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ORIGINAL PAPER

Examining the century dynamic change of forest oxygen production in Heilongjiang Province, China

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Abstract During the past century, Heilongjiang Province, the highest forest coverage province of China, has experienced rapid deforestation, with coverage decreasing by an estimated 40 %. As the important role that forest vegetation plays in oxygen production and environmental optimization, dynamic change analysis of forest and forest oxygen production has become more and more important. In this study, we examined changes in forest and forest oxygen production, as well as the impact of natural and human activities on such change in Heilongjiang Province, China. In particular, the net ecosystem productivity (NEP) of the forest was generated by the C-FIX model, and the relationship between NEP and forest oxygen production was examined. Analysis results indicate that in the past century, the forest area and oxygen production of Heilongjiang Province has been reduced by about 106,667.57 km^2 (37.16 %) and 56.22 million tons (33 %), respectively. Moreover, the spatial analysis results suggest significant spatial variation of forest oxygen production in Heilongjiang Province, China. Specifically, oxygen production in the southwest has shifted from the highest area to the lowest area, and significant decreases in forest oxygen production have been observed in the Sanjiang Plain and the central part of Heilongjiang Province. In addition, oxygen production also presents decreasing tendencies (>90 %) in Daqing City and Qiqihar. The analysis of the impact of climate change and human activities on forest oxygen production indicates that human activities have the largest impact on forest oxygen production, accounting for about 67.95 % of the decrease.

Keywords Forest oxygen production · Forest cover change · Century dynamic change · Heilongjiang

Introduction

With further research on air quality, concerns have been raised on the changes of oxygen content in the atmosphere. More and more studies have demonstrated that the earth's atmospheric oxygen content peaked in the planet's early days, with an average prehistoric content of atmospheric oxygen of between 30 and 35 %; however, it is only 21 % now and 15 % or even less in the cities or industrial parks with high pollution rates (Bekker et al. 2004; Kasting et al. 1979; Kump and Mark 2007; Chuai et al. 2012). Scholars also found that the oxygen content of the lower atmosphere is decreasing at an average rate of 2 ppm per year (Manning et al. 2003; Li and Wu 2013; Li et al. 2012), and atmospheric oxygen content decreases both annually and seasonally (Keeling and Stephen 1992). The decreasing atmospheric oxygen content influences several issues associated with human health and environmental degradation. For example, when the atmospheric oxygen content is below 18 %, people can experience anoxia and chronic pain and diseases caused by cell hypoxia (Jacobsen 2008; Zhou 1999). In addition, the decrease in oxygen and increases in other atmosphere components, such as carbon dioxide (CO_2), can exert a significant negative effect on the

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surrounding environment. Therefore, the analysis of the dynamic change of oxygen production and assessment of the impacts of natural forces and human activities on such change has become more and more important.

Numerous methods have been developed and applied to estimate oxygen production. One general approach was implemented by calculating the oxygen level in fossil bubbles. Specifically, oxygen content was estimated through a biochemical model (Manning et al. 2003; Keeling and Stephen 1992; Keeling et al. 1998; Abbaspour et al. 2012) based on fossil carbon storage, atmospheric methane content, and soil iron metal content (Claire et al. 2006; Goldblatt et al. 2006; Bangian et al. 2012). Moreover, there were many reports that from the perspective of oxygen sources based on the photosynthesis principle (Sreenivas and Murakami 2005), regional oxygen production could be estimated by the carbon–oxygen balance method (Johnson and Francis 1970a, 1970b; Bortkovskii et al. 2007). According to the carbon–oxygen balance method, two approaches can be employed for calculating regional oxygen production. The first involves converting the consumption of the estimated regional oxygen (Ma et al. 2011), and the second estimates organic carbon produced by regional plants (Chen and Shan 2009; Zhang et al. 2007; Guang et al. 1998). In comparison, the first approach was much more subjective, and the second approach was applied more frequently and widely. In addition to the two carbon–oxygen balance-based approaches, some scholars attempted to estimate oxygen production from vegetation gross primary production (GPP) (Chen and Shan 2009; Zhang et al. 2007) or net primary production (NPP) (Ma et al. 2011; Guang et al. 1998). The former method used the initial organic carbon produced by plants through photosynthesis; the latter one considered the residual organic carbon after plant respiration. Due to different theoretical basis, there was a significant difference between the estimated results. Based on the mechanisms of photosynthesis and respiration and the comparison of GPP and NPP, the consumption of organic carbon caused by plant respiration and incorporation was fully considered in net ecosystem productivity (NEP), which was net photosynthetic production (Lu 2003). Few relevant reports have determined net oxygen production estimated by NEP, and the existing studies rarely combine remote sensing and geographic information system (GIS) technology to analyze the spatial distribution and variation characteristics of regional oxygen production.

The decrease in the number of green plants areas can result in decreased oxygen production. Therefore, changes in atmospheric oxygen content can be indirectly revealed by simulating changes in oxygen sources. Forested land is an important part of terrestrial green vegetation and a significant ecological system for carbon fixation and oxygen release. Heilongjiang Province has the richest forest resources in China, accounting for 1/7 of the country's total forested area. The vast forest is an important source of oxygen and a reservoir of CO_2, both of which play an important role in regulating the regional eco-environment. Due to the impact of human activities, the forested area in Heilongjiang has decreased by about 40 % in the past 100 years, which can decrease forest oxygen production. However, in terms of natural influences, the released quantity of forest oxygen will theoretically increase due to climate warming and increasing CO_2 concentration. No study has assessed the synergistic effects of these two opposing processes on forest oxygen production in Heilongjiang in the last century.

According to the forest cover information of Heilongjiang collected in 1900 and 2009, we simulated forest NEP using the C-FIX model. Based on the carbon–oxygen balance principle, forest oxygen quantities of Heilongjiang in the early and late twentieth century were simulated and analyzed with the GIS spatial analysis method to investigate the influence of changing forest properties and climate on the forest oxygen production.

Materials and methods

Study area

The Heilongjiang Province in northeastern China (see Fig. 1), covering an area of 460,000 km^2 at 121°11′–135°05′E longitude 43°26′–53°33′N latitude, was selected as the study area for this research. Heilongjiang Province is

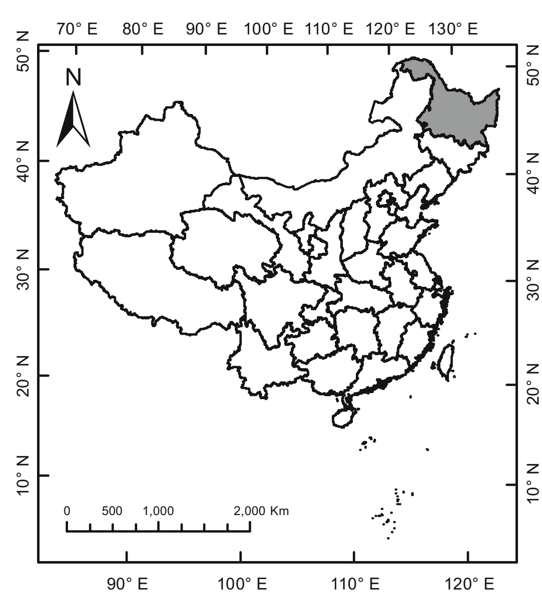


Fig. 1 Location of the study area

the most forested province in China, and approximately 36.7 % of its land is covered with forests, accounting for 1/7 of the forested area in China. Heilongjiang is one of three famous black soil belts in the world (Zhang 2009). Natural temperate and boreal forests dominate the lands in this province and are distributed in the Greater Khingan Mountains, the Lesser Khingan Mountains, the Changbai Mountains, and the Wanda Mountains. Natural forests in this region have suffered as a result of long-term logging and unreasonable management. The climate in Heilongjiang Province is a typical temperate–boreal continental monsoon, with an annual average temperature of −4 to 5 °C and annual total precipitation of around 400–650 mm. The temperature decreases from southeast to northwest, with the largest difference up to 10 °C. The Heilongjiang Province has abundant resources of solar radiation about 46×10^8–50×10^8 J/m^2. The total sunshine duration in the province is 2300–2800 h, of which 44–48 % is during the growing season.

Materials

Forest cover information

Forest cover information was assessed for Heilongjiang in 1900 and 1986. Firstly, a paper map (Li 1993) illustrating the forest distribution of Heilongjiang in 1900 and 1986 was scanned and registered with a geographic coordinates system map for vectorization (see Fig. 2a, b). Then, the normalized difference vegetation index (NDVI) of the forest in 1900 was calculated using a 1986 forest cover map. Forest cover information was also assessed for Heilongjiang in 2009. Based on Landsat ETM + remote sensing images collected from the Institute of Remote

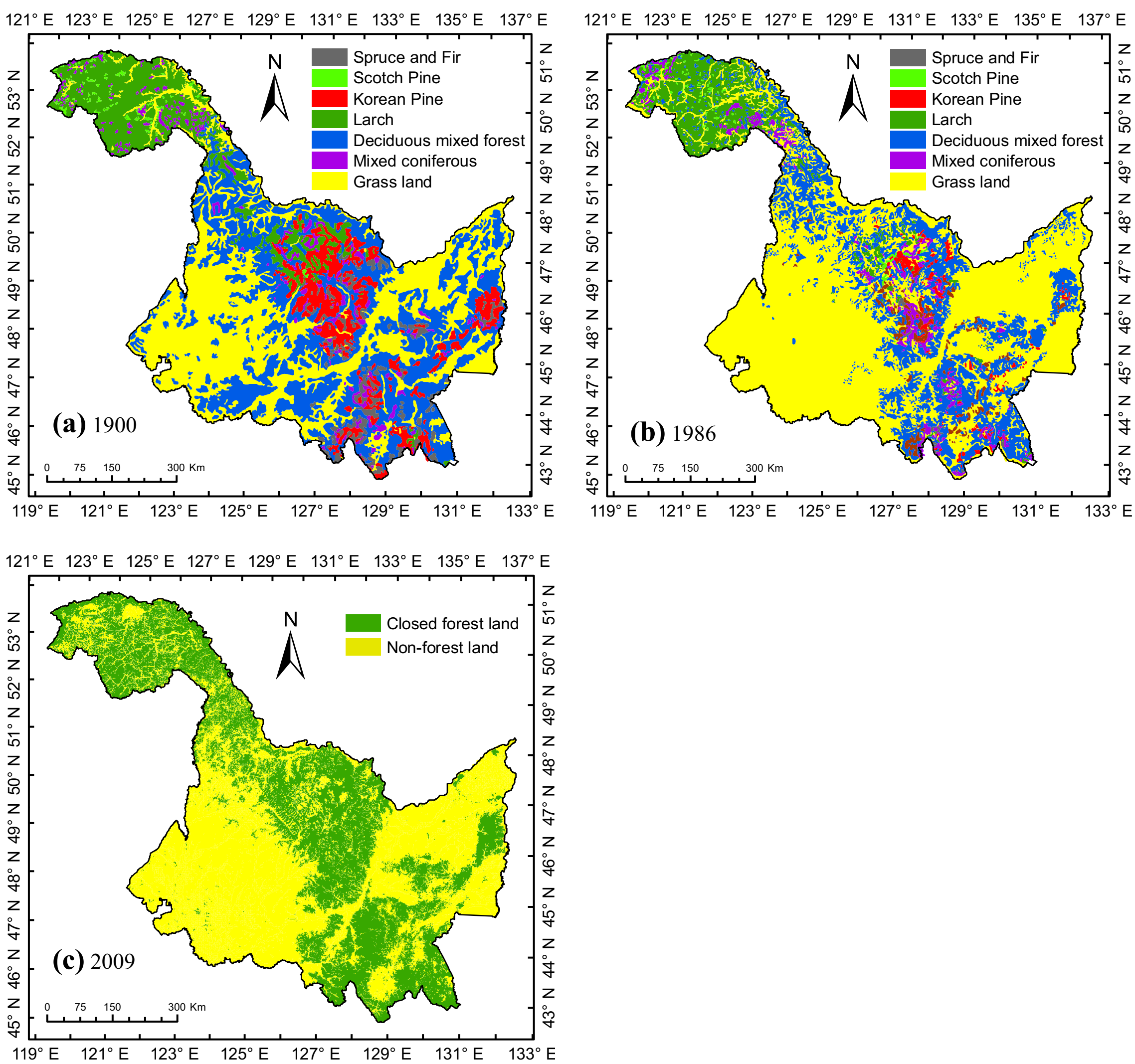


Fig. 2 Forest covers of Heilongjiang in 1900, 1986, and 2009

Table 1 NDVI of vegetation cover form March to November between the 48°N and 49°N

Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Korean Pine	0.2912	0.3482	0.6096	0.8571	0.8328	0.7749	0.7090	0.4707	0.3321
Larch	0.1928	0.2681	0.5413	0.8523	0.8350	0.7745	0.6786	0.3715	0.2269
Spruce and Fir	0.2527	0.3365	0.6008	0.8526	0.8447	0.7649	0.6993	0.4452	0.3111
Scotch Pine	0.2598	0.3229	0.5840	0.8461	0.8187	0.7596	0.6921	0.4434	0.2915
Mixed coniferous forest	0.2818	0.3388	0.5956	0.8548	0.8292	0.7733	0.7038	0.4530	0.3108
Deciduous mixed forest	0.1725	0.2601	0.5318	0.8308	0.8282	0.7672	0.6711	0.3713	0.2214

Sensing, Chinese Academy of Sciences, the land-use patterns were divided into six types by supervised classification, including cultivated land, forestland, grassland, water area, construction land, and unused land. The forest cover information of forestland is shown in Fig. 2c.

Acquisition of temperature and radiation information

To ensure that the simulation results were comparable and reduce the impact of anomalies over the years, temperature and radiation data from 1900 and 2009 were replaced with average temperature and radiation values for 1900–1905 and 2005–2009, respectively. The average monthly temperatures were also calculated. The 0.5° × 0.5° monthly grid temperature data were obtained from the Institute of Climate Research Unit (CRU), University of East Anglia. The climatic elements data from the CRU were calculated by interpolating the actual land surface observation data into the 0.5° × 0.5° latitude and longitude grid data. Fortunately, the CRU data were found to be in accordance with the sequence of the actual observation data, passing significance tests in the regional scale of China (Fang et al. 2010; Zhang et al. 2004). The grid data, including Heilongjiang and nearby areas (comprising a total of 256 points), were extracted, and the Kriging interpolation method was used to construct a 1 km × 1 km temperature grid map of Heilongjiang, covering dates from March to November in both 1900 and 2009. The monthly radiation flux data were subsequently considered. As the CRU data only included cloud cover data and not surface radiation data, the flux of solar radiation reaching the surface of the earth was calculated using astronomic radiation and cloud cover data (Huang and Pan 2008).The daily amount of astronomic radiation was calculated using a previously published formula (Zhou 2003).

A total of 256 points of grid data were extracted covering Heilongjiang and nearby areas during both 1900–1905 and 2005–2009. Solar radiation flux on the ground was subsequently calculated. The 1 km × 1 km grid maps of ground radiation flux were then obtained through the Kriging interpolation method, covering dates from March to November during 1900–1905 and 2005–2009.

Acquisition of NDVI information in Heilongjiang Province

According to previous research, there have not been any obvious changes in NDVI for the vast zonal vegetation types found in northeast China, and there have been no large variations in the inter-annual change of NDVI for forest vegetation types (Chen et al. 2002, 2005; Li et al. 2013; Melemez 2013). We randomly selected larch, Korean pine, and deciduous forest as representatives to extract ten samples for averaging based on the NDVI data in August 1982–2009. The results indicated that there was not too much change for forest NDVI; the coefficients of variations were 0.00278, 0.00208, and 0.0028 for larch, Korean pine, and deciduous forest, respectively. Based on the above findings, anomalous fluctuations of NDVI over the years were disregarded, and the forest distribution map of Heilongjiang in 1986 and the NDVI information from 1984 to 1988 were super-positioned to obtain the monthly NDVI. Therefore, the monthly NDVI of every forest species for each latitude was extracted (take 48–49°N as an example, see Table 1). According to the latitude and forest type, the NDVI was assigned to the relevant forest type of 1900, and the 1 km × 1 km grid map of forest NDVI was obtained for Heilongjiang in 1900 from March to November. The NDVI for 2009 and the 1984–1988 period were downloaded from the United States National Aeronautics and Space Administration (NASA) Web site for the periods between March and September. This information was then superimposed onto the forest cover maps of Heilongjiang in 1986 and 2009 to extract the NDVI distribution map.

Methods

Simulation of forest NEP using the C-FIX model

The C-FIX model is a model of efficiency for solar energy utilization and is capable of achieving an estimation of

NEP on a regional scale. The advantages of the model include a low requirement for input parameters, high computational efficiency, and high spatial-temporal resolution of output (Lu 2003). The C-FIX model can also efficiently simulate the daily NEP value (gC/m^2/day) of each grid. The input parameters of the model are numbered at 15, including the efficiencies for solar energy utilization, the gas constant, and meteorological elements, among others. The input parameters that need to be achieved include the daily average temperature, daily radiation flux, and NDVI, while the rest are constants or empirical values. Previous research has demonstrated that the C-FIX model can simulate vegetation productivity at all levels of Heilongjiang (Zhang 2009).

Estimation of oxygen production by NEP

During photosynthesis, CO_2 and water (H_2O) in the atmosphere under sunlight are absorbed by chlorophyll in plants and transformed into organic matter ($C_6H_{12}O_6$) and oxygen. At the same time, organic carbons and oxygen are consumed by plant respiration. The amount of residual organics after respiration is known as the NEP (gC/m^2/a). The amount of oxygen that corresponds to the NEP is the net amount of plant-produced oxygen. The mass ratio of output C simulated by the C-FIX model and oxygen has been established as 1:2.667.

Spatial analysis method

The ArcGIS spatial overlay, spatial statistics, and various other methods were employed to calculate the total forest oxygen production in each month and year in Heilongjiang Province and its subdivided cities and counties.

Results and discussion

Changes in Forestry Area between 1900 and 2009

The forestry area in Heilongjiang was 287,024.575 km^2 in 1900, and it decreased to 180,357.005 km^2 in 2009. This was an overall reduction of 106,667.570 km^2 or 37.16 % compared with 1900 (Table 2). Among the overall reduction, Heihe City had the largest decrease, with a 19,609.354 km^2 loss, while Qitaihe had the smallest decrease at about 1583.426 km^2. In terms of the percentage decrement rate, Suihua City, Jiamusi City, Jixi City, Qiqihar City, and Daqing City were reduced by more than 50 %. However, Daqing City lost the largest ratio at 94.67 %. In general, the southwest had the largest reductions, followed by the east, central, and north areas (see Fig. 3).

Changes in the forest oxygen production between 1900 and 2009

To avoid anomalous influences from atypical years, daily average temperatures, radiation, and CO_2 concentration (Yan 2009) were replaced by daily average values from the periods of 1900–1905 and 2006–2009 to simulate NEP. These values were then converted into oxygen production. The simulated values of monthly and annual oxygen production in both 1900 and 2009 are shown in Table 3. The spatial distributions of annual oxygen production are shown in Fig. 4. The annual forest oxygen levels produced in 1900 and 2009 in Heilongjiang were 209.719 million tons and 153.503 million tons, respectively. In 2009, forest oxygen production was reduced by 26.81 % (56.216 million tons less than the amount produced in 1900). Oxygen

Table 2 Forest area changes of Heilongjiang from 1900 to 2009 (km^2)

District	1900	2009	Reduction in forest area	Percentage of reduction in forest area
Greater Khingan Mountains	56,729.425	44,655.934	−12,073.491	−21.28
Yichun	30,257.183	24,930.616	−5326.567	−17.60
Mudanjiang	33,394.696	26,768.776	−6625.920	−19.84
Hegang	7554.764	4922.680	−2632.084	−34.84
Harbin	32,686.656	22,529.469	−10,157.187	−31.07
Heihe	49,803.650	30,194.296	−19,609.354	−39.37
Qitaihe	4192.208	2608.782	−1583.426	−37.77
Shuangyashan	12,987.010	7922.788	−5064.222	−39.00
Jixi	14,263.712	6083.324	−8180.388	−57.35
Jiamusi	14,885.318	3873.499	−11,011.819	−73.98
Suihua	16,161.840	4618.782	−11,543.058	−71.42
Qiqihar	7695.127	906.444	−6788.683	−88.22
Daqing	6412.986	341.615	−6071.371	−94.67
Total	287,024.575	180,357.005	−106,667.570	−37.16

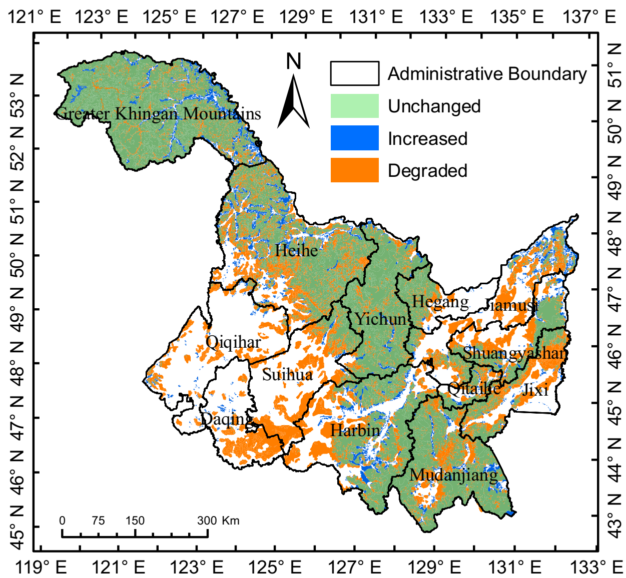


Fig. 3 Spatial variation for the centennial forest of Heilongjiang from 1900 to 2009

production was distributed as expected within the year. Increasing temperatures in March correspond with increased plant photosynthesis and greater oxygen production; both processes peaked in July. Oxygen production then decreased following lower temperatures after the July peak. There were obvious changes in the spatial distributions of the amount of forest oxygen produced annually for both 1900 and 2009. The highest levels of forest oxygen production were in the southwest of Heilongjiang in 1900. However, in 2009, the same area had the lowest levels of forest oxygen production, at essentially zero. Most of the Sanjiang Plain produced forest oxygen in 1900, compared to only east areas of the Sanjiang Plain in 2009. Forest oxygen production also significantly decreased in the central areas of Heilongjiang Province.

With the exception of Yichun, all of the counties and cities in Heilongjiang showed decreased oxygen production in 2009 (Table 4). Oxygen production significantly decreased by more than 90 % in Daqing City and Qiqihar City; more than 50 % in Jiamusi City, Suihua City, and Jixi City; and more than 25 % in Shuangyashan, Qitaihe, Heihe, and Hegang City. A significance test for oxygen was conducted for the years 1900 and 2009 in all cities and yielded a value of 0.000, indicating that oxygen production was significantly different throughout the 100-year period. Therefore, it was evident that oxygen production in 2009 was significantly reduced compared with 1900.

Analysis of reasons for the forest oxygen production change in Heilongjiang

The impact of climate change (including climate warming and increased CO_2 concentrations) on forest oxygen production

Over the past century (1900–2009), the average temperature change in Heilongjiang corresponded to the increasing trend in forest photosynthesis (March–November). The linear trend coefficient was 0.134 °C/10a (see Fig. 5), and the significance probability test value was 0.000, demonstrating a significant upward trend in the average monthly temperature from the March to November period over 100 years. Indeed, the average annual temperature of Heilongjiang from March to November was 1.24 °C higher in 2006–2009 than in 1900–1905. There were few changes in radiation over the century (1900–2009) in Heilongjiang. However, significant increases were seen in atmospheric CO_2 concentrations. In 2009, the CO_2 concentration had increased by 84 ppm compared with 1900. Three control experiments were conducted as part of this research. In the first, invariance in the forest cover NDVI of 1900 was

Table 3 Simulation results for forest oxygen production of Heilongjiang (10^7 kg)

Month	Jan	Feb	Mar	Apr	May	Jun
1900 estimates	0	0	67.622	403.793	2209.667	4951.906
2009 estimates	0	0	49.522	313.5861	1917.915	3334.077
Control experiment 1	0	0	71.490	484.207	2801.132	5954.824
Control experiment 2	0	0	70.661	437.536	2517.261	5268.017
Control experiment 3	0	0	66.833	422.413	2441.600	5871.619

Month	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
1900 estimates	5229.030	4836.383	2739.034	475.995	58.474	0	20,971.907
2009 estimates	3968.617	3615.644	1846.385	269.542	35.054	0	15,350.343
Control experiment 1	6948.197	6039.552	3005.160	590.528	57.317	0	25,952.407
Control experiment 2	5264.704	4991.595	2781.467	554.376	56.848	0	21,942.465
Control experiment 3	6333.483	5805.046	3113.375	495.912	57.557	0	24,607.838

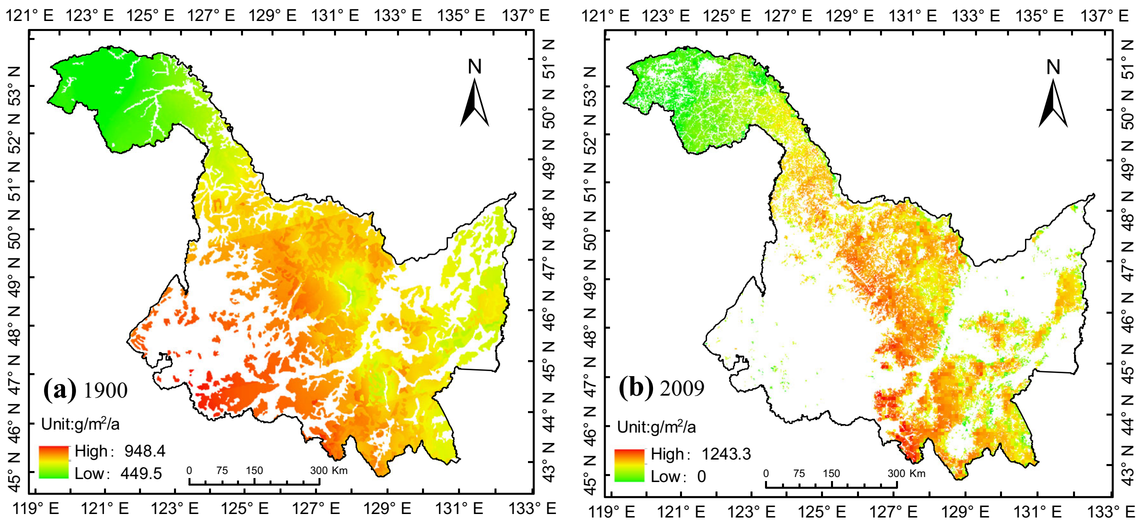


Fig. 4 Spatial distribution for annual amounts of forest oxygen production for Heilongjiang in 1900 and 2009

Table 4 Oxygen production changes in the forest vegetation of Heilongjiang in 1900 and 2009

District	1900 ($\times 10^7$ kg)	2009 ($\times 10^7$ kg)	Oxygen production changes ($\times 10^7$ kg)	Rate of oxygen production change (%)
Daqing	582.904	20.423	−562.481	−96.50
Qiqihar	664.312	72.433	−591.879	−89.10
Jiamusi	1072.91	330.655	−742.255	−69.18
Suihua	1386.593	482.854	−903.739	−65.18
Jixi	1030.339	510.848	−519.491	−50.42
Shuangyashan	921.746	680.901	−240.845	−26.13
Qitaihe	310.171	229.262	−80.909	−26.09
Heihe	3829.228	2833.676	−995.552	−26.00
Hegang	578.123	441.986	−136.137	−23.55
Harbin	2701.851	2255.278	−446.573	−16.53
Greater Khingan Mountains	3037.534	2754.864	−282.670	−9.31
Mudanjiang	2544.448	2385.527	−158.921	−6.25
Yichun	2311.748	2351.636	39.888	1.73
Total	20,971.907	15,350.343	−5621.564	−26.81

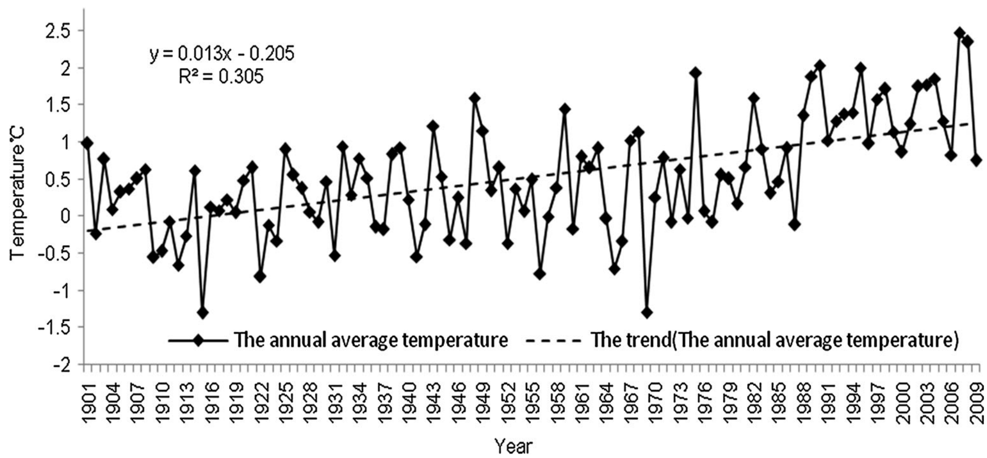
maintained, and the simulated value of forest oxygen production was subsequently obtained using the drive model of 2009 temperature, radiation, and CO_2 concentration values. The difference between the simulated and actual oxygen produced yielded a value that illustrated that the amount of forest oxygen production was influenced by climate change (increased CO_2 concentration and climate warming).

$$\Delta O_{2,\mathrm{climate},CO_2} = O_{2,\mathrm{control1}} - O_{2,1990} \quad (1)$$

where $\Delta O_{2,\mathrm{climate},CO_2}$ is the change value of forest oxygen production influenced by climate changes, $O_{2,\mathrm{control1}}$ is the simulation value of forest oxygen production in control experiment 1, and $O_{2,1900}$ is the simulation value of forest oxygen production in 1900.

The results of control experiment 1 are shown in Table 3. The results demonstrated that $O_{2,\mathrm{control1}}$ was 259.524 million tons, $O_{2,1900}$ was 209.719 million tons, and $\Delta O_{2,\mathrm{climate},CO_2}$ was 49.805 million tons. This was equivalent to a 23.75 % increase when compared with oxygen production in 1900. Evidently, the amount of forest oxygen produced has increased by about 25 % due to climate changes (see Fig. 6a). Meanwhile, the spatial distribution showed significant increases in oxygen production in the southwest. This suggests that forest oxygen production is highly sensitive to changes in natural conditions.

Fig. 5 Average temperature trend changes of Heilongjiang Province between March and November from 1900 to 2009



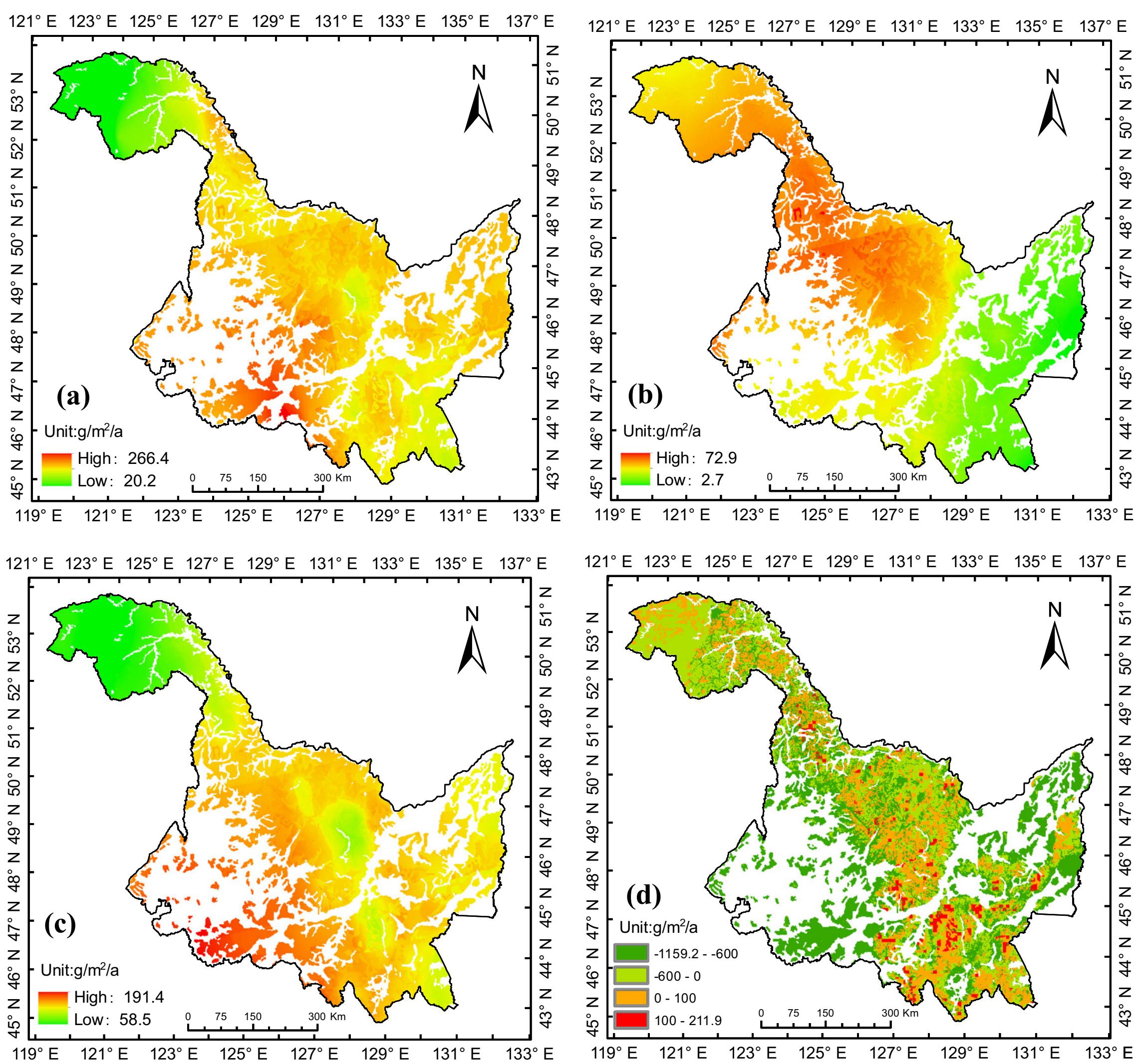


Fig. 6 Effect of climatic change (**a**), climatic warming (**b**), CO_2 density change (**c**), forest changes (**d**) on forest oxygen production

Simulation of the impact of climate warming on forest oxygen production

By maintaining the invariance of the forest cover properties and CO_2 concentration in Heilongjiang Province during the past century, the simulated value of forest oxygen production could be obtained using the drive model of NDVI in 1900, CO_2 concentration and radiation in 1900, and temperature in 2009. The difference between the simulated value and the actual oxygen produced provided the value of forest oxygen production influenced by climate change (climate warming).

$$\Delta O_{2,\mathrm{climate}} = O_{2,\mathrm{control2}} - O_{2,1990} \quad (2)$$

where $\Delta O_{2,\mathrm{climate}}$ is the change value of forest oxygen production influenced by climate warming, $O_{2,\mathrm{control2}}$ is the simulation value of forest oxygen production in control experiment 2, and $O_{2,1900}$ is the simulation value of forest oxygen production in 1900.

The results of control experiment 2 are shown in Table 3. Quantity changes in the spatial distribution of forest oxygen (Fig. 6b) under the conditions of control experiment 2 were obtained by the superposition of forest oxygen production in 1900. The results of control experiment 2 demonstrated that $O_{2,\mathrm{control2}}$ was 219.425 million tons, $O_{2,1900}$ was 209.719 million tons, and $\Delta O_{2,\mathrm{climate}}$ was 9.706 million tons. This is equivalent to a 4.63 % increase in oxygen production compared with 1900, which is attributable to climate warming. As shown in Fig. 6b, oxygen production markedly increased due to climate warming, while the spatial distribution demonstrated a significant increase in oxygen production in the central area of the province. This suggests that forest oxygen production in the central region is highly sensitive to the influence of climate warming.

Simulation of the impact of CO_2 concentration increases on forest oxygen production

By maintaining the invariance of the forest cover properties and climate changes in Heilongjiang during the past century, control experiment 3 was performed to obtain the simulated value of the forest oxygen production with the use of the drive model of NDVI, climate conditions of 1900, and CO_2 concentration of 2009. The difference between the simulation value and actual oxygen production was pinpointed as the value of forest oxygen production influenced by increases in CO_2 concentration.

$$\Delta O_{2,CO_2} = O_{2,\mathrm{control3}} - O_{2,1990} \quad (3)$$

where $\Delta O_{2,CO_2}$ is oxygen production change influenced by increased CO_2 density, $O_{2,\mathrm{control3}}$ is the simulation value in control experiment 3, and $O_{2,1900}$ is the simulation value of forest oxygen production in 1900.

The results of control experiment 3 are shown in Table 3. The superposition of forest oxygen production in 1900 was used to identify the increasing quantity of forest oxygen under the conditions of control experiment 3. The results demonstrated that $O_{2,\mathrm{control3}}$ was 246.078 million tons, $O_{2,1900}$ was 209.719 million tons, and $\Delta O_{2,CO_2}$ was 36.359 million tons. This is equivalent to a 17.34 % increase in oxygen production compared with 1900 due to higher CO_2 concentration. As illustrated in Fig. 6c, the oxygen production of the entire province increased due to higher CO_2 concentration. Meanwhile, the spatial distribution showed the most significant increases in forest oxygen production in southwest Heilongjiang Province, indicating that this area is more sensitive to increased CO_2 levels.

Simulation of the impact of changes in the forest properties on forest oxygen production

The difference between the results of control experiment 1 and the simulated value of actual forest oxygen production in 2009 indicates that the simulated value of forest oxygen production was influenced by forest property changes.

$$\Delta O_{2,\mathrm{forest}} = O_{2,2009} - O_{2,\mathrm{control1}} \quad (4)$$

where $\Delta O_{2,\mathrm{forest}}$ is the change value of oxygen production influenced by the forest property change, $O_{2,\mathrm{control1}}$ is the simulation value in control experiment 1, and $O_{2,2009}$ is the simulation value of forest oxygen production in 2009.

The results of control experiment 1 demonstrate that $O_{2,\mathrm{control1}}$ was 259.524 million tons, $O_{2,2009}$ was 153.503 million tons, and $\Delta O_{2,\mathrm{forest}}$ was −106.021 million tons. This was equivalent to a decrease of 50.55 % in oxygen production compared with 1900 due to forest changes. The results of control experiment 1 and the oxygen production map of 2009 were super-positioned to obtain a space variation map of forest oxygen production that indicated the influence of forest changes (Fig. 6d). Forest oxygen production decreased by 202,622 km^2 in some areas, but it also increased by 80,993 km^2 in others due to forest changes by spatial statistics. The area that caused decreases in oxygen production was 2.5 times more influential than the area causing increased oxygen production. The latter was located in the central region of the province and showed a zonal distribution from south to north. As there were no human activities in this area, oxygen production increased, and the forest became thicker as a result of climate change. However, forest area decreased in the areas influenced by human activities, resulting in an overall decrease in oxygen production, even though the climate conditions were beneficial for vegetation growth.

Comparative analysis of the impact of natural and human activities on forest oxygen production

Firstly, based on the above results, a comparison of different influences on forest oxygen production, including changes in forest properties, climate warming, and CO_2 concentration increases, is shown in Fig. 7. Two conclusions could be concluded from this comparison. Changes in natural factors, such as climate changes, climate warming, and CO_2 density changes, are likely to cause an increase in forest oxygen production, while forest changes are likely to decrease oxygen production. When considering the total variation of oxygen production as 100 %, forest change accounted for 67.95 %, compared to 32.05 % for natural factors. More precisely, forest change could be considered as the key factor in decreased forest oxygen production in Heilongjiang. In addition, among the natural factors, climate warming accounted for 23.30 % and increases in CO_2 concentration accounted for 77.70 %, indicating that increases in CO_2 concentration were more influential than climate warming. Lastly, there were increases in temperature and in CO_2 concentration, but minimal increase in radiation over the 100-year period in Heilongjiang, which proved highly beneficial for photosynthesis. However, oxygen production decreased over this period, further indicating that a decrease in the forest area was the significant driving factor for reductions in regional oxygen production.

Secondly, the average temperature difference between 1900 and 1905 in Heilongjiang was 0.3 °C, increasing to 1.54 °C between 2006 and 2009. This was an overall average temperature increase of 1.24 °C. The annual precipitation in Heilongjiang was 405.8 mm in 1900 and 486.8 mm in 2009. This was an annual precipitation increase of 81.0 mm. The CO_2 concentration in the atmosphere also increased by 84 ppm. These natural conditions were conducive for lush forest growth and should have

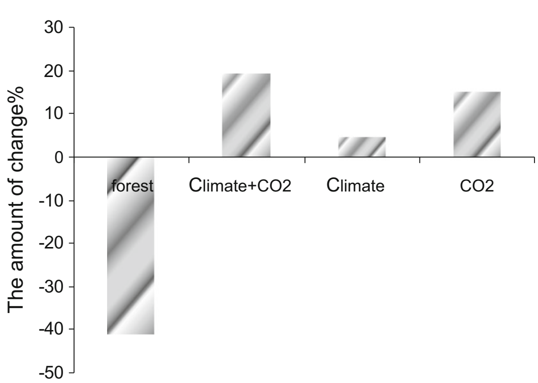


Fig. 7 Comparison between the impact of forest change and climate change on forest oxygen production

increased forest oxygen production. However, due to changes in forest properties and area over the 100-year period, oxygen production dropped by nearly a third. This can be attributed in large part to artificial activities that led to decreases in the forest area. If adverse climate conditions had also occurred, in turn affecting forest growth, there would have been an even more significant decrease in forest oxygen production.

Simulating the results test for forest oxygen production and NEP

Most other studies employed the carbon–oxygen balance approach for estimating forest annual oxygen production for different areas. Zhang et al. (2007) estimated the annual forest oxygen production for Zhengzhou, China as 24.0 t/hm^2 in 2010; Peng (2003), and Guang et al. (1998) estimated these values for Guangzhou and Pearl River Delta as 12.70 and 10.59 t/hm^2, respectively, based on NPP; Su et al. (2010) calculated the annual forest oxygen production for broad-leaved and coniferous forests in Nanjing as 12.52 and 13.51 t/hm^2, respectively, using NPP. In addition, Deng and Gong (2010) examined the forest oxygen production for evergreen broadleaf, deciduous, and boreal forests as 18.53, 17.11, and 11.39 t/hm^2, respectively. Nakazawa (1997) concluded that broadleaf forest production is 18.25 t/hm^2; Berbigier et al. (2001) estimated the annual forest oxygen production in France as 11.468 t/hm^2. In this study, we simulated the annual forest oxygen production for Heilongjiang Province, China as 8.055 t/hm^2, with the annual forest oxygen production for different forest types ranging from 6.049 to 8.697 t/hm^2. In comparison, although all studies mentioned above assessed different study areas with different estimated quantities of annual forest oxygen production, they are all in the same order of magnitude. Because there is no full consideration of respiration for GPP- and NPP-based approaches for the estimation of annual forest oxygen production, the estimated quantity is quite different from the simulated results in this study. In addition, the other reason could be that different approaches have been used for estimating NPP, including forest volume-based, biomass-based, and literature review-based methods. The simulated results in this study indicate that spruce–fir and Korean pine forests have the highest levels of oxygen production, a result that is consistent with the findings described by Su et al. (2010).

In addition, we also validated the C-FIX model-generated NEP in Heilongjiang Province. In particular, the NPP was calculated using the stock volume-productivity model (Fang et al. 1996) in 37 randomly selected sample regions based on the forest inventory data for Yichun in 2000. Further, the NEP was examined through the heterotrophic respiration northeast model (Zhou et al. 2004), with gC/m^2/

a as the final unit. The RMSE is 16.33, which is about 3.8–5.0 % of the original data, and indicates that the model performed well. The annual average value for NEP in Heilongjiang Province is 316.727 gC/m^2/a. Although the simulated results are slightly lower than the general average forest NEP (578 gC/m^2/a, Zhang et al. 2010), it is reasonable because the average temperature for Heilongjiang Province is lower. In this study, we revealed the change of forest oxygen production in Heilongjiang Province in the twentieth century. Therefore, the error generated by the C-FIX model for NEP can be considered as a systematic error that has minimal impact on the change trend of oxygen production.

Conclusion

Spatial variation in forest oxygen production was relatively obvious in the southwest and the Sanjiang Plain. Falling from its status as the highest oxygen production area, the southwest subsequently became the lowest producing area, at values of almost zero. Due to a reduction in forest area, there have been obvious oxygen production decreases in the Sanjiang Plain. There was also a clear decrease in oxygen production in central Heilongjiang. Over the past 100 years, the overall amount of forest oxygen produced in all regions of Heilongjiang declined, with the exception of Yichun. Notably, forest oxygen production significantly decreased by more than 90 % in Daqing City and Qiqihar City; more than 50 % in Jiamusi City, Suihua City, and Jixi City; and more than 25 % in Shuangyashan City, Qitaihe City, Heihe City, and Hegang City.

Changes in natural factors, such as climate warming and increases in CO_2 concentration, have caused subsequent increases in forest oxygen production. However, a significant decrease in forest area due to human activities has contributed to an overall decrease in forest oxygen production. Changes in forest oxygen production were found to be 67.95 % due to changes in forest area and 32.05 % as a result of natural factors. During the increase in forest oxygen production caused by natural factors, 23.30 % was attributed to climate warming, and 77.70 % was attributed to increases in CO_2 concentration. Collectively, the data demonstrate that an increase in CO_2 concentration was the most influential natural factor in the increase in forest oxygen production.

Further research in this area would be highly beneficial. This study focused on the simulation of regional oxygen production; however, consideration also needs to be given to the large amount of oxygen consumed through human breathing, fuel combustion, and industrial production, among other factors. As the net increase in oxygen was defined using the difference between regional oxygen production and consumption, additional studies are required into the influences of these factors. In addition, air flow introduces a vertical exchange in addition to a horizontal exchange. Therefore, considering atmospheric exchange conditions and converting regional oxygen production into atmospheric oxygen concentration is a very complicated process. A long-term, in-depth study is required to verify this process. Lastly, the absence of long-term observation data of oxygen means that the results estimated in this study would benefit from comparison with other results.

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