *Eucalyptus* and *Pinus* plantations accounts for approximately 30% of the global plantation area ^[2]. *Eucalyptus* species commonly used in afforestation include *E. dunnii* Maiden, *E. globulus* Labill, *E. grandis* Hill ex Maiden, *E. tereticornis* Smith, and *E. urophylla* S. T. Blakely ^[3, 4]. In 1990, *Eucalyptus* plantations covered a total of 1.34×10^7 hm² worldwide, which increased to 1.46×10^7 hm² in 1995, with more than 1.0×10^7 hm² of *Eucalyptus* plantations in 81 countries ^[5]. The total area of *Eucalyptus* plantations worldwide reached 2.0×10^7 hm² in 2010. In China, *Eucalyptus* plantations have been developed rapidly since the mid-1990s. According to the national forest resource inventory, the area of *Eucalyptus* plantations in China expanded from 6.07×10^5 hm² in 1998 to 4.455×10^6 hm² in 2013; the average annual rate of increase was 1.92×10^5 hm², ranking first worldwide.

The large-scale establishment of *Eucalyptus* plantations, with their social and ecological benefits, has caused increasing concern and created substantial controversy ^[3, 4, 6-9]. The development of *Eucalyptus* plantations have been debated from different perspectives, and

the controversial issues have mainly focused on: (1) an excessive consumption of nutrients (trees as ‘fertility pumps’); (2) an excessive consumption of water (trees as ‘water pumps’); (3) a reduction in biological diversity (creation of ecological ‘green deserts’); and (4) poor ecological stability ^[9–12]. The following questions address these concerns: (1) How can ecological problems related to *Eucalyptus* plantations be addressed while improving their cultivation patterns and achieving technological innovation? (2) How can the adverse effects of *Eucalyptus* afforestation in the environment be minimized in a way that allows *Eucalyptus* plantations to play a role in substituting natural forest harvesting? How can the short supply of timber be augmented while maintaining forest resources, such as preserving important niches and rare species habitats? These practical problems urgently need to be addressed to achieve sustainable development of *Eucalyptus* plantations.

Chinese researchers have investigated the ecological effects of *Eucalyptus* plantations by setting up continuous observation points and comparative tests in local areas, which provided some quantitative results ^[6]. However, there have been few investigations of the dynamic changes in the distribution area of *Eucalyptus* plantations in China using data from multiple continuous inventories of permanent sample plots. Meanwhile, with the development of geographic information systems (GIS) and geostatistics, there has been increasing concern over the quantitative expression of the geospatial and geographical distribution patterns of *Eucalyptus* plantations, as well as remote sensing measurements of stand factors (height, density, and biomass). Remote sensing is a macroscopic, effective, and repeatable technology that provides an ideal tool for studies related to *Eucalyptus* resources. Good results have been obtained by remote sensing in studies on the dynamic changes in *Eucalyptus* resource inventory, harvesting, and reforestation ^[15–16]. Moreover, significant progress has been made using laser radar and hyperspectral remote sensing data in quantitative studies on the density, height, and aboveground biomass of *Eucalyptus* resources ^[17–18].

In the present study, we analyzed the geospatial distribution of *Eucalyptus* productivity in southern China and its relationship with rainfall, temperature, and elevation, to reveal the spatial distribution and change patterns of *Eucalyptus* plantations in this country. The analysis was performed using geostatistical methods and Kriging interpolation by a combination of computer application technology and spatial analysis techniques, based on sample plot data from four national forest resource inventories (5th–8th) and meteorological data. Meanwhile, we continuously measured the annual mean productivity of *Eucalyptus* plantations in permanent sample plots during multiple time periods, to reflect the dynamic changes in *Eucalyptus* productivity. This study will provide an important reference for scientific and rational management as well as for improving the productivity of *Eucalyptus* plantations.

2. Data and methods

2.1 Data sources

The data used in this study mainly included data from the 5th–8th national forest resource inventories, a national 1:250,000 digital elevation model (DEM), and meteorological data related to temperature and rainfall in southern China over the period of 1981–2010. The forest resource inventory data included statistical report, sample plot, and sample tree databases. The sample plot database included 48 factors, e.g., plot number, vertical and horizontal coordinates of the plot, mean age, mean diameter at breast height (DBH), mean tree height, canopy density, and stand volume; the sample tree database included 11 factors, e.g., tree number, type of standing trees, DBH, and volume. Meteorological data mainly included digital grid data of annual mean temperature and rainfall in Chongqing, Fujian, Guangdong, Guangxi, Hunan, Jiangxi, Sichuan, Yunnan, and other provinces over the period 1981–2010. These data were downloaded from the China Meteorological Data Sharing Service System, with a grid horizontal resolution of $0.5^{\circ} \times 0.5^{\circ}$.

2.2 Data processing

2.2.1 Plot data processing and calculation of annual mean productivity

(1) Calculation of productivity

Forest productivity represents the annual mean biomass or volume growth of a stand per unit area with a combination of environmental factors including certain water and heat conditions as well as soil and terrain features. In this study, we used the annual mean volume growth per unit area to reflect the level of forest productivity.

The sample plots of *Eucalyptus* plantations were extracted from the sample plot database of the four national forest resource inventories. The location of GPS coordinates recorded in the sample plots were imported into the GIS system to generate point vector data of sample plot distribution in four time periods for use in further analysis.

The stand volume and mean age were recorded in each plot and the mean productivity of *Eucalyptus* plantations was calculated as follows:

$$P = \frac{V}{T} \quad (1)$$

where P is the annual mean productivity of the stand ($\text{m}^3 \text{hm}^{-2} \text{a}^{-1}$), V is the stand volume per unit area ($\text{m}^3 \text{hm}^{-2}$) and T is the mean age of the stand (a , where a is the stand age).

(2) Calculation of sampling accuracy

1) Area estimation

The plantation area was calculated using the following systematic sampling formula:

$$p_i = \frac{m_i}{n} \quad (2)$$

$$S_{p_i} = \sqrt{\frac{p_i(1 - p_i)}{n - 1}} \quad (3)$$

where n is the total number of sample plots, m_i is the plot number for type i (including land type, vegetation type, and forest type, and other types of land classification attributes); p_i is

the estimated area percentage for type i ; S_{P_i} is the standard deviation of estimated area percentage for type i . The P_{A_i} can be calculated as:

$$P_{A_i} = \left(1 - \frac{t_a \times S_{P_i}}{p_i}\right) \times 100\% \quad (4)$$

where P_{A_i} is the sampling accuracy of area estimates for type i and t_a is the reliability index; p_i and S_{P_i} are the same as denoted above.

2) Volume estimation

① Sample mean:

$$\bar{V}_i = \frac{1}{n} \sum_{j=1}^n V_{ij} \quad (5)$$

where \bar{V}_i is the mean volume of sample plots; V_{ij} is the volume of sample plot j for type i .

② Sample variance:

$$S_{V_i}^2 = \frac{1}{n-1} \sum_{j=1}^n (V_{ij} - \bar{V}_i)^2 \quad (6)$$

$$S_{\bar{V}_i} = \frac{S_{V_i}}{\sqrt{n}} \quad (7)$$

where $S_{V_i}^2$ is the sample variance; $S_{\bar{V}_i}$ is the sample standard deviation; V_{ij} is the volume of sample plot j for type i ; and n is the total number of sample plots for type i .

③ Sampling accuracy:

$$P_{V_i} = \left(1 - \frac{t_a \times S_{\bar{V}_i}}{\bar{V}_i}\right) \times 100\% \quad (8)$$

where P_{V_i} is the sampling accuracy of volume estimates for type i ; t_a is the reliability index; \bar{V}_i and $S_{\bar{V}_i}$ are the same as denoted above.

2.2.2 Extraction of meteorological and elevation information from sample plots

First, the spatial data including point vector data of sample plots, DEM data, and

meteorological data of annual mean temperature and rainfall were integrated and projected into less deformed Albers latitude and longitude projection and the Krasovsky ellipsoid coordinate system; we established a central meridian of 105°E and an origin latitude of 0°. Because the point vector database of sample plots lacked climatic factors such as annual mean temperature and rainfall, we used a GIS to assign each vector plot. For example, the annual mean rainfall was assigned to each plot by GIS spatial overlay analysis of the sample plot data and digital raster maps of rainfall. The information for annual mean temperature and elevation was extracted following the same procedure.

2.3 Geostatistics-based Kriging interpolation

Geostatistics is a branch of applied statistics that deals with the spatial distribution of variables. The basic goal of using geostatistics is to achieve local optimal estimation of geological variables by linear weighting. The Kriging method, also known as spatial local estimation or spatial local interpolation, is one of the two main topics in the field of geostatistics [19–23]. The Kriging method is essentially an approach for linear optimal estimation of regionalized variables at unknown sampling points using the original data of regionalized variables and structural characteristics of a variogram. The Kriging method maximizes the use of information provided by spatial sampling. When estimating an unknown sampling point, this method takes the data at the unknown point into consideration as well as data for the adjacent points. Moreover, it considers the spatial position of the target point and its adjacent known points, as well as the positional relationship between adjacent samples [19]. In this study, geostatistics-based Kriging interpolation was adopted to analyze the spatial distribution pattern of productivity of *Eucalyptus* plantations in southern China, with data from four forest resource inventories.

3. Results and discussion

3.1 Productivity dynamics

The mean productivity of *Eucalyptus* plantations was analyzed based on the data from four forest resource inventories. Table 1 shows that over the period 1998–2013, the mean productivity exhibited a continuously growing trend in the distribution areas of *Eucalyptus* plantations in southern provinces of China: the productivity increased from 5.34 m³ hm⁻² a⁻¹ in 1998 to 9.88 m³ hm⁻² a⁻¹ in 2013. Among these provinces, Guangxi and Fujian showed the most significant growth trend, which is closely related to the increased development of *Eucalyptus* plantations in these regions.

Table 1 Numbers assigned to sample plots as well as mean and maximum productivity of *Eucalyptus* plantations in southern provinces of China based on different forest inventory time periods

| Province | 5 th Inventory | | | 6 th Inventory | | | 7 th Inventory | | | 8 th Inventory | | |
|-----------|---------------------------|------|-------|---------------------------|------|-------|---------------------------|------|-------|---------------------------|-------|-------|
| | (1994–1998) | | | (1999–2003) | | | (2004–2008) | | | (2009–2013) | | |
| | No. | M. | Max. | No. | M. | Max. | No. | M. | Max. | No. | M. | Max. |
| Fujian | 4 | 2.81 | 6.96 | 7 | 3.95 | 10.72 | 66 | 7.82 | 33.32 | 113 | 13.75 | 36.69 |
| Jiangxi | -- | -- | -- | -- | -- | -- | -- | -- | -- | 7 | 1.79 | 8.15 |
| Hunan | -- | -- | -- | -- | -- | -- | -- | -- | -- | 7 | 1.20 | 3.44 |
| Guangdong | 61 | 4.53 | 24.49 | 85 | 5.38 | 34.91 | 276 | 5.38 | 37.15 | 357 | 6.80 | 38.38 |
| Guangxi | 15 | 5.43 | 10.23 | 31 | 6.29 | 19.37 | 111 | 4.04 | 24.12 | 344 | 9.76 | 38.51 |
| Hainan | 142 | 3.88 | 18.72 | 139 | 4.21 | 22.26 | 161 | 4.64 | 24.50 | 122 | 4.70 | 14.15 |
| Chongqing | -- | -- | -- | -- | -- | -- | 3 | 2.33 | 3.41 | 29 | 0 | 0 |
| Sichuan | -- | -- | -- | 4 | 2.50 | 4.97 | 13 | 2.65 | 7.86 | 33 | 4.29 | 14.50 |
| Guizhou | -- | -- | -- | -- | -- | -- | -- | -- | -- | 3 | 2.88 | 7.66 |
| Yunnan | 4 | 3.86 | 6.50 | 6 | 6.43 | 24.17 | 50 | 2.99 | 14.89 | 81 | 6.50 | 27.88 |
| Total | 226 | 4.40 | 24.49 | 273 | 5.84 | 34.91 | 687 | 4.83 | 37.15 | 1096 | 7.98 | 38.51 |

Note: 1) “No.” refers to the sample plot number; “M.” refers to mean productivity; “Max.” refers to maximum productivity; 2) “--” indicate areas with no sample plots.

Based on the analysis of permanent sample plots in four continuous inventories, we found 226 sample plots of *Eucalyptus* plantations in the 5th Inventory, and 150 of them were retained in the 6th Inventory, with a retention rate of 66.37%. There were 273 sample plots in the 6th Inventory, and only 179 of them were retained in the 7th Inventory, with a retention rate of 65.57%. The 7th Inventory recorded 687 sample plots, and only 544 of them were retained in the 8th Inventory, with a retention rate of 79.18%. That is, the area of *Eucalyptus* plantations in each 5-year inventory period decreased by a third in the next 5-year inventory period. A track analysis of 226 sample plots in the 5th inventory revealed that the numbers of sample plots retained in the 6th, 7th, and 8th inventories were 150, 112, and 70, respectively. This is also in line with the trend that the number of sample plots decreased by one third in each 5-year interval. At the 8th Inventory, approximately 70% of the original *Eucalyptus* plots had been withdrawn from afforestation. Moreover, the sample plots withdrawn in the four intervals did not re-enter the inventory. Nevertheless, the number of sample plots reached 1096 during the 8th Inventory. Clearly, significant changes occurred in the sample plots of *Eucalyptus* plantations over the study period. This reflects the fact that *Eucalyptus* plantations were established in southern China mostly based on a short rotation period and high-intensity management. This also indicates that a higher level of productivity at a regional level was maintained, to some extent, by constantly changing the planting regions of *Eucalyptus* plantations and selecting a large amount of land with preferred site conditions.

We analyzed the average and frequency distribution of annual mean productivity in 70 sample plots included plots in all the four inventories. No large differences were observed in the annual mean productivity from 1998 to 2013; the values were generally in the range of 7–

8 m³ hm⁻² a⁻¹, except for the relatively low productivity observed in 1994–1998 (Fig. 1). Additionally, 90% of the annual mean productivity was concentrated below 15 m³ hm⁻² a⁻¹, indicating that the productivity of newly reclaimed land was significantly higher, where the productivity of *Eucalyptus* plantations could reach 8–15 m³ hm⁻² a⁻¹.

The planting area of *Eucalyptus* plantations and their mean productivity per unit area showed 4.85- and 1.85-fold increases by 2009–2013, respectively (Fig. 2). However, these did not necessarily indicate an improvement in the quality of management of *Eucalyptus* plantations. The above changes were mainly due to an increased proportion of newly reclaimed land for *Eucalyptus* afforestation and the relatively high productivity of newly planted fertile land. A simultaneous reduction in the existing area of *Eucalyptus* plantations was also observed, resulting in an increase in the national average productivity of *Eucalyptus* plantations. Although other factors might be involved during the study period, such as improved cultivation techniques for *Eucalyptus* species and improved soil fertility by fertilization, these factors could not be directly reflected in this study.

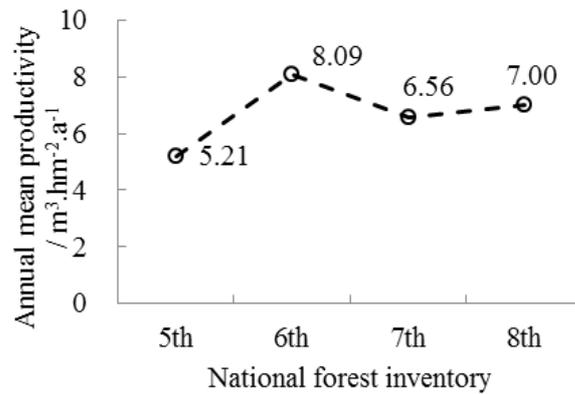


Fig. 1 Average of annual mean productivity of *Eucalyptus* sample plots included in all the four national inventories (5th to 8th)

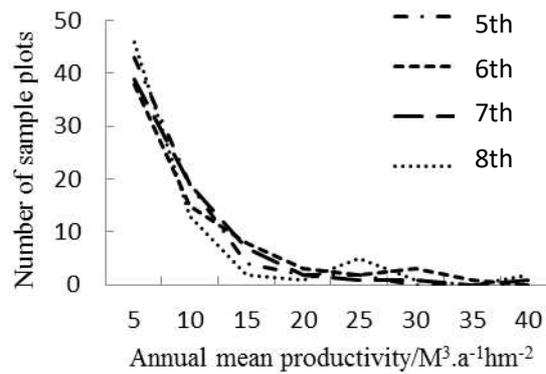


Fig. 2 Frequency distribution of annual mean productivity of *Eucalyptus* sample plots included in all the four national inventories (5th to 8th)

3.2 Geospatial distribution pattern of productivity

We obtained the geospatial distribution of productivity of *Eucalyptus* plantations in the four inventory periods by Kriging interpolation. From 1998 to 2013, the spatial range of productivity distribution gradually developed from the Leizhou Peninsula in Guangdong and Hainan towards the north (Guangxi, Hunan, and Guizhou), east (Fujian and Jiangxi), and west (Yunnan and Sichuan) (Fig. 3). This is generally consistent with the development of *Eucalyptus* plantations in China over the past 20 years. With regard to the variation in the

spatial pattern of the productivity, multiple high-yield distribution centers were formed towards the north, east, and west, with Leizhou Peninsula as the center. The high-yield regions of productivity were mainly distributed in the Leizhou Peninsula in Guangzhou, which spread to southeastern Guangxi in 2003 and further to central Guangdong and southern Guangxi. In 2013, several high-yield distribution centers of *Eucalyptus* plantations were formed in the southern Leizhou Peninsula and in Qingyuan in central Guangdong, Guigang and Yulin in southern Guangxi, Sanming and Longyan in southwestern Fujian, and Puer and Linchang in southwestern Yunnan.

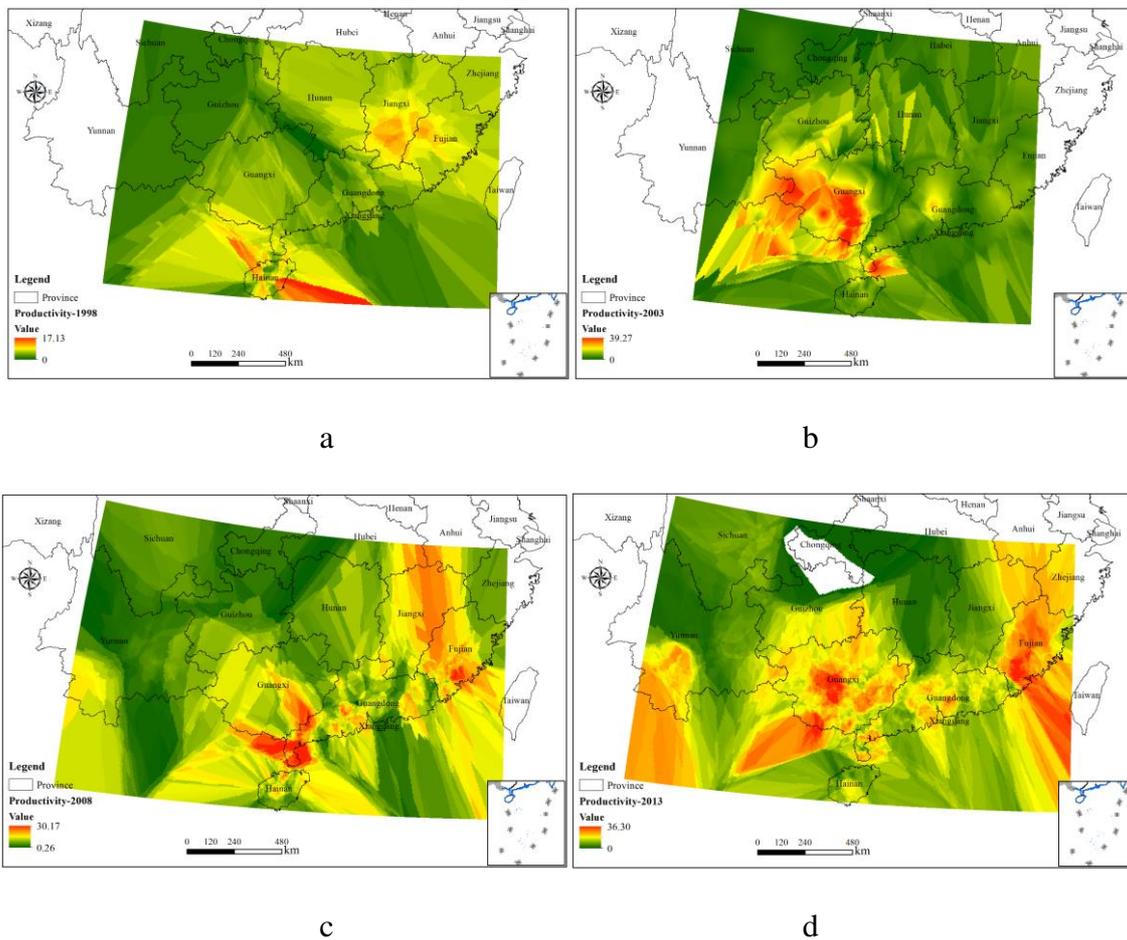


Fig. 3 Distribution maps of *Eucalyptus* productivity obtained by geospatial interpolation (a. 1998; b. 2003; c. 2008; d. 2013)

3.3 Spatial distribution pattern of *Eucalyptus* plantations

Based on vector data for the spatial distribution of sample plots, we built a spatial database for the sample plots of *Eucalyptus* plantations using GIS software, with geographical data related to latitude and longitude, elevation, annual mean temperature, annual mean rainfall, and other information extracted from the DEM and meteorological data. The spatial database was then used to analyze the relationship between annual mean productivity as well as the area distribution of *Eucalyptus* plantations with annual mean temperature, annual mean rainfall, and elevation. Using a statistical analysis of the spatial database of sample plots in the 8th Inventory, the geographic distribution of the sample plots was: longitude 110°23'–120°5', latitude 18°21'–30°39'. With respect of geographical and climatic conditions, the annual mean temperature ranged between 11 °C and 23 °C, with an average of 19.5 °C; the annual mean rainfall ranged between 600 and 2000 mm, with an average of 1455 mm; the elevation ranged between 0 and 2500 m, with an average of 338 m.

Taking the elevation of 300 m as a boundary, we classified the areas below 300 m into Grade 1; the areas above 300 m were classified at 300-m intervals until 2100 m was reached (grades 2 to 7; the small areas above 2100 m were excluded from statistical analysis). The annual mean productivity and area distribution of *Eucalyptus* plantations were then analyzed for the seven grades of elevation. Similarly, annual mean temperature was classified into seven grades with 12 °C as the boundary; the temperatures above 12 °C were classified at 2 °C intervals until 23 °C was reached. Annual mean rainfall was classified into seven grades with 600 mm as the starting point; the rainfall above 600 mm was divided at 200-mm intervals until 1800 mm, and the values higher than 1800 mm were classified into Grade 7.

Figure 4 depicts the spatial distribution of *Eucalyptus* plantations for different grades of elevation, temperature, and rainfall. The correlation analysis between *Eucalyptus* plantations and rainfall revealed that *Eucalyptus* plantations were distributed most widely in areas with rainfall in the range of 1400–1600 mm; the largest distribution was $146.29 \times 10^4 \text{ hm}^2$,

accounting for 32.84% of the total area of *Eucalyptus* plantations. With rainfall in the range of 600–800 mm, *Eucalyptus* plantations showed the smallest distribution, 4.56×10^4 hm², which only accounted for 1.02% of the total area of *Eucalyptus* plantations. The small distribution of *Eucalyptus* plantations in low-rainfall regions was mainly caused by the strong effects of water availability on the growth of *Eucalyptus* trees.

The correlation analysis between *Eucalyptus* plantations and temperature showed that *Eucalyptus* plantations were distributed most widely in regions with a temperature of 19–20°C; the largest distribution was 291.49×10^4 hm², accounting for 65.43% of the total area of *Eucalyptus* plantations. The smallest distribution of *Eucalyptus* plantations was found at the temperatures of 15–16 °C, i.e., 0.72×10^4 hm². The small distribution of *Eucalyptus* plantations in low-temperature regions was associated with the thermophilic property and poor cold resistance of *Eucalyptus* trees. This is slightly different from the results of previous studies [2, 3], which reported that an annual mean temperature above 20 °C is the most suitable for *Eucalyptus* trees. For example, the regions south of the annual mean 20 °C isotherm (i.e., Hexian, Zhaoping, Luzhai, Yishan, Hechi, and Donglan) in Guangxi are recognized as the cultivation centers of *Eucalyptus* trees; the regions north of the annual mean isotherm of 20 °C are considered unsuitable for the cultivation of *Eucalyptus* trees.

The correlation analysis between *Eucalyptus* plantations and elevation showed that *Eucalyptus* plantations were distributed most widely at elevations below 300 m; the largest distribution reached 301.1×10^4 hm², accounting for 67.58% of the total area of *Eucalyptus* plantations. The smallest distribution of *Eucalyptus* plantations was found at elevations of 900–1200 m, i.e., only 5.40×10^4 hm², which accounted for 1.21% of the total area of *Eucalyptus* plantations. The large distribution of *Eucalyptus* plantations in low-elevation regions was mainly associated with the convenience of production and management activities.

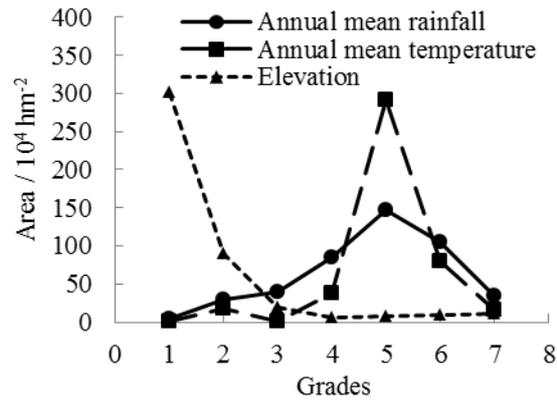


Fig. 4 Area distribution of *Eucalyptus* plantations at different grades of elevation (graded from low to high elevation), temperature, and rainfall

We deleted the sample plots of *Eucalyptus* plantations with harvesting operations and DBH below the scaling condition (<5 m), or those with forest volume of 0 from the spatial database for the 8th Inventory. A total of 470 sample plots were obtained for correlation analysis between the annual mean productivity of *Eucalyptus* plantations and rainfall, temperature, and elevation. Stand productivity was positively correlated with rainfall (correlation coefficient 0.299) and temperature (0.223), while it was negatively correlated with elevation (-0.295). The low correlation coefficients were attributed to the use of climatic factors such as rainfall and temperature. These factors were unavailable in the exiting forest inventory data and were acquired using the GIS software with the support of large-scale climatic data. The large and extensive scale of these climate data caused errors of local results and thus resulted in low correlation coefficients.

3.4 Dynamic change in *Eucalyptus* resources

Table 2 shows the area and volume of *Eucalyptus* plantations in southern provinces calculated from the data of four inventories. The distribution of *Eucalyptus* plantations gradually expanded from 1998 to 2013. *Eucalyptus* plantations were mainly distributed in five provinces, namely, Fujian, Guangdong, Guangxi, Hainan, and Yunnan, in 1998, and

gradually spread to ten provinces/autonomous regions to include Jiangxi, Hunan, Chongqing, Sichuan, and Guizhou in 2013. The area of *Eucalyptus* plantations expanded from $60.70 \times 10^4 \text{ hm}^2$ in 1998 to $445.52 \times 10^4 \text{ hm}^2$ in 2013, and the volume grew from $1387.08 \times 10^4 \text{ m}^3$ in 1998 to $16036.17 \times 10^4 \text{ m}^3$ in 2013. Meanwhile, the volume per hectare grew from $22.85 \text{ m}^3/\text{hm}^2$ in 1998 to $35.99 \text{ m}^3/\text{hm}^2$ in 2013. The proportion of *Eucalyptus* plantation area in the national forest area also increased from 0.47% in 1998 to 2.71% in 2013. The results indicate that the distribution of *Eucalyptus* plantations constantly expanded and accounted for an increasing proportion in the national forest area. *Eucalyptus* has become the major tree species for afforestation in southern China and plays a critical role in the forest area in southern provinces, particularly Guangdong and Guangxi. According to the statistical results of the 8th Inventory, the area of *Eucalyptus* plantations accounted for 23.96% and 18.28% of the forest area in Guangdong and Guangxi, respectively. The high proportions of *Eucalyptus* plantations in these two provinces were attributed to the high economic benefits of *Eucalyptus* and the vigorous development of *Eucalyptus* plantations in these regions. It should be noted that as the area of *Eucalyptus* plantations increased, the original native tree species (e.g., *Pinus massoniana*) showed a constantly decreasing trend. Figs. 5 and 6 clearly show that the area of *Eucalyptus* plantations constantly increased in Guangxi and Guangdong from 1998 to 2103, whereas the area of *P. massoniana* constantly decreased over the same period.

Table 2 The area and volume of *Eucalyptus* plantations in different time periods

| Province | 1994–1998 | | 1999–2003 | | 2004–2008 | | 2009–2013 | |
|----------|------------------------------|-----------------------------|------------------------------|-----------------------------|------------------------------|-----------------------------|------------------------------|-----------------------------|
| | A (10^4 hm^2) | V (10^4 m^3) | A (10^4 hm^2) | V (10^4 m^3) | A (10^4 hm^2) | V (10^4 m^3) | A (10^4 hm^2) | V (10^4 m^3) |
| Fujian | 0.96 | 19.27 | 1.68 | 23.12 | 15.87 | 444.64 | 27.14 | 2040.65 |
| Jiangxi | -- | -- | -- | -- | 1.28 | 0.00 | 4.49 | 54.49 |

| | | | | | | | | |
|-----------|-------|---------|-------|---------|--------|---------|--------|----------|
| Hunan | -- | -- | -- | -- | 1.60 | 0.00 | 2.25 | 8.36 |
| Guangdong | 29.27 | 460.82 | 40.77 | 912.44 | 132.41 | 2119.90 | 171.27 | 5177.83 |
| Guangxi | 7.20 | 290.07 | 14.88 | 216.49 | 53.36 | 1001.37 | 165.24 | 6049.76 |
| Hainan | 17.03 | 504.43 | 16.67 | 538.92 | 19.30 | 507.38 | 14.62 | 524.90 |
| Chongqing | -- | -- | -- | -- | 0.48 | 22.24 | 4.65 | 79.07 |
| Sichuan | -- | -- | 2.43 | 72.22 | 6.32 | 127.77 | 16.02 | 408.20 |
| Guizhou | -- | -- | -- | -- | -- | -- | 0.96 | 10.42 |
| Yunnan | 6.24 | 112.49 | 5.76 | 171.54 | 24.00 | 354.59 | 38.88 | 1682.49 |
| Total | 60.70 | 1387.08 | 82.19 | 1934.73 | 254.62 | 4577.89 | 445.52 | 16036.17 |

Note: “A” refers to area and “V” refers to stand volume; “--” indicate areas with no sample plots

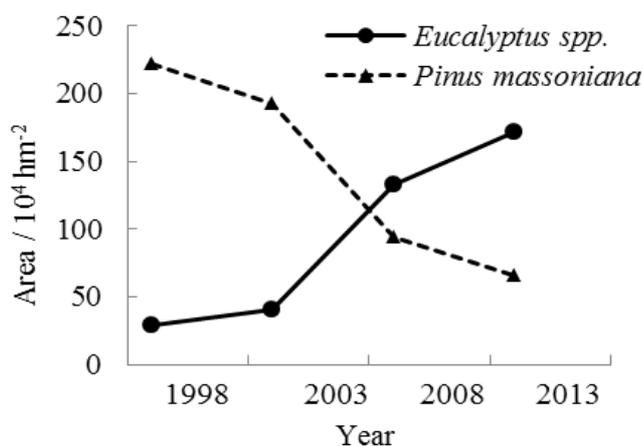


Fig. 5 The area distribution of *Eucalyptus* and *Pinus massoniana* in Guangxi Province in different time periods

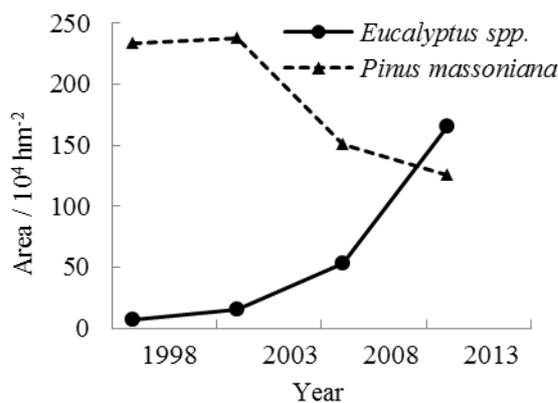


Fig. 6 The area distribution of *Eucalyptus* and *Pinus massoniana* in Guangdong Province in different time periods

3.5 Sampling accuracy of *Eucalyptus* resources

We calculated the sampling accuracy for the area and volume of *Eucalyptus* plantations using formulae (2–7). The results (Table 3) show that the sampling accuracy for the volume was relatively high and reached more than 80% in different time periods. However, the sampling accuracy for the area was relatively low, with the highest value of less than 60% and the lowest value of only 24.48%.

Table 3 The sampling accuracy for area and volume of *Eucalyptus* plantations in different time periods in southern China

| Stages | Area (%) | Volume (%) |
|------------------------------|----------|------------|
| 1994–1998 (5 th) | 24.48 | 84.27 |
| 1999–2003 (6 th) | 37.70 | 85.18 |
| 2004–2008 (7 th) | 43.42 | 90.35 |
| 2009–2013 (8 th) | 58.58 | 94.06 |

4. Conclusions

This study generated geospatial distribution maps of the mean productivity of *Eucalyptus* plantations in four time periods using Kriging interpolation in GIS, with annual mean productivity as the indicator and based on dot maps of sample plots in four national forest resource inventories. The productivity maps reflect the development of *Eucalyptus* plantations and the patterns of change in *Eucalyptus* productivity in southern China. The results are generally consistent with the reality in China, indicating that Kriging interpolation can be effectively used in analysis and research on the distribution patterns of geospatial

location and realistic productivity of tree species. Although the sampling accuracy was relatively low for the area of *Eucalyptus* plantations, the forest investigations generally reflected the trends in the area, and were in line with subjectively observed changes in the actual area.

(1) Over the period 1998–2013, *Eucalyptus* plantations were initially distributed in Leizhou Peninsula in Guangdong and Hainan, and their spatial distribution range gradually expanded northward (Guangxi, Hunan and Guizhou), eastward (Fujian and Jiangxi) and westward (Yunnan and Sichuan) in China. Meanwhile, the spatial pattern of *Eucalyptus* productivity changed and multiple high-yield distribution centers emerged towards the north, east, and west, with Leizhou Peninsula as the center. The area of *Eucalyptus* plantations steadily extended from $60.7 \times 10^4 \text{ hm}^2$ in 1998 to $445.5 \times 10^4 \text{ hm}^2$ in 2103, with an average annual increase of $19.2 \times 10^4 \text{ hm}^2$. The growth rate of the spatial extent of *Eucalyptus* plantation in China showed an accelerating trend.

(2) The distribution of productivity in *Eucalyptus* plantations was closely related to temperature and rainfall. The regions with a temperature above $19 \text{ }^\circ\text{C}$ and rainfall of 1400–1600 mm constituted the main and highest *Eucalyptus* plantation production areas in China. The production operation of *Eucalyptus* plantations was closely related to elevation, and *Eucalyptus* plantations were mainly distributed at the elevations below 300 m.

(3) Significant changes were observed in the plots of *Eucalyptus* plantations. Despite constant increases in the area of *Eucalyptus* plantations, one third of the original *Eucalyptus* plantation area was removed from production every 5 years, and almost no plots were replanted with *Eucalyptus* trees after areas were withdrawn from production. The annual productivity of *Eucalyptus* plantations generally ranged between 7 and $8 \text{ m}^3 \text{ hm}^{-2} \text{ a}^{-1}$, while it was significantly higher in newly reclaimed land, up to $8\text{--}15 \text{ m}^3 \text{ hm}^{-2} \text{ a}^{-1}$. In China, *Eucalyptus* plantations are associated with high management intensity, short rotation periods,

significant benefits, and rapid development. The planting area and productivity of *Eucalyptus* plantations showed 1.85- and 4.85-fold increases in 1994–1998 and 2009–2013, respectively. However, the improvement in annual productivity was mainly caused by the constant increase in the newly afforested areas with good site conditions and simultaneous reduction in the area of the original *Eucalyptus* plantations. This result did not necessarily indicate the improvement in the management techniques and deserves increased attention.

(4) *Eucalyptus* trees are excellent fast-growing species. Because *Eucalyptus* species feature vigorous growth, strong competitiveness, short maturity time, and high growth requirements of nutrients and water, they are difficult to cultivate with other tree species and thus are suitable for planting in regions with relatively high annual mean temperature and rainfall. While the present evaluation of *Eucalyptus* plantations as it related to the poor ecological stability of the genus is objective, it is also one-sided. We must respect the biological characteristics of *Eucalyptus* trees, take advantage of their rapid-growth, and select suitable tree species for each site, to better enhance China's ability to supply wood. Additionally, the use of remote sensing technology has the advantages of low cost and high efficiency when compared with traditional ground surveys. Therefore, the monitoring and analysis of dynamic change in the spatial extent and volume of *Eucalyptus* plantations using remote sensing will be the direction of our next research study.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no any competing financial and non-financial interests.

Funding

This research was supported by the National Natural Science Foundation of China (No. 41601368 and 41861144026).

Authors' contributions

Conceptualization, W.C.; formal analysis, W.C. and Q.Z.; investigation, Y.D.; methodology, W.C. and Q.Z.; supervision, T.S.; validation, Y.D.; writing—original draft, W.C.; writing—review and editing, Y.D. and T.S.

Acknowledgements

The National Forestry and Grassland Administration were thanked for providing the geographical locations of Eucalyptus plantations.

Figures

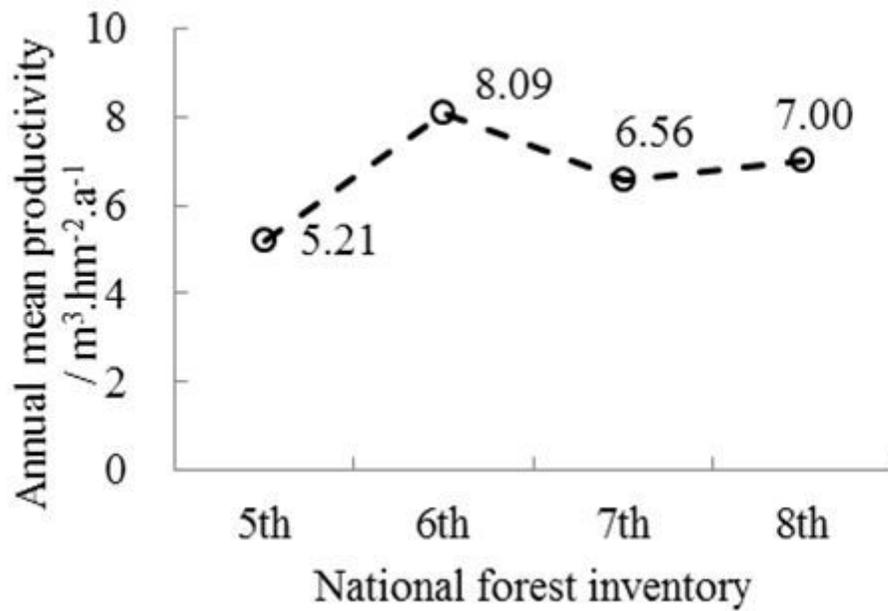


Figure 1

Average of annual mean productivity of Eucalyptus sample plots included in all the four national inventories (5th to 8th)

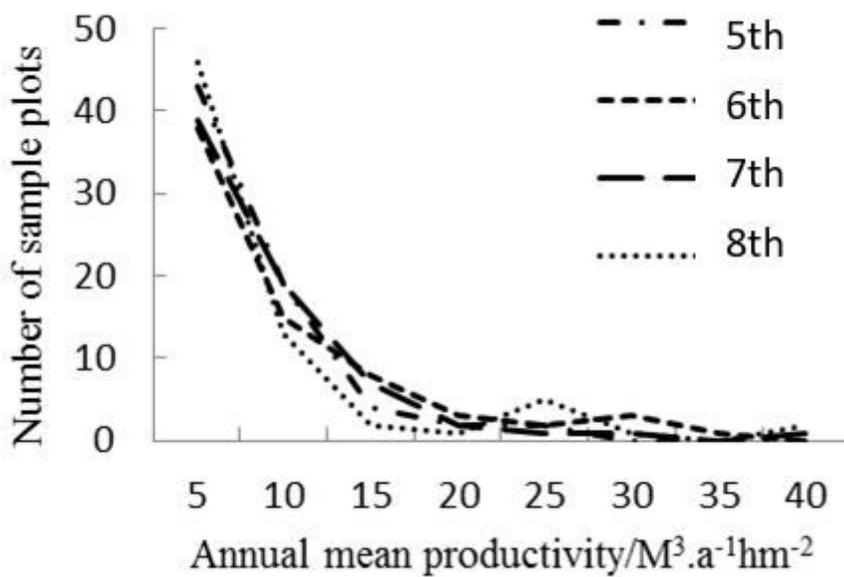


Figure 2

Frequency distribution of annual mean productivity of Eucalyptus sample plots included in all the four national inventories (5th to 8th)

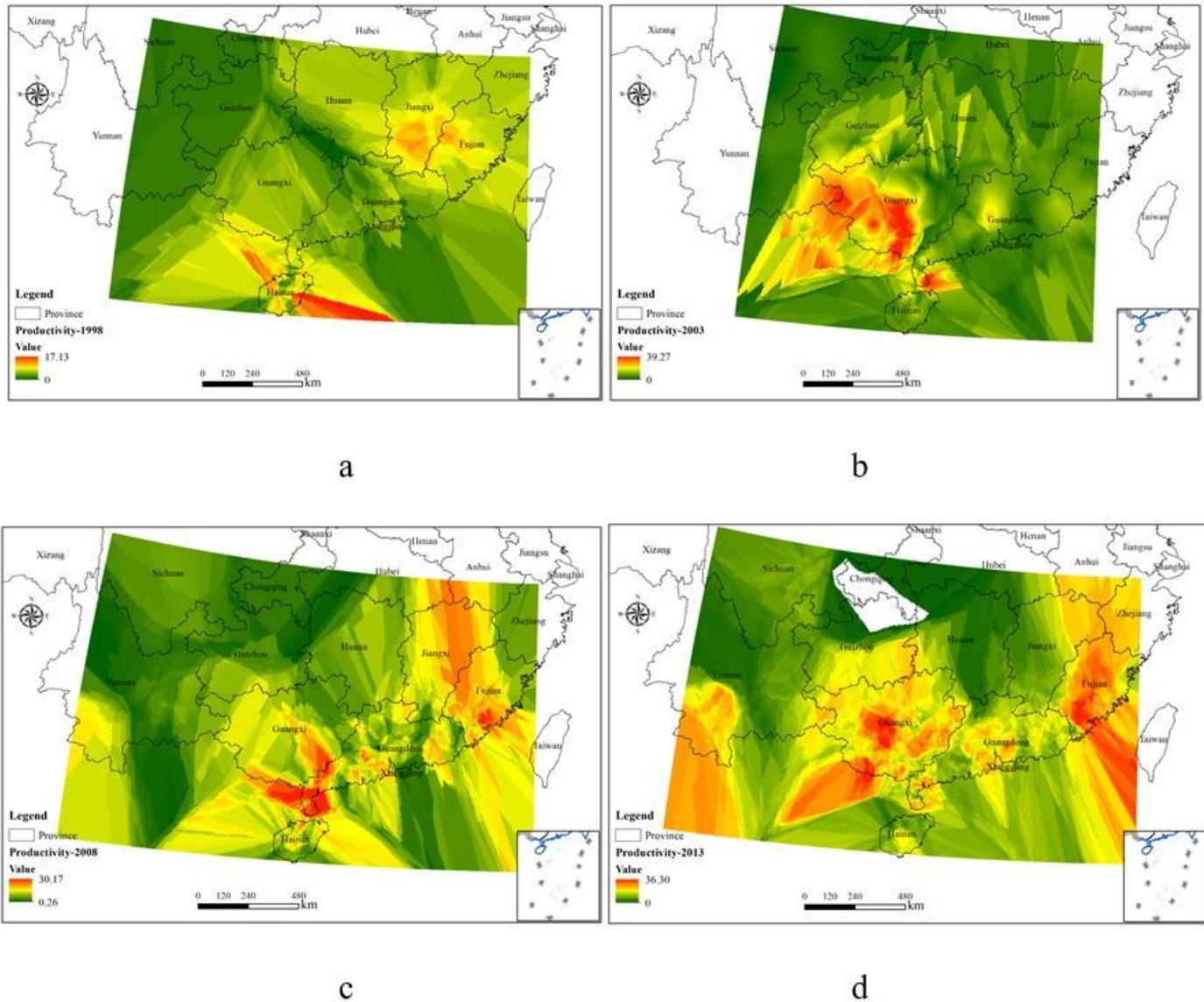


Figure 3

Distribution maps of Eucalyptus productivity obtained by geospatial interpolation (a. 1998; b. 2003; c. 2008; d. 2013) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

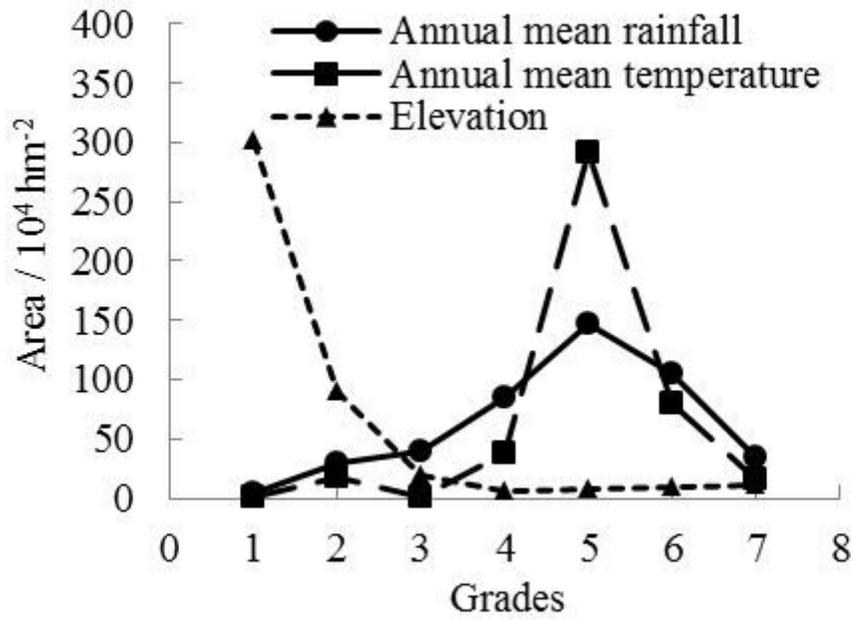


Figure 4

Area distribution of Eucalyptus plantations at different grades of elevation (graded from low to high elevation), temperature, and rainfall

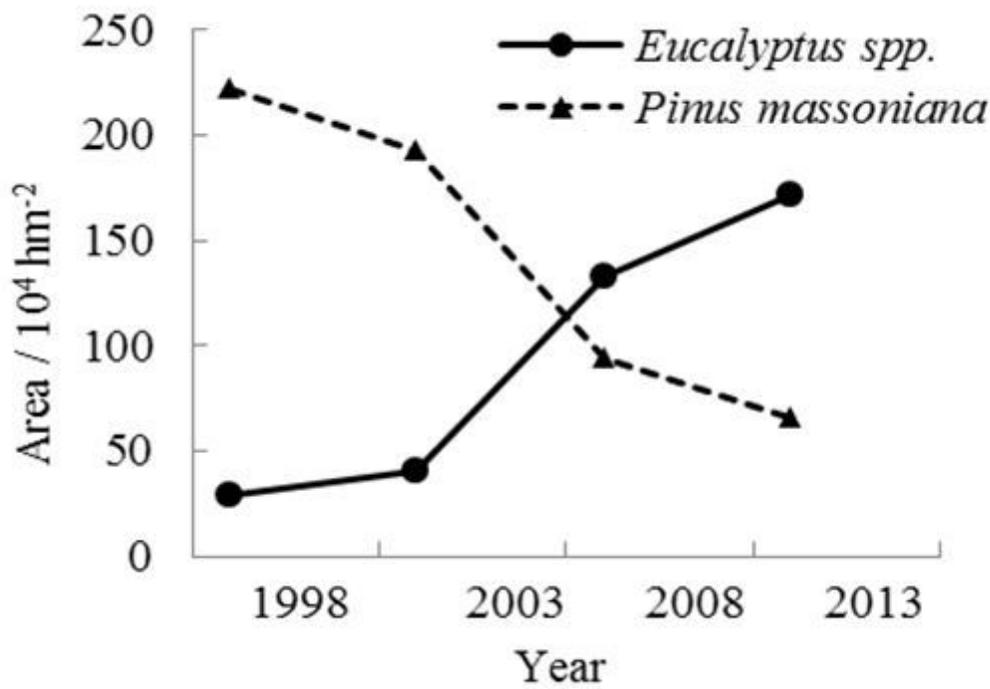


Figure 5

The area distribution of Eucalyptus and *Pinus massoniana* in Guangxi Province in different time periods

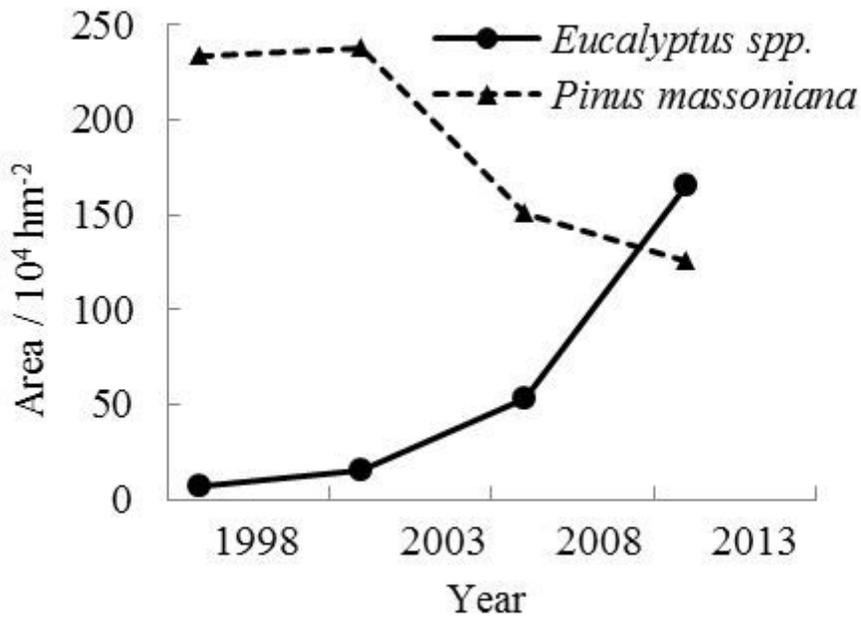


Figure 6

The area distribution of Eucalyptus and Pinus massoniana in Guangdong Province in different time periods