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Tree-ring growth patterns of Masson pine (*Pinus massoniana* L.) during the recent decades in the acidification Pearl River Delta of China

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ABSTRACT

Long-term changes of the ring-widths of Masson pine (*Pinus massoniana* L.) growing at polluted and unpolluted sites in the Pearl River Delta of south China were compared to evaluate the growth patterns in response to the atmospheric pollution since the late 1970s. Trees at the currently polluted sites had statistically lower ring-widths than those at the unpolluted site since the early 1980s. Standard chronologies at the polluted sites showed consistent decrease in growth since the 1990s. Climate-growth model developed by the multi-stepwise regression at the unpolluted site explained 91.1% of the tree growth variation from year to year and thus it was suggested to be a control chronology index to predict the growth patterns of the pine trees in the study. Growth patterns at the polluted sites estimated by the model revealed negative departure from the control chronology index since the 1980s. The actual and estimated tree-ring indices even at the polluted sites showed synchronousness and statistical correlation in growth patterns prior to the 1980s. The significant increase of the mean differences between the actual and estimated indices and the statistical decrease of the correlation between the control index and the polluted ones after 1980 (especially after 1990) also demonstrated that the growth of pine trees deceased during the most recent years and the atmospheric pollution might be the main factor contributing to the growth decrease. The method of tree-ring analysis demonstrated high suitability and urgent necessity to assess the pine forest health and to improve the forest management in south China where potential forest decline (in particular, current die back) of Masson pine was on process.

1. Introduction

Atmospheric pollution and climate change are two key factors threatening to forests health and their sustainability. It was estimated that global forest area at risk from S deposition might reach 5.9 million km^2 by 2050 and 49% of forests would be exposed to damaging concentrations of tropospheric O_3 by 2100 (Percy and Ferretti, 2004). Dendrochronology of pine species has been widely used to examine specific effects of pollutants on ring-width and to investigate the responses of forest health to atmospheric emissions (Hirano and Morimoto, 1999; Long and Davis, 1999; Dittmar et al., 2003; Tolunay, 2003; Muzika et al., 2004). In terms of pollution, the Pearl River Delta of south China has been one of the severely polluted areas since the period before and after the late 1970s when the open-door policy and economic reforms with special regulations and taxation to attract foreign investments were implemented in the Pearl River Delta, and thereafter the Delta region has undergone a rapid transition from a traditional agriculture-based economy to an increasingly industry- and technology-based economy. Concentrations of the atmospheric pollutants have still remained at fairly high levels (Wong et al., 2002). The pollutants, especially SO_2 and NO_x contributed from the lasting inputs of acid deposition from a growing amount of industrial emissions, have been reported to inflict significant damage on local plants in intensive industrial areas like Guangzhou, Foshan in the Delta (Yuan, 2002).

Masson pine (*Pinus massoniana* L.) is a dominant and local native tree species in south China. There had been a huge increase of forest area planted with this species in south China during the several decades due to its fast and easy growing at the lean soils. Planting and constructing ecological forests which are managed to

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provide ecological services, social benefits and public-welfare provisions, has been one of major actions subjected to environmental quality improvement and wildlife protection at different level of governments in Guangdong province in recent decades. Total areas of Masson pine were estimated to account for more than 45% of the total ecological forests in the province (Zhou and Yan, 2000). Although damages on local plants caused by a great amount of industrial emissions have been well documented at the polluted areas in the Delta since the late 1990s (Hu and Su, 1999; Luo et al., 2001; Jin, 2002; Yu et al., 2005; Wen et al., 2006), focuses were still mainly concentrated on short-term ecophysiological behaviours of plants in response to the pollution stress (in particular the acid deposition) (Wen et al., 2004; Yu et al., 2005), nutritional status and heavy metals concentrations (Kuang et al., 2007) in pine needles. The question how the ring growth pattern of Masson pine responded to the long-term impacts of atmospheric pollution occurred during the past decades was scarcely concerned for lacking long-term measurements. The volume losses of pine forest caused by atmospheric pollution in Guangdong province during 1985–1990 was reported to be nearly 2.5 million m^3 $year^{-1}$ (Hu and Su, 1999). Thus, understanding the growth patterns of Masson pine in relation to the environmental pollution was basically needed for the forest managements in the future.

We intend to, in the present study, ascertain if the growth of Masson pine growing at the industrial sites evidently decreased in the period extending about 50 years back in time, particularly in the period since China's opening and reforming policy was implemented in the early-1980s, using tree-ring analysis, and to test if this method is applicable for the forest health assessment in the whole Delta in south China experiencing rapid industrialization and urbanization.

2. Materials and methods

2.1. Site selection

The Pearl River Delta in south China covers nine prefectures of the Guangdong province, namely Guangzhou, Shenzhen, Zhuhai, Dongguan, Zhongshan, Jiangmen, Foshan, Zhangqing and Huizhou, and two SARs of Hong Kong and Macao. During the past 30 years, expansion of industries and urbanization has caused severe environmental degradation (Yuan, 2002), prominently, the increased emission and deposition of acidic pollutants (Xie et al., 2002; Huang, 2003) in this region. Acid rain has been the major environmental problem in Guangdong since the 1980s (Jin, 2002), and the Delta has become one of the four regions severely polluted by acid rain (the other three are Middle of China, Southwestern China and Eastern China) in China (Yang et al., 1996). Gaseous SO_2 and NO_x have appeared to be the dominant toxicants for forest ecosystems in the Delta (Luo et al., 2001).

In the present study, Guangzhou, Foshan and Zhaoqing were selected as the polluted sites, and Huizhou was as the relatively clear one with a variety of reasons. The former three regions received large amount of industrial SO_2 each year since the 1990s (Huang, 2003) and high mean emissions of SO_2 from 1998 to 2000 (Fig. 1). Specifically, the industrial emission of SO_2 in 2000 reached 200 100 t at Guangzhou, 104 900 t at Foshan, and 31 900 t at Zhaoqing, representing over 55% of the total emissions in the Delta, and the lowest SO_2 emissions (8300 t) was recorded at Huizhou (Guangdong Statistical Bureau, 2001). In addition, forests with total area over 120 million hectares exposed to damaged concentrations were mainly distributed in Guangzhou, Foshan and Zhaoqing (Hu and Su, 1999) and forest damage was rarely reported from Huizhou.

At the polluted sites, South China Botanical Garden (SBG), Xiqiaoshan forest park (XQS) and Dinghushan National Natural Reserve (DHS) were selected as representative for sampling in Guangzhou, Foshan and Zhaoqing, respectively. At the relatively clear region, Nankunshan Natural Reserve (NKS) in Huizhou was selected for sampling (Fig. 2). SBG located at southeast of urban Guangzhou, is the largest botanical garden in subtropical China, which was affected by the release and transport of gaseous and particulate pollutants from urban industries and vehicles. Die back of large scale Masson pines was observed near the petrochemical industry and around the SBG as well in recent years. Though the causes for pines dieback are not clearly understand, pine needles collected from SBG and near industrial sites show fairly high sulfur and heavy metal concentrations than those from remote rural site NKS (unpublished data). XQS is located near Nanhai, one of the largest ceramic industrial centres in China. It was estimated that there were 94 ceramic factories and over 300 burning kilns within 78 km^2 (Ma, 2002). Previous monitoring data showed the rate of sulfating and the deposition of fluorine compounds near a village forest from June to November was far above the national standards (Wen et al., 2003). Damages on vegetation close to ceramic industries (Wen et al., 2006), and decreased photosynthetic pigments and photochemical efficiency of pine needles at XQS (Yu et al., 2005) were reported. DHS, one of the earliest national natural reserves in China is established in 1956 and located at the west of Foshan and Guangzhou. Few industries were recorded in the surroundings of the reserve and the pollution sources were mainly from the industries of the Delta transported by the southwest prevailing wind in the summer (Qi et al., 2001). Wet nitrogen deposition at DHS increased from 35.57 kg hm^{-2} a^{-1} in 1989–1990 (Huang et al., 1994) to 38.40 kg hm^{-2} a^{-1} in 1998–1999 (Zhou and Yan, 2001), implying DHS has become one of the acid deposition areas in the Pearl River Delta. NKS locates at Longmen county of municipal Huizhou and at Zengcheng of Guangzhou. Forest trees including Masson pines on the Longmen side of NKS grows healthy, and sulfur and heavy metals in pine needles at NKS are much lower than in urban Guangzhou industrial site and SBG (unpublished data). Forest decline and vegetation damage at NKS have not been reported till now.

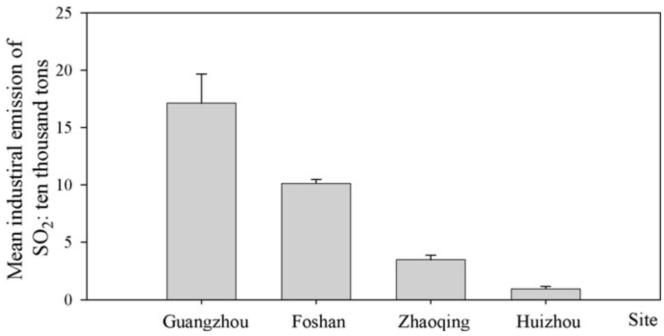

Fig. 1. Mean industrial emissions of SO_2 at the study sites from 1998 to 2000. Data were from Guangdong Statistical Bureau (2001).

At each site, mixed forest stands containing at least 60% broadleaf trees were selected for pine trees sampling. All sampling sites were characterized as subtropical monsoon climates and laterite soils developed from granite and sand shale. The co-dominant broadleaf species with pines are *Schima superba, Castanopsis chinensis, Melastoma candidum, Eucalyptus spp* and *Broussonetia papyrifela* at SBG, *Schima superba*, *Randia canthioides*, *Lindera metcalfiana*, *Castanopsis chinensis*, *Cryptocarya concinna*, *Schefflera octophylla*, *Syzygium rehderianum* at DHS, *Schefflera octophylla*, *Schima superb*, *Machilus chinensi*, *Cinnamomum camphora*, *Mallotus apelta*, *Aporosa dioica*, *Garcinia oblongifolia* at XQS,

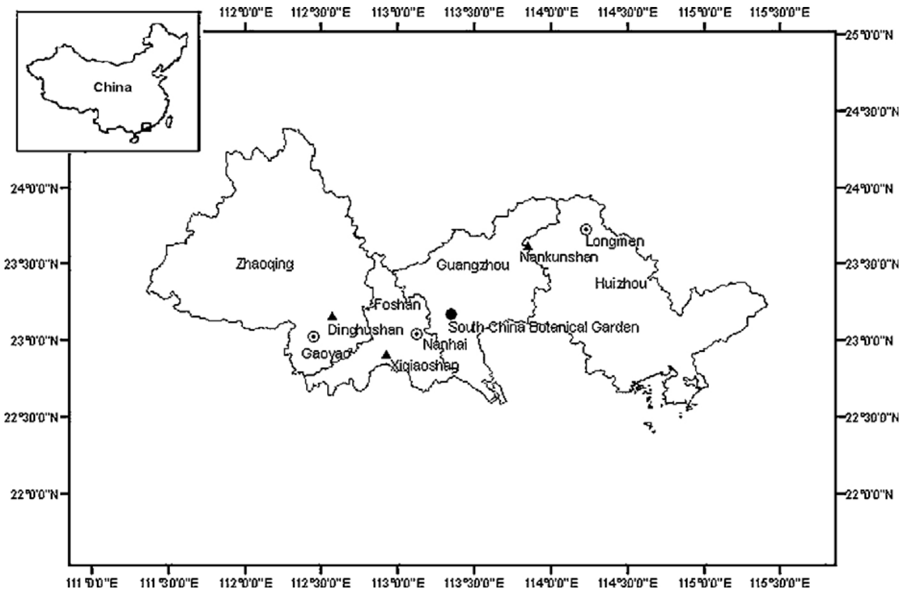

Fig. 2. Map of sampling sites in the Pearl River Delta, south China.

and *Schima superba, Castanopsis chinensis, Aporosa yunnanensis, Broussonetia papyrifela and Cinnamomum camphora* at NKS.

2.2. Tree sampling

A minimum of 10 pine trees were randomly selected at each site. Crowded trees were avoided in order to minimize any growth reduction associated with shading and individual competition. Trees that had no visible injury in needles and no reduction in crown density were selected from each site. Given a selected sample had tree(s) died adjacently, sampling was deliberately given up to avoid the effect of growth release from competition following tree death. All trees around 40 cm in diameter were selected at least 200 m away from the roads and at least 100 m away from each other. Two cores from the vertical directions were extracted from each tree at the 1.3 m height above the ground. The cores were mounted, and dried naturally in laboratory for days, and sanded. Ring-widths were determined by Windendro™ system (V 6.1D, Canada) with the accuracy of 0.01-mm unit.

2.3. Tree-ring analysis

Insufficient ring-width series, which were shorter than 40 years, were first excluded. The remaining series were dated by Windendro™ system. The dating was verified statically using the program COFECHA (Holmes, 1994). After successful dating, the mean ring-width was calculated for each tree with two series. Consequently, 38, 34, 16 and 16 data sets of ring-widths were obtained at DHS, XQS, SBG and NKS, respectively.

To remove no-climatic variance due to age trend and differential growth rates, ring-width data were double-detrended with a negative cubic spline which fit successively to the ring width data by the program ARSTAN (Cook and Peters, 1981; Holmes, 1994). Detrended, standardized ring-width indices were then averaged by year into a robust mean value standard chronology for each site. In order to remove the time dependence and enhance the common signal, tree-ring index was modeled as an autoregressive process (Cook and Kairiukstis, 1990). The standardized index of the NKS chronologies was used to develop climatic models using stepwise multiple linear regressions for the period 1971–2000. Mean monthly temperature and total monthly precipitation of current- and previous-year were selected as candidates for variables to predict growth of the current year. To determine the long-term effects of pollution on pines in the studied areas, tree ring index was divided into four periods: (1) before 1970, with low industries and urbanization; (2) 1971–1980, the period before China's opening and reforming; (3) 1981–1990, a transition period from low to heavy pollution and (4) after 1990, period of severe deterioration. Most of large industrial operations in the Pearl River Delta emerged at the early-1980s, industrial emissions were assumed to be corresponded to the deterioration during this period. One-sided *t*-test of Pearson correlations and their significant levels were calculated between the polluted and control chronologies. Mean differences between the actual and the estimated chronologies at each site were also determined in the periods.

2.4. Climatic data

Climate data used for regressions was from the nearest meteorological monitoring stations which were Gaoyao station for DHS, Nanhai Station for XQS, Guangzhou station for SBG, Longmen station for NKS. Annual changes in the monthly mean air temperature and mean precipitation averaged from 1970 to 2000 at the four stands were shown in Fig. 3. Annual mean air temperature and total precipitation averaged during 1970–2000 were 22.3 °C and 1671 mm at DHS, 22.5 °C and 1618 mm at XQS, 22.5 °C and 1736 mm at SBG, and 21.0 °C and 1855 mm at NKS. The seasonal changes of temperature and precipitation were similar at each station. The annual precipitation at the four sites was within the range of 1600–1900 mm, which mainly distribute in the wet season from April to September. These comparisons suggested that the four sites were very similar in climate despite the difference in air pollution.

3. Results

3.1. Mean width of tree-rings

Numbers of single-year tree-rings, tree ages, ring-widths and results of the statistical tests among the ring-widths in different periods at the four sites were given in Table 1. As suspected, ring-

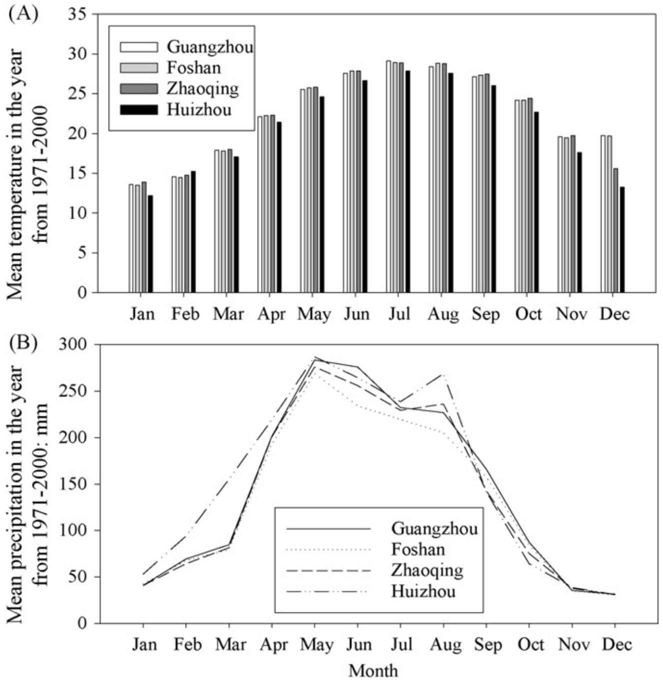

Fig. 3. Annual changes in the monthly mean air temperature (A) and mean precipitation (B) averaged from 1970 to 2000 at the four stands. Data were from the nearest meteorological monitoring stations by the forest sites: Guangzhou station (Guangzhou) for SBG, Nanhai Station (Foshan) for XQS, Gaoyao station (Zhaoqing) for DHS, Longmen station (Huizhou) for NKS.

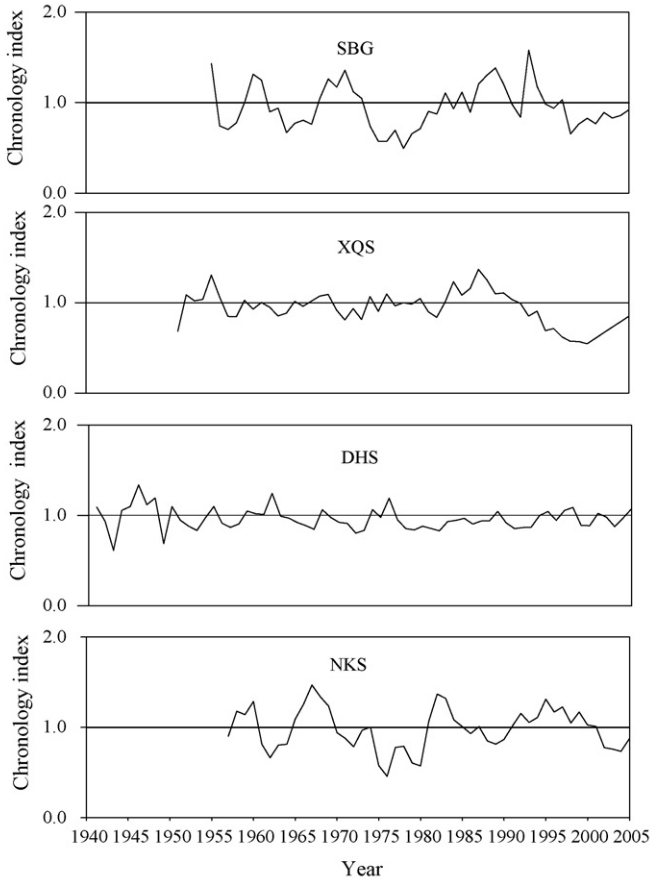

Fig. 4. Standard chronology of Masson pine developed from trees at the sites.

widths at the control site (NKS) were not always higher than those at the polluted sites (DHS, XQS and SBG) in the two periods before 1981 at the 0.05 level of significance. In fact, in the period before 1970, pines at NKS had lower ring-widths than those at XQS and DHS. In the periods after 1980, trees at the polluted sites decreased significantly in mean ring-width compared to trees at NKS, though tree-ring width among the three polluted sites differed statistically from each other. However, unexpected trends that ring-widths after 1980 were significantly higher then those before 1980 were observed at NKS, which were different from the growth patterns at the polluted sites where ring-widths decreased with the time.

3.2. Standard chronology indices and climate-growth model

The standard chronology indices developed from each site showed somewhat different growth patterns (Fig. 4). First-order autocorrelation coefficients, mean sensitivities, and standard deviations (S.D.) of the indices were also given in Table 1. A period of below-average growth since the mid-1970s and since the early-1990s was evident for chronologies of DHS and XQS, respectively. Below-average growth for SBG chronology appeared in the periods from the mid-1970s to the mid-1980s and the mid-1990s. Reductions in ring-growth were also somewhat evident in the latest years at NKS (Fig. 4).

Results of regressions by using the actual NKS standard chronology index and the climatic data of 1971–2000 were summarized in Table 2. Eight variables were accepted as significant for the climate-growth model. The model dedicated that the radial tree growth of the Masson pine was depressed by the coldness in January of the current years, promoted by the warmth in December and November of previous years and precipitation in March and July of the current years, which were indicated by the magnitude of the standardized coefficients, respectively (Table 2). The model

Table 1
Mean ring-width for Masson pine and the statistical characteristics of the standard chronology of the series under the pollution gradients

	DHS	XQS	SBG	NKS
Number of single-year ring-width measurements	1936	1508	599	523
Age at 1.3 m height (year)	50.7 ± 3.2[a]	42.8 ± 5.1	50.0 ± 3.6	44.5 ± 4.7
Mean ring-width (mm)				
Before 1970	2.87 ± 1.60c[b]	3.81 ± 2.47b	5.13 ± 2.3a	3.39 ± 2.15c
1971–1980	2.06 ± 1.22b	3.06 ± 1.60a	2.97 ± 2.29a	3.28 ± 2.63a
1981–1990	1.47 ± 1.01d	2.78 ± 2.16b	2.20 ± 1.12c	4.36 ± 2.69a
After 1990	1.08 ± 0.76d	1.43 ± 1.38c	1.87 ± 1.06b	3.68 ± 1.48a
First-order autocorrelation coefficients of indices	0.46	0.68	0.53	0.68
Mean sensitivity of indices	0.12	0.12	0.19	0.16
S.D. of indices	0.12	0.19	0.25	0. 23

[a] Mean ± S.D.
[b] The significant differences among the sites in the same period were marked with different letters. The significance is set at 0.05 levels.

Table 2
Stepwise regression results for the climatic model developed using the 1971–2000 climatic data to predict growth of the NKS chronology

Variable	Standardized regression coefficients	S.E.
Temperature		
Previous November	0.716	0.015
Current January	−0.498	0.014
Current February	0.245	0.016
Current August	−0.339	0.000
Previous December	0.618	0.000
Precipitation		
Current July	0.418	0.033
Current March	0.269	0.001
Previous December	−0.184	0.001
R^2	0.911	
R^2 adjusted for d.f.	0.872	

explained 91.1% of the tree growth variation from year to year at NKS and could be efficiently used to predict the growth of the pines at the four sites.

Based on the model, estimated chronology indices at DHS, XQS and SBG in the period of 1971–2000 were achieved by entering the climatic variables into the model. The estimated chronology at NKS was regarded as the control one to predict the radial growth of Masson pine at the other three sites. Negative departures from NKS chronology indices were evident at DHS since 1980 and at XQS

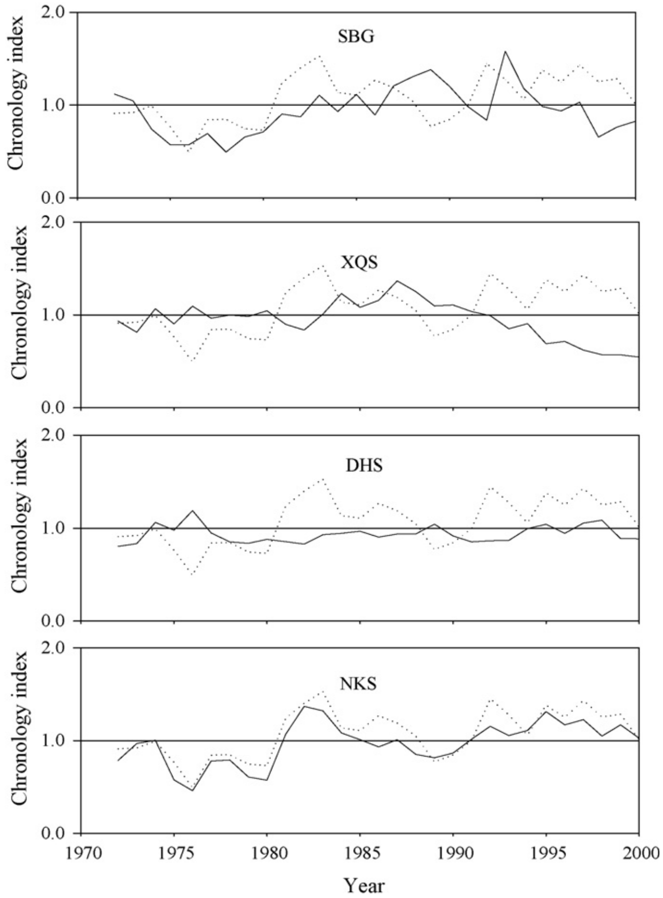

Fig. 5. Plots of the estimated chronology indices at the sites for the period 1971–2000. Dashed lines represented the control chronology indices (NKS) and the solid lines represented the individual site chronologies.

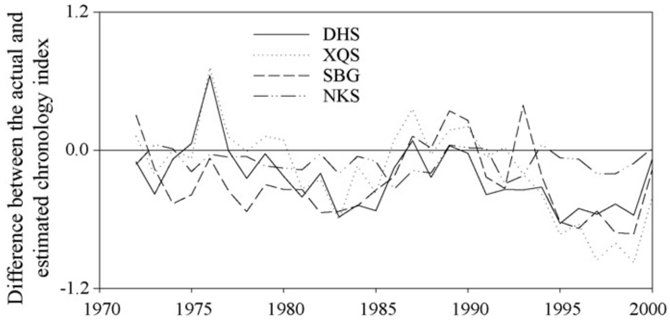

Fig. 6. Differences between the actual and estimated chronology indices for 1971–2000 at the sites.

since 1991. At SBG, the chronology index showed almost always negative departure from the control index except several years in the modeled period (Fig. 5).

3.3. Comparison of actual and estimated chronology indices at the polluted sites

Mean differences between the actual and estimated chronology index at the polluted sites were indicated in Fig. 6 and were statistically evaluated with one-tailed *t*-tests in Table 3. The differences in the period of 1991–2000 significantly increased relative to the period of 1971–1980 at all sites. Significant differences of the measured tree growths were not found from the estimated ones in the period 1971–1980, while found in the period 1991–2000 at the three polluted sites.

Comparisons of the control chronology at NKS and the individual ones at the polluted sites in the modeled periods were also tested by the Pearson correlations (Table 4). In the period 1971–1980, chronology indices were highly correlated. However, statistical correlations were not found in the period 1991–2000 at the all polluted sites.

4. Discussion

Adverse effects of atmospheric pollutants on the growth of many coniferous species have been implicated and consistent relationships between pollutants and tree-ring growth have been well documented (Hirano and Morimoto, 1999; Long and Davis, 1999; Dittmar et al., 2003; Muzika et al., 2004). Reductions of ring width of tree samples were observed in the exposure of air pollution (Tolunay, 2003). Coupling tree-ring chronologies, pollution history and meteorological data provides a valuable method

Table 3
Mean differences between the actual and estimated indices at the sites

Period	DHS	XQS	SBG	NKS
1971–1980	−0.040	0.096	−0.257	−0.078
1981–1990	−0.249**	−0.096	−0.175	−0.122
1991–2000	−0.420**	−0.515**	−0.385**	−0.010

** Indicate significant levels at $P < 0.01$.

Table 4
Pearson correlations between the control chronology and the individual chronologies at the polluted sites for the selected time periods

Period	DHS	XQS	SBG
1971–1980	0.803**	0.809**	0.755**
1981–1990	0.390	0.577**	0.715**
1991–2000	0.508	0.396	0.465

** Indicate significant levels at $p < 0.01$.

for understanding forest responses with respect to spatial and temporal changes in the environment of tree growth (Pärn, 2003). In this study, the significant decrease of ring-width at the polluted sites after 1980 compared to those at the control site coincided with the vigor losses (e.g. rapid defoliating of current needles, visible damage of needles, even the die back of pine trees, etc.) of the pine species in recent years caused by the increasing industrial emissions at the polluted sites in the Delta (Luo et al., 2001; Yu et al., 2005).

First-order autocorrelation coefficients reflected low-frequency variance in a chronology, mean sensitivities measured the high-frequency variations in chronology, and standard deviations included both low-frequency and high-frequency components of variance (Fritts, 1976). At the polluted sites, mean sensitivity and standard deviation were found highest at SBG, suggesting the effect of disturbance on the tree-ring chronologies may be high at Guangzhou, where the industrial SO_2 emission kept at highest levels for long time. Similar results were previously obtained from chronologies of western larch (*Larix occidentalis*) (Fox et al., 1986) and Japanese black pine (*Pinus thunbergii* Parl.) (Hirano and Morimoto, 1999) exposed to SO_2 emissions. The large variation of the ring-width at polluted sites might indicate the complex effect of pollution and climate on growth. In the present study, autocorrelation and mean sensitivity of the control chronology at NKS were also high, implying that great ring-width variation could exist at the relatively clear site, too.

Tree-ring growth reductions illustrated the effects of the atmospheric pollutants on pine species (Muzika et al., 2004). High level concentrations of atmospheric SO_2 could greatly decrease the growth of trees (Fox et al., 1986), which explained the decrease of tree-ring growth of Masson pine since the mid-1970s at the polluted sites in the study. Actually, continuous increase of SO_2 emissions at certain rapidly industrialized areas (i.e. Foshan) has caused increase in acute exposure episodes for the pine species (Kong et al., 2003). Visible damages, even die back of Masson pine caused by air pollution were observed at Guangzhou, Foshan and Zhaoqing (Luo et al., 2001; Wen et al., 2006). Abnormally high S content (Kuang et al., 2007) and low chlorophyll (Yu et al., 2005) in the species needles from those areas were also detected. Declining of pine trees generally experiences growth reductions and crown damage including needle loss and yellowing foliage (Innes, 1993; Torelli et al., 1999). According to Cherubini et al. (2002), decreasing growths were among the most obvious growth-related characteristics of tree dying, which is not only a species-specific, but also a site-specific feature. The process of dying often takes decades (Villalba and Veblen, 1998). For example, Bigler et al. (2004) found the growth of now dead trees decreased for about 50 years. Reduced wood formation often occurs prior to visual symptoms of crown decline (Torelli et al., 1999). The significant decrease of the tree-ring widths at the polluted sites compared with the control site since the mid-1980s in this study and the large-scale of needle losses at the polluted sites (Luo et al., 2001) implied a high risk of Masson pine forest decline.

The subsequent tendency towards a recovery of ring growth in the most recent years (Fig. 4) coincided with the reducing of industrial emissions in recent years in the Delta. In the study, NKS was a relatively unpolluted area for long time though reductions in growth were also detected since 2000 (Fig. 4). This reduction might be affected by transport of the sustained industrial emissions from the polluted areas. However, NKS chronology index could still be used to estimate the general pattern of Masson pine growth in the macroclimatic locations for the high explanation on the tree growth variation in the climate-growth model (Table 2) and for the little mean differences between the model and the observed indices (Table 3).

Climate is one of the most important factors influencing tree-ring index (Fritts, 1976). Stepwise multiple linear regressions were used for climatic model development because co-linearity diagnostic did not indicate substantial multicolinearity in the climatic data (Montgomery and Peck, 1992). The continuous reduction in the estimated tree-ring indices at the polluted sites since 1980 compared with the estimated one at NKS (Fig. 5) indicated that the radial growth of Masson pine trees were influenced by other factor(s) except for climate. In the macroclimatic and similar soil conditions, trees demonstrated synchronous residual pattern without exogenous factors.

Mean differences between the actual chronology indices and the estimated ones prior to 1980 at the polluted sites were not significant and the correlations between the control index and the polluted indices were all statistically high (Tables 3 and 4), demonstrating the synchronous residual pattern of DHS, XQS and SBG was indicative of the macroclimatic signal common to all sites chronologies. In the period 1991–2000, however, the patterns were revealed non-synchronously by the statistical difference and the low correlations (Tables 3 and 4), suggesting the exogenous influence of some other factor(s) on the tree growth increased. Emissions of SO_2 in the Delta might contribute to the severe effects. Due to lacking of long-term monitoring data of atmospheric SO_2, indirect evidence was only available to explain the effects of atmospheric pollution on tree growth. For instance, the frequency of acid rain increased consistently and the pH values of precipitation decreased significantly in the past three decades at the three polluted sites (Xie et al., 2002; Huang, 2003; Wu, 2006). Additionally, a large-scale die back of Mason pine and Eucalyptus trees were also observed around the ceramic industrial centres where SO_2 levels kept fairly high near XQS in the very recent years (Wen et al., 2006).

In the period 1971–1980, the correlation between the control chronology and the polluted ones were high and statistically significant at all sites (Table 4), implying tree growths at the presently polluted sites were similar as that at NKS. During the period 1981–1990, tree growth at DHS decreased compared to that at NKS, the correlation between the chronologies decreased from 0.803 to 0.390 (Table 4). Correlations of the polluted chronologies and NKS chronology were statistically decreased after the beginning of China's opening and reforming operation (at DHS), especially in the 1990s (XQS and SBG) when compared with the previous period, implying again the mean differences of trees growth statistically increased with the time and the growth of Masson pine trees were influenced by some factors other than climate at the polluted sites.

5. Conclusions

This study attempted to compare the magnitude of air pollution effects on the growth of Masson pine trees in the period before and after early 1980s when China open-door policy and economic reforms were implemented in the Pearl River Delta. The results confirmed that the growth of Masson pine at the currently polluted sites was significantly suppressed during the most recent decades. The significant differences between the actual and estimated chronologies at the polluted sites and the low correlations between the individual chronologies and the control one in the latest decade implied further forest decline would extend at a large scale if effective emission control, policy regulation and forest management were not done. High statistical quality of tree ring chronologies in the study demonstrated high suitability and urgent necessity for dendroecological analysis in the Delta where potential forest decline (in particular current die back) of Masson pine was at high risk.

Acknowledgements

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