

# Life pattern of urban trees: A growth-modelling approach

Aline Canetti<sup>1</sup> · Patrícia Póvoa de Mattos<sup>2</sup> · Evaldo Muñoz Braz<sup>2</sup> · Sylvio Pellico Netto<sup>1</sup>

Published online: 29 March 2017  
© Springer Science+Business Media New York 2017

**Abstract** Urban afforestation improves life quality in urban centers providing social and environmental benefits. Understanding growth of urban trees exposed to air pollution will support planning, managing and expanding urban areas. This approach intends to determine growth patterns of urban trees to support future urban planning. Non-destructive samples were collected from trees of *Araucaria angustifolia* (Bertol.) Kuntze in Araucaria city, Parana State, Brazil. Growth rings were related to pollutant concentrations and meteorological series. Growth reduction was observed except in the border areas of the city. Trees established during or after the period of industrialization incentives were most affected by air pollution, indicating that immature plants are more vulnerable. Sulphur dioxide and nitric oxide significantly affected growth of smaller trees. Those greater than 60 cm dbh did not demonstrate significant correlation with any identified pollutant. As the trees established before accentuated urbanization were less affected by air pollution, it is reinforced the importance of preserving remaining urban trees. We suggest that

planning urban afforestation should precede industries placing. When urban planning is impossible, new planted trees should not be expected to grow as in free pollution areas, but they will still present satisfactory diameter increment, contributing to improve local urban environment.

**Keywords** Tree life cycle · Dendrochronology · *Araucaria angustifolia*

## Introduction

Urban trees contribute to improve life quality in urban centers in many ways, providing social (regarding education, recreation, new employments, wood and food supply and others) and environmental benefits (Küchelmeister 2000). Leaves' water transpiration and radiation block alter the atmospheric environment in which trees are established, generating thermal stability (Nowak et al. 1998).

Urban trees habitat has specific traits different from forests. The environment is heterogeneous regarding soil, nutrients and human intervention, such as silvicultural treatments, vandalism, presence of nearby electricity networks and emission of pollutants (Sjörman and Nielsen 2010).

Many studies have shown the negative effect of atmospheric pollutants on human health (Pope III 1989; Brunekreef and Holgate 2002; Kampa and Castanas 2008; Danni-Oliveira 2008; Malik et al. 2012). However, little is known about air pollution interference on trees life cycle (McPherson and Peper 2012). We can find some studies on the environmental risks of pollutants on forests in Europe and North America (Katz 1949; Baes and McLaughlin 1984; McLaughlin and Bräker 1985; Bussotti and Ferretti 1998; Nowak et al. 1998; Long and Davis 1999; Brack 2002; Tolunay 2003; Muzika et al. 2004; Wilczyński 2006; Stravinskiene and Erlickyte-

---

✉ Patrícia Póvoa de Mattos  
patricia.mattos@embrapa.br

Aline Canetti  
canetti@ufpr.br

Evaldo Muñoz Braz  
evaldo.braz@embrapa.br

Sylvio Pellico Netto  
sylviopelliconetto@gmail.com

<sup>1</sup> Federal University of Paraná, Av. Pref. Lothario Meissner 900, Curitiba, PR 80210-170, Brazil

<sup>2</sup> Embrapa Florestas, Estrada da Ribeira Km 111, Caixa Postal 319, Colombo, PR 83411-000, Brazil

Marčiukaitiene 2009; Serengil et al. 2011; Bartens et al. 2012; Malik et al. 2012; McPherson and Peper 2012; Stravinskiene et al. 2013) but few studies discuss the effect on tropical and subtropical trees and forests (Escobedo et al. 2008; Alcalá et al. 2009; Hermida 2015).

Considering that it is impossible to stop the emission of all atmospheric pollutants, the goal should be to reduce them to a level that they are not damaging (Flagan and Seinfeld 2012). Studying tree species growth exposed to different levels of air pollution will allow an understanding of the role that these forest areas can play in mitigating pollution in more sensitive areas (Serengil et al. 2011; Malik et al. 2012) and in planning the expansion of urban areas. It will also allow arboriculture planning considering tree growth rhythm and cycle, as larger trees tend to extract more carbon dioxide from the atmosphere and have larger leaf area to capture air pollutants. In addition, they provide shade and intercept rain (Brack 2002).

Researches based on measurement of visual damage on leaves, stems and roots of trees are important in forming a basis for studies of their growth dynamic. However, these studies usually do not identify the moment that changes preceding visual symptoms start, or the causes of such changes (McLaughlin 1985). Long term data is essential to study the influence of adverse factors on growth and mortality of forests since these processes involve cumulative effects in trees and soil (Musika et al. 2004).

Growth models allow the extrapolation of tree growth with good precision, understanding its pattern over time. However, the application of these models requires at least 10 years of growth records (Vanclay 1994). Dendrochronology makes possible the reduction of data collection to months. Moreover, it is a very powerful tool to the understanding of pollution effects on trees as it is possible to recover growth pattern changes throughout the growth-rings series of the examined trees (McLaughlin et al. 2002; Wilczynski 2006; Musika et al. 2004; Malik et al. 2012).

The objective of this study was to determine growth patterns of urban trees, obtaining an approach of their development, aiming to overcome the challenges inherent to the heterogeneity of the urban habitat. These results may support the effective urban arboriculture planning.

## Material and methods

### Study area

The city of Araucaria, in Parana State, Brazil, was chosen as the studying area because of its significant urban growth since the 1970s. This growth was a consequence of incentives offered by the state government to encourage the creation of an industrial zone in the region as part of its strategic development plan (Silva 2006; Souza 2006). The city started to collect data on air quality as a result of pressure from the local population, unhappy with the high levels of pollution reached in the industrial zone (Souza 2006).

Trees were sampled in four different neighbourhoods surrounding air quality automatic monitoring stations (appendix Fig. 7). The soil in the sampled areas is classified as typical haplorthox (Embrapa 1984). The areas main characteristics were: 1) Residential (ASSIS). The sampled trees were in sidewalks or in gardens near houses with low car traffic; 2) Downtown (UEG). The trees were found in sidewalks and small plazas, close to commercial buildings and busy streets; 3) Steel Company (CSN). The neighbourhood is occupied by residences and industries; 4) Petroleum Refinery (REPAR). This region is a transition between the city and the countryside, with no paved streets.

### Sampled trees

We defined *Araucaria angustifolia* as studying tree species because it is widely distributed within the city of Araucaria. Its logging is forbidden by law (Brasil 2008; IAP 2008) as a consequence of high exploitation in the past all over Araucaria Forest, so the species is highly conserved in the city.

Furthermore, *A. angustifolia* was previously mentioned as suited for dendrochronological studies in South of Brazil (Seitz and Kanninen 1989; Mattos et al. 2007a, b 2010; Hess et al. 2009; Santarosa et al. 2007; Oliveira et al. 2009 and 2010).

Street trees presenting diameter at 1.3 m above ground (dbh) higher than 15 cm and free from external injuries were selected randomly (Table 1). Geographic coordinates, dbh and height were recorded for each tree. There were no available records about trees origin or silvicultural treatments during their lifetime.

**Table 1** *Araucaria angustifolia* trees sampled in the city of Araucaria, PR, Brazil

Site	Number of trees measured	Height <sub>average</sub> (m)	dbh <sub>average</sub> (cm)	dbh <sub>min</sub> (cm)	dbh <sub>max</sub> (cm)
ASSIS	39	14.0	51.3	16.5	86.9
CSN	35	15.3	44.9	31.0	65.2
REPAR	35	14.3	45.0	25.1	89.1
UEG	35	15.5	55.6	27.4	83.7

**Table 2** Number of *Araucaria angustifolia* trees sampled per dbh class and its descriptive data in Araucaria, PR, Brazil

Site	dbh class (cm)	Number of trees measured	Height <sub>average</sub> (m)	dbh <sub>average</sub> (cm)	dbh <sub>min</sub> (cm)	dbh <sub>max</sub> (cm)
Assis	20–40	5	13.7	28.5	24.3	31.0
	40–60	8	13.3	43.3	33.2	51.4
	60–80	8	16.0	63.0	53.3	75.9
CSN	20–40	7	14.7	28.1	23.7	32.6
	40–60	16	15.1	38.7	33.8	48.4
	60–80	3	17.0	56.4	55.5	57.1
Repar	20–40	13	12.6	25.8	18.4	32.6
	40–60	14	15.4	42.2	33.2	51.4
	60–80	4	17.7	62.6	53.0	79.9
UEG	20–40	5	12.7	24.6	20.5	27.0
	40–60	14	15.5	45.7	34.8	52.1
	60–80	11	16.9	62.5	52.4	75.2

### Growth series sampling and processing

Two perpendicular non-destructive samples were collected per tree at dbh, using increment borer ( $\varnothing = 5$  mm). Sample wounds were sealed with beeswax to prevent wood pathogens (Stepka et al. 2014). The samples were prepared and measured in the laboratory using Lintab tree-ring-width measurement device and TSAP Win software (Rinn 1996). Growth series of each tree was formed by the average of rings from each year. Cross-dating was carried out among trees growth series, using electronic spreadsheet, as series were mostly shorter than 50 years. In sections showing less differentiation between early and late wood it was still possible to visually estimate the number of growth rings, which was subsequently confirmed by cross dating. When this evaluation was not possible, the samples were disregarded. Samples from 144 trees were analysed and only 36 were left out.

The majority of samples bark was missing. So, trees dbh with bark was estimate using the equation (Eq. 1) proposed by Nascimento et al. (2010) for *A. angustifolia* for an urban forest remnant in a county located nearby Araucaria municipality.

$$dbh_b = -6.0302 + 0.9707 dbh_{nb} \quad (1)$$

**Table 3** Air pollutants concentration limits applied in Brazil, USA, Europe and Canada

Pollutant ( $\mu\text{g m}^{-3}$ )	Sampling interval (hours)	Brazil	USA	Europe	Canada
CO	1	40	40		35
NO <sub>2</sub>	1	320	188	200	400
O <sub>3</sub>	1	160			160
SO <sub>2</sub>	24	365		125	300
PTS	24	240			120
PM <sub>10</sub>	24	150	150	50	

\*Source: Santana et al. (2012)

Where  $dbh_{nb}$  = diameter without bark, and  $dbh_b$  = diameter with bark.

### Growth analysis and modelling

Average annual increments of tree growth during the last five decades were analysed. As growth rings in juvenile phase can overestimate the overall average tree growth, retrospective analysis was considered only for  $dbh > 10$  cm.

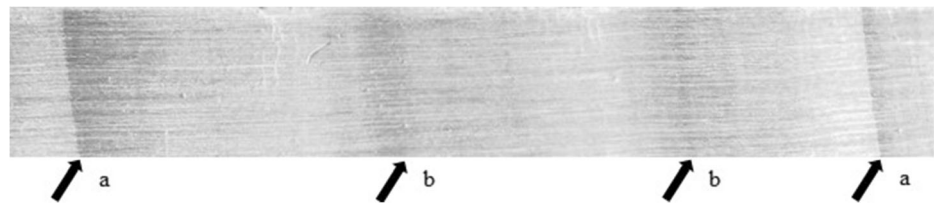
Using growth series and current dbh it was possible to regressively calculate trees diameters yearly. Data presented large variation due to trees diameter variation. So, data were stratified in three diameter classes (Table 2).

Bootstrap method (Davison and Hinkley 1997) was used to improve diameter growth modelling, generating the growth trajectory of 100 trees in each diameter class and at each site by recombination among growth rings, as previously used by Brien et al. (2006), Mattos et al. (2015), among others.

We tested seven regression models suggested by Burkhardt and Tomé (2012) relating diameter and age generating growth equations for each studying site. The models were Gompertz, Johnson-Schumacher, Linear, Logistical, Monomolecular, Richards and Schumacher.

Except of linear model, the other models are biostatistical, derived from organisms allometric functions, which

**Fig. 1** Distinct (a) and poorly defined or indistinct growth rings (b) of *Araucaria angustifolia* from an urban area in Araucaria, PR, Brazil



follow the sigmoidal relationship between individual dimensions (Scolforo 2005). These models are appropriate to describe changes in the time dimension of individuals or population (Burkhardt and Tomé 2012).

To compare growth among sites, we used the same growth model for all diameter classes and sites.

The model was selected evaluating the statistical parameters: coefficient of determination ( $R^2$ ), standard error of estimate ( $S_{xy}$ ) and F value. It was also considered the adjustment to real data.

Annual increment of each tree using 5 years lag was compared among sites using Fisher's least significant difference (LSD) with 95% confidence level. Comparison was carried out for each diameter class, as increment from different diameter trees could present discrepancy due to intrinsic growth differences of different growth stages of trees. We considered the last 35 years, so all diameter classes from all sites presented satisfactory number of data, as younger trees do not present increment in previous years.

### Relationship between air quality and tree growth

Hourly data of pollutant concentrations and meteorological conditions at the studying sites over the period of 2003 to 2013 was supplied by IAP (Environmental Institute of Parana). Data before this period were not available.

The critical air pollutants concentrations applied in Brazil, USA and Europe are presented in Table 3. The percentage of days above limits was calculated for each studied air pollutant, which where CO (carbon monoxide), NO<sub>2</sub> (nitrogen dioxide), O<sub>3</sub> (ozone), SO<sub>2</sub> (sulphur dioxide), TSP (total suspended particulates) and PM<sub>10</sub> (particulate matter with 10 μ or smaller).

Only climatic and pollution variables recorded at all monitoring stations were considered in tree growth analysis (NO,

NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub> and temperature). Missing data was estimated from recorded averages of the following years. Pearson correlation at 95% probability was used to relate growth with climatic and pollution variables between 2003 and 2013.

## Results

### Growth analysis

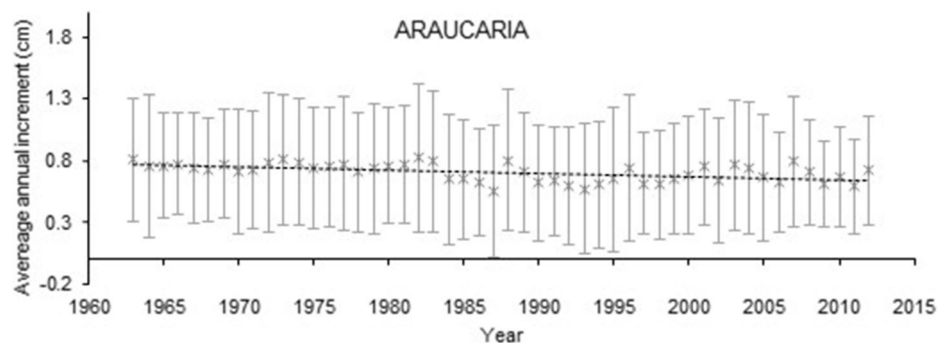
Growth rings of *Araucaria angustifolia* are visible to naked eyes and in general present clearly defined annual growth limits. However, in samples collected in sites closest to downtown of Araucaria (UEG e CSN) some growth rings and limits between early and late wood were poorly defined (Fig. 1), mainly closest to the bark of the trees.

When analysing tree growth at all sites throughout the recent decades and their linear tendencies (Fig. 2) a gradual reduction in annual increment was observed. However, when each site was analysed separately, an increasing growth was observed in REPAR region (Fig. 3a), while in the remaining regions a gradual reduction of increment values was observed (Fig. 3b and c), although this was less evident in CSN region (Fig. 3d).

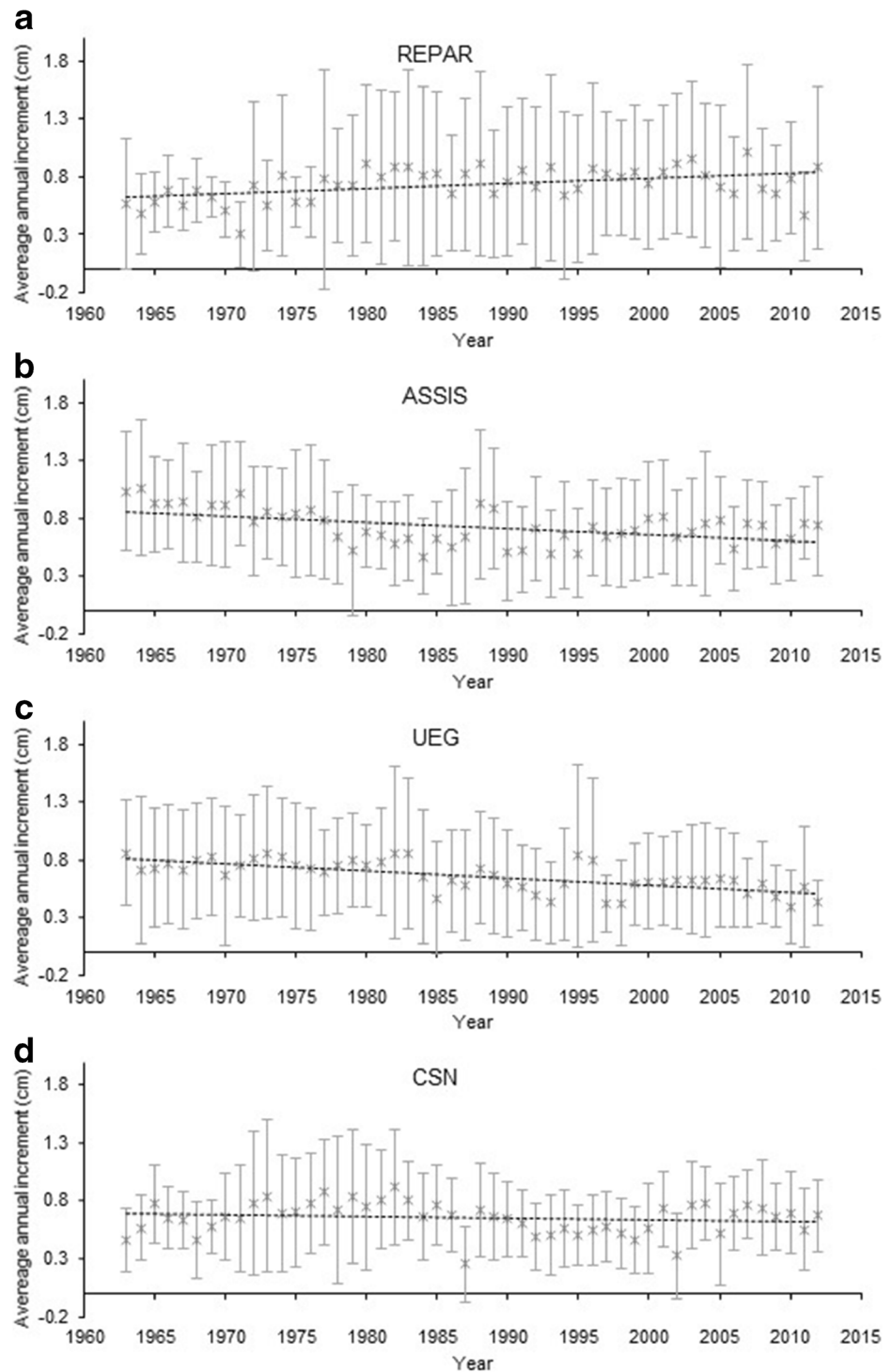
### Growth pattern

Schumacher growth model was chosen from those tested. Statistical parameters of fitted equations are shown in Table 4 and growth equation parameters generated and their confidence limits in Table 5. Parameters confidence limits of tested equations were different in each case, confirming the necessity of developing different growth equations for each class size.

**Fig. 2** Linear trends and standard deviation on diametric growth of *Araucaria angustifolia* in Araucaria (PR, Brazil) city considering all samples



**Fig. 3** Linear trends and standard deviation on diametric growth of *Araucaria angustifolia* in Araucaria (PR, Brazil) city considering each site individually



Growth equations are presented by class in Fig. 4. The models were applied up to the higher diameter of each dbh class. Class 1 showed significantly less growth in the 4 sites. Trees in class 2 showed growth rates greater than in class 1 but less than in class 3. The oldest and largest trees always showed significantly greater growth in all sites.

Growth curves of all trees from diameter classes 1 and 2 showed inflections earlier than older trees, which showed only

slight inflection at a later age (Fig. 4). A greater inflection in the growth curve may be observed in trees of diameter class 3 in sites ASSIS, CSN and UEG (Fig. 3a, b and d respectively). Growth curve of trees in diameter class 3 in REPAR rural site presented the mildest inflection and greatest growth of all trees in all sites (Fig. 4c).

When comparing trees periodic annual increment between sites every 5 years (Fig. 5), it was possible to notice that trees



**Table 4** Statistical parameters of Schumacher model of sampled trees of *Araucaria angustifolia* shown by diameter class and study site in the city of Araucaria, PR, Brazil

Diameter class	Site type	R <sup>2</sup> <sub>ajust</sub>	S <sub>yx</sub> (%)	F
20–40 cm	ASSIS	0.996	9.4	994,512
	CSN	0.980	22.4	410,171
	REPAR	0.979	22.3	414,302
	UEG	0.995	10.8	1,095,138
40–60 cm	ASSIS	0.996	10.1	2,169,398
	CSN	0.969	27.2	597,482
	REPAR	0.986	7.1	291,555
	UEG	0.985	18.5	1,251,124
Above 60 cm	ASSIS	0.987	16.8	862,217
	CSN	0.988	16.4	387,098
	REPAR	0.994	11.1	1,008,760
	UEG	0.990	15.1	1,764,732

Where R<sup>2</sup><sub>ajust</sub> is the coefficient of determination adjusted and S<sub>yx</sub> (%) is the relative standard error of estimate

from class 1 from ASSIS (residential neighborhood) and REPAR (rural area) presented greater average increment than the other sites that are closer to city center (Fig. 5a). Greater increment was observed in class 2 only in trees from REPAR (Fig. 5b) and for greater diameter class (class 3) smaller increment was detected in trees from UEG (Fig. 5c), closer to more urbanized neighborhood of the city.

As presented in Fig. 6, trees age is consistent on each diametric class.

**Table 5** Analysis of parameters estimated by Schumacher model of sampled *Araucaria angustifolia* trees presented by diameter class and studying site in the city of Araucaria, PR, Brazil

Diametric class	Site	Parameters*		Parameters confidence limits*			
		β <sub>0</sub> *	β <sub>1</sub> *	β <sub>0</sub> *	β <sub>1</sub> *	β <sub>0</sub> *	β <sub>1</sub> *
20 – 40 cm	ASSIS	48.1	17.4	47.9	48.3	17.3	17.5
	CSN	37.4	20.5	37.2	37.6	20.4	20.7
	REPAR	36.4	10.7	36.2	36.6	10.6	10.8
	UEG	34.4	14.0	34.3	34.5	14.0	14.1
40–60 cm	ASSIS	60.8	20.2	60.6	60.9	20.1	20.3
	CSN	44.7	16.7	44.5	44.9	16.5	16.8
	REPAR	49.0	14.8	48.6	49.4	14.7	15.0
	UEG	55.9	17.1	55.8	56.1	17.0	17.2
Above 60 cm	ASSIS	88.2	33.2	87.8	88.6	32.9	33.4
	CSN	64.6	21.5	64.3	64.9	21.3	21.7
	REPAR	85.6	25.2	85.3	85.8	25.1	25.4
	UEG	78.5	26.4	78.3	78.7	26.3	26.5

\*Significant at 95% probability

### Air pollution analysis

The number of hours that exceeded the limits of pollutants in the air stipulated by CONAMA resolution No. 03/90 (Brasil 1990) and SEMA No. 054/06 (Paraná 2006) (Table 3) were not superior to 0.02% (Table 6) in the four air monitoring stations from 2003 to 2013. The pollutant concentration limits stipulated by Brazilian law are more flexible than those stipulated by the US, Canada and European laws air quality (Table 3). However, when considering those limits, the number of hours that exceeded the maximum limits was less than 0.2%.

### Relationship between air quality and tree growth

The growth increments of trees in diameter classes 1 and 2 showed significant correlation with SO<sub>2</sub> (positive) and NO (negative) (Table 7).

### Discussion

Problems to identify growth rings limits in urban areas are not unusual. Bartens et al. (2012) used *Quercus virginiana* Mill. samples from urban areas in Florida, USA, and since the limits marked by the terminal parenchyma were not always visible, the transition from small to large vases was selected as the identifying criteria of growth rings. According to these authors, inappropriate pruning, vandalism, infestations of insects and specific local factors can affect urban tree growth. These factors may also have caused the variation of growth observed in samples of *Araucaria angustifolia* (Fig. 1) closest to downtown of Araucaria (UEG e CSN).

As samples of *A. angustifolia* in this work were collected from trees growing in widely different conditions, typical of urban ecosystems, the considerable variation in growth rings were expected. It is common in urban areas where many variables significantly influence tree growth that trees do not respond to climatic stimuli as they would normally do in natural forest (Wilczynski 2006).

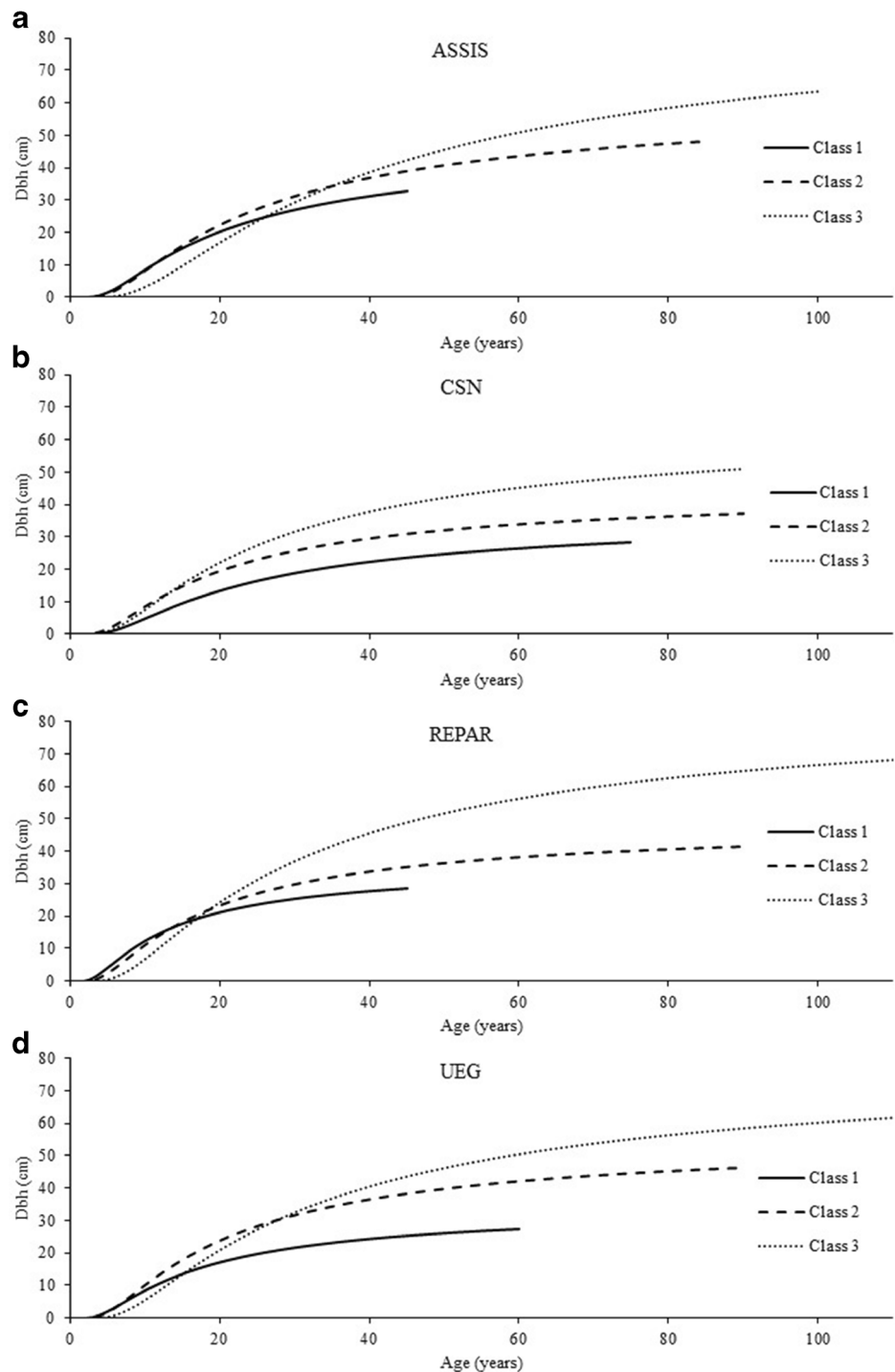
In an urban area in south of Poland, Wilczynski (2006) observed a reduction in growth of *Pinus sylvestris* L., evidenced mainly through high variation in ring width, low similarity in chronology and absence of years with common signs, similar to the effects found for *A. angustifolia* in Araucaria city. The author established that control of atmospheric pollution after 1990 was immediately reflected in growth rings, principally in those areas where initial stress caused by air pollution was most severe. From this decade onwards trees of *P. sylvestris* started to produce wider rings, and uniformity of growth and common signs between rings became more evident.

*A. angustifolia* is a long-lived species reaching easily over 150 years (Mattos et al. 2007a; Oliveira et al. 2010; Stepka

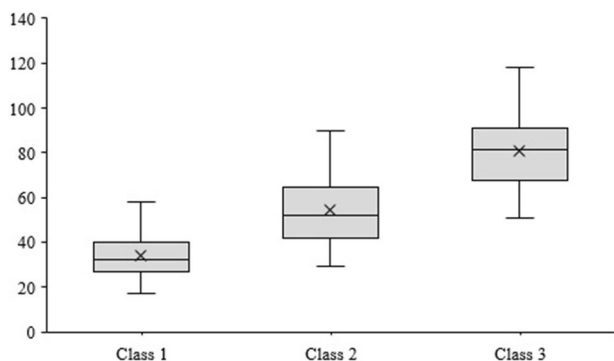
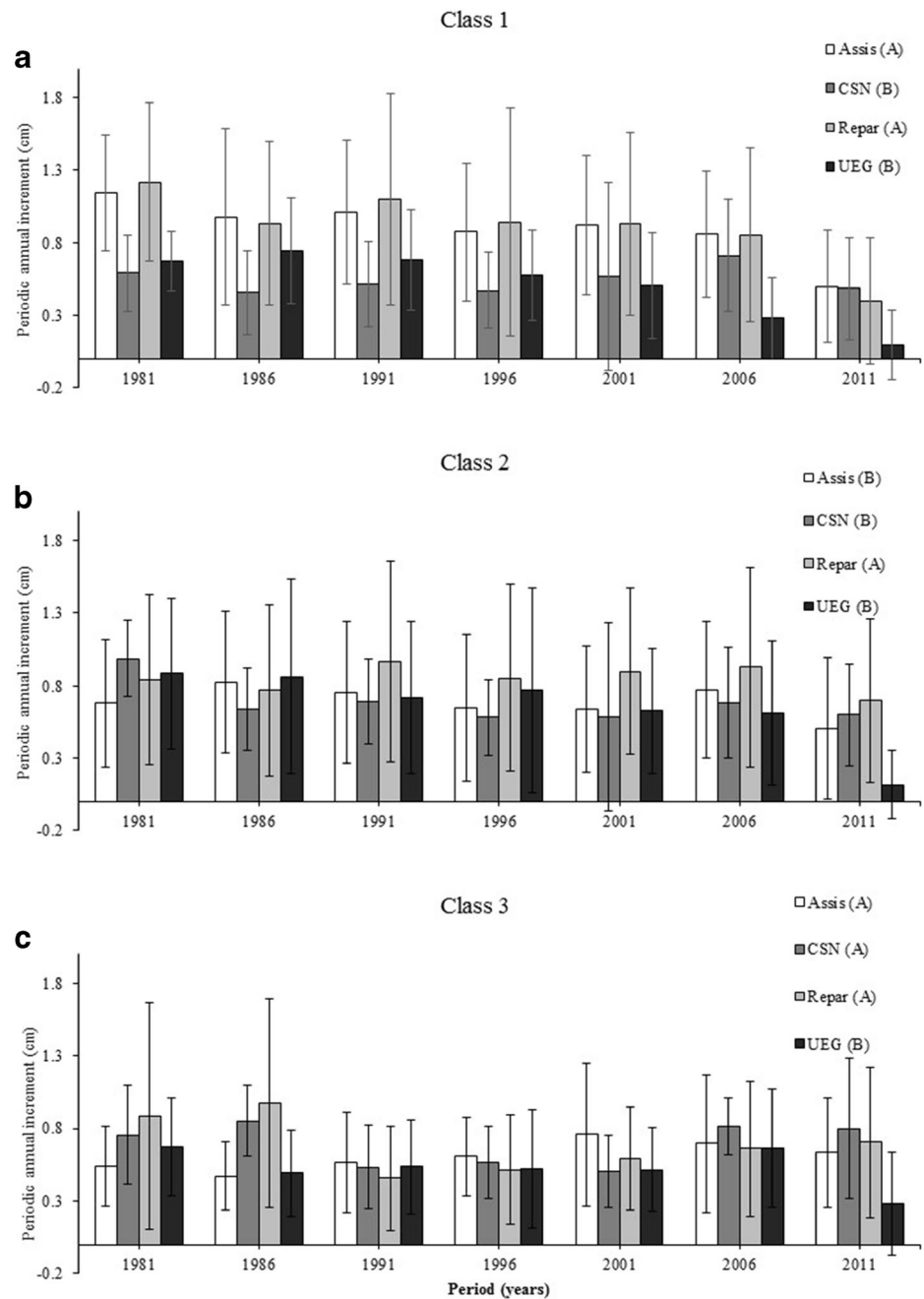
et al. 2014). It is therefore possible that reduction in increments observed in this study (Figs. 2 and 3) results as a negative effect of growing urbanization in the city of Araucaria from the 1970s onward, and not from a natural growth tendency of the species, since the average age of trees analyzed in this study was 58 years, a phase in which decelerated growth of the species would not usually be expected. Dendrochronological studies showing reduced levels of growth in sites with air

pollution were also observed by several authors (Musika et al. 2004; Wilczynski 2006; Stravinskiene and Erlickyte-Marčiukaitiene 2009; Malik et al. 2012). Ashby and Fritts (1972) noted that pollution caused growth reduction of *Quercus alba* Deam in the USA. According to these authors even at a great distance from a source of pollution, tree growth is harmful because toxic substances inhibit capacity for photosynthesis and other metabolic processes. The effects can

**Fig. 4** *Araucaria angustifolia* Schumacher equations by diametric class for the studied sites in Araucaria, PR, Brazil. Note: dbh = diameter at 1.3 m above ground



**Fig. 5** Periodic annual growth of *Araucaria angustifolia* every five years for 35 years for each diametric class on each studied site in Araucaria, PR, Brazil. Note: dbh = diameter at 1.3 m above ground. Different letters on legend show significant differences ( $p < 0.05$ )



**Fig. 6** Box plot of age as a function of diametric class of *Araucaria angustifolia* trees in the city of Araucaria, PR

**Table 6** Percentage of hours with values above critical levels concentrations of air pollutants in the period 2003–2013, considering Brazil, United States, European Union and Canada criteria

	Hours over limit (%)					
	CO	NO <sub>2</sub>	O <sub>3</sub>	SO <sub>2</sub>	PTS	PM <sub>10</sub>
Local						
Brazil	0.0000	0.0002	0.0002	0.0066	0.0187	0.0127
USA	0.0000	0.0037				0.0127
Europe		0.0030		0.0361		0.1827
Canada	0.0000	0.0001	0.0002	0.0092	0.1004	



**Table 7** Pearson correlation of *Araucaria angustifolia* growth increments by class with annual averages of temperature and concentration of atmospheric pollutants in the city of Araucaria, PR, Brazil

Variable	Increments		
	Class 1	Class 2	Class 3
Temperature	-0.227	-0.099	-0.170
<i>p</i> -value	0.183	0.567	0.323
SO <sub>2</sub>	0.343*	0.333*	0.155
<i>p</i> -value	0.041	0.047	0.368
NO	-0.476*	-0.375*	-0.076
<i>p</i> -value	0.003	0.024	0.660
NO <sub>2</sub>	-0.291	-0.311	-0.015
<i>p</i> -value	0.085	0.065	0.931
O <sub>3</sub>	-0.018	0.094	-0.038
<i>p</i> -value	0.916	0.587	0.827

\*Correlation significant at 95% probability

accumulate over years and cause a gradual decline, shown in the width of growth rings, more marked than changes caused by annual temperature variation.

Although we did not investigate the influence of distance from pollutant source, we strongly believe that we would find similar results of growth influence as observed by Stravinskiene and Erlickyte-Marčiukaitiene (2009) when studying growth of *P. sylvestris* in industrialized areas. These authors concluded that the degree of impact of pollution in the radial growth of trees increases linearly with their proximity to a source of pollution.

Crossing urban limits in Araucaria County there are several farms that grow trees for commercial purposes. Tolunay (2003) mentioned that when a forest near to urban or industrial locations is managed on a financial basis, the reduction in diametric growth due to concentration of pollutants represents a loss of volume, prejudicing profitability. Even if growth reduction is subtle, it is important to reduce industries pollutants emission to avoid economic loss.

Since there is a relationship between trees dbh's and age (Table 5 and Figs. 4 and 6), it is possible to estimate in which period trees were established. The data shows that smaller trees (class 1) established themselves in the 1980s, after the development of industry within the city, what means that they were affected by pollution for their entire life. This could be the cause of their reduced growth rates when compared to trees of larger diameter class. Trees of intermediate dimension (class 2) established themselves in the 1960s. After industrialisation started in the 1970s they were already about ten years old, which probably guaranteed greater growth than trees from class 1, but not as great as trees from class 3. Finally, older and larger trees have established themselves before the 1970s. When urbanisation and industrialisation

accelerate, these trees were already near 40 years old with 35 cm of dbh, which guaranteed faster growth.

By observing growth curve inflection of trees in diameter classes 1 and 2 earlier than inflection in class 3, we can notice the acceleration of senescence of these younger trees growing in urban conditions. The more accentuated inflection in growth curves of trees from class 3 of dbh in CSN and UEG sites (Fig. 4b and d, respectively) may result from environmental characteristics in more urbanized sites closer to Araucaria downtown and the greater circulation of people near them. The growth pattern of older trees in this work is similar to that of *A. angustifolia* in natural forest recorded by Stepka et al. (2014). However, younger trees of classes 1 and 2 reached their maximum growth potential more rapidly, probably due to environmental stress.

Smaller average periodic annual increment every 5 years in more urbanized sites were also observed in diameter classes 1 and 2 (Fig. 5), corroborating the indication that trees exposed in their young growth stages to higher aerial pollution and closer to city center were negatively affected. Moreover UEG trees from diameter class 3 presented smaller increment than other sites when comparing trees from the same diameter class, indicating that this neighborhood may have being exposed to higher air pollution due to urbanization even earlier than industrial incentive. Nevertheless trees established before strong urbanization presented similar growth between sites and average increment was consistent to that observed for araucaria trees from natural forests (Mattos et al. 2007a; Oliveira et al. 2010; Stepka et al. 2014).

These observations suggest that *A. angustifolia* growth is more susceptible to anthropic impact when trees are young. So, more recently established trees or those that will be established in the future will need greater care to avoid severe loss of growth or early onset of senescence, mainly because urbanization and industrialization are inherent to developed and developing economies.

Although the air pollution in Araucaria is within acceptable levels (Table 6) as required by Brazilian law (Table 3) it may be inferred from correlation values between *A. angustifolia* and pollutants concentration (Table 7) that SO<sub>2</sub> could have stimulated growth of smaller trees, while oxides of nitrogen do not favor tree growth. Kawamura et al. (2006) recorded an increase in concentration of sulphur in the wood depending on the quantity of the element released into the atmosphere.

Trees in diameter class 3 are probably in mature or near to senile stage and did not respond to the stimulus of the studied pollutants. In experiments with adult trees a number of authors found negative relationship between SO<sub>2</sub> in the atmosphere and tree growth when exposed to high levels of SO<sub>2</sub> emissions (Baes and McLaughlin 1984; Hirano and Morimoto 1999; Long and Davis 1999; Musika et al. 2004). However, effects of SO<sub>2</sub> on growth of trees are sometimes not apparent if the concentrations are below toxic levels or if the soil is deficient

in soluble sulphates and also depend on the length of time of exposure to high concentrations (Katz 1949).

Growth rate reduction of *A. angustifolia* caused by high levels of nitrogen oxides in the air (Table 7) was similar to that observed in *P. sylvestris* near to fertilizer manufacturing plants in Lithuania (Stravinskiene et al. 2013). These authors complemented that after environmental pollution control was implemented, the rates of increase stabilized and there was no reduction of growth.

It is important to emphasize that apart from atmospheric conditions there are innumerable factors that influence tree growth, such as the site, the genetics of the plants, silvicultural intervention among others (Fritts 2012). This means that effects of pollutants and meteorological variables of the atmosphere can only partly explain growth patterns of trees. For this reason, we suggest that future studies should include climatic variables to highlight the variables that mostly influence on growth of tree species.

## Conclusions

The stratification of urbanization level was important to the understanding of trees growth under pollutant effects.

*Araucaria angustifolia* trees growing far from city center presented similar growth to those growing in sites free of pollution or intensive anthropic impact.

Younger trees are more vulnerable to urbanization, that might be even decisive to their life cycle. This reinforces the impact of pollution and the importance of preserving remaining urban trees.

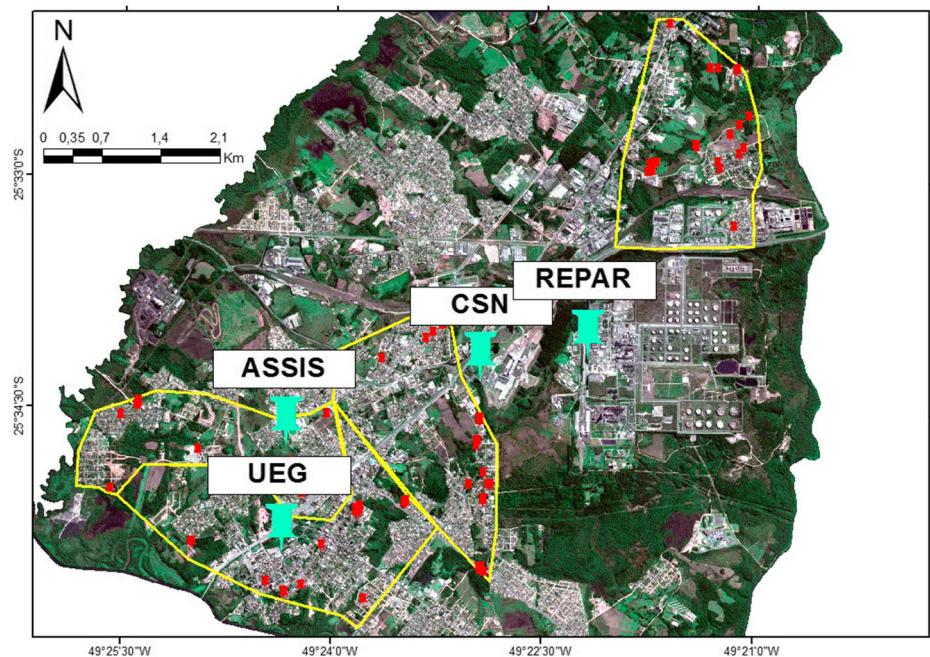
Since industrialization and urbanization in the studied sites affected growth of trees established after industrialization incentives, it is suggested that planning of urban afforestation should precede industries placing. This should even be foreseen in the legislation that oversees urban expansion.

When urban planning is not possible, new planted *A. angustifolia* trees should not be expected to grow as in free pollution areas, nevertheless they will still present satisfactory diameter increment, contributing to improve local urban environment.

**Acknowledgements** We are grateful to IBAMA (Brazilian Institute of Environment and Renewable Natural Resources) and Araucaria Town Hall for authorizing the collection of specimens (IBAMA/MMA/SISBIO license number 37679/2014) and Simon Drew for language translation and review. This work was supported by CAPES (Coordination for the Improvement of Higher Education Personnel) and Embrapa Forestry (Brazilian Agricultural Research Corporation).

## Appendix

**Fig. 7** Map of sampled areas in the city of Araucaria, PR



## References

- Alcalá J, Sosa M, Moreno M, Rodríguez JC, Loredó C, Lara JL, Tapia J (2009) Concentraciones de Fe, Mn y Mg en material foliar de cinco especies arbóreas indicadoras de la contaminación urbana en la ciudad de Chihuahua, México. *Multequina* 18(1):37–51
- Ashby WC, Fritts HC (1972) Tree growth, air pollution, and climate near LaPorte, Ind. *Bull Am Meteorol Soc* 53(3):246–251. doi:10.1175/1520-0477(1972)053<0246:TGAPAC>2.0.CO;2
- Baes CF, McLaughlin SB (1984) Trace elements in tree rings: evidence of recent and historical air pollution. *Science* 224(4648):494–497
- Bartens J, Grissino-Mayer HD, Day SD, Wiseman PE (2012) Evaluating the potential for dendrochronological analysis of live oak (*Quercus virginiana* mill.) from the urban and rural environment — an explorative study. *Dendrochronologia* 30(1):15–21. doi:10.1016/j.dendro.2011.04.002
- Brack CL (2002) Pollution mitigation and carbon sequestration by an urban forest. *Environ Pollut* 116:195–200. doi:10.1016/S0269-7491(01)00251-2
- Brasil (1990) Resolução/CONAMA/Nº 003 de 28 de junho de 1990. <http://www.mma.gov.br/port/conama/res/res90/res0390.html> Accessed 08 november 2016
- Brasil (2008) Lista Oficial das Espécies da Flora Brasileira Ameaçadas de Extinção. Instrução Normativa nº 6 de 23 de setembro de 2008 [http://www.mma.gov.br/estruturas/179/\\_arquivos/179\\_05122008033615.pdf](http://www.mma.gov.br/estruturas/179/_arquivos/179_05122008033615.pdf) Accessed 08 november 2016
- Brienen RJ, Zuidema PA, Daring HJ (2006) Autocorrelated growth of tropical forest trees: unraveling patterns and quantifying consequences. *For Ecol Manag* 237(1):179–190. doi:10.1016/j.foreco.2006.09.042
- Brunekreef B, Holgate ST (2002) Air pollution and health. *Lancet* 360(9341):1233–1242. doi:10.1016/S0140-6736(02)11274-8
- Burkhardt HE, Tomé M (2012) Modeling forest trees and stands. Springer Science & Business Media 457 pp
- Bussotti F, Ferretti M (1998) Air pollution, forest condition and forest decline in southern Europe: an overview. *Environ Pollut* 101(1):49–65. doi:10.1016/S0269-7491(98)00039-6
- Danni-Oliveira IM (2008) Poluição do ar como causa de morbidade e mortalidade da população urbana. Raega-O Espaço Geográfico em Análise 15:113–126. doi:10.5380/raega.v15i0.14249
- Davison AC, Hinkley DV (1997) Bootstrap methods and their applications, Cambridge series in statistical and probabilistic mathematics 582 pp
- Embrapa (1984) Levantamento de reconhecimento dos solos do Estado do Paraná. Londrina: EMBRAPA-SNLCS/IAPAR 2v 791 pp
- Escobedo FJ, Wagner JE, Nowak DJ, Maza CL, Rodriguez M, Crane DE (2008) Analyzing the cost effectiveness of Santiago, Chile's policy of using urban forests to improve air quality. *J Environ Manag* 86(1):148–157. doi:10.1016/j.jenvman.2006.11.029
- Flagan RC, Seinfeld JH (2012) Fundamentals of air pollution engineering. Courier corporation 542 pp
- Fritts HC (2012) Tree rings and climate. Elsevier 567 pp
- Hermida GC (2015) Agroforesteria periurbana una opción para la producción sustentable en los alrededores de Buenos Aires. *Revista Scientia Agroalimentaria* 2(1):7–17
- Hess AF, Schneider PR, Finger CAG (2009) Crescimento em diâmetro de *Araucaria angustifolia* (Bertol.) Kuntze em função da idade, em três regiões do Rio Grande do Sul. *Ciência Florestal* 19(1):7–22
- Hirano T, Morimoto K (1999) Growth reduction of the Japanese black pine corresponding to an air pollution episode. *Environ Pollut* 106(1):5–12. doi:10.1016/S0269-7491(99)00063-9
- IAP (2008) Instituto ambiental do Paraná. Lista oficial de espécies da flora ameaçadas de extinção no Paraná. Procedimento Operacional Padrão Nº 5 de 20 de junho de 2008
- Kampa M, Castanas E (2008) Human health effects of air pollution. *Environ Pollut* 151(2):362–367. doi:10.1016/j.envpol.2007.06.012
- Katz M (1949) Sulfur dioxide in atmosphere and its relation to plant life. *Industrial Engineering Chemistry* 41(11):2450–2465. doi:10.1021/ie50479a025
- Kawamura H, Matsuoka N, Momoshima N, Koike M, Takashima Y (2006) Isotopic evidence in tree rings for historical changes in atmospheric sulfur sources. *Environmental science technology* 40(18):5750–5754. doi:10.1021/es060321w
- Küchelmeister G (2000) Trees for the urban millennium: urban forestry update. *Unasylva* (FAO) 51:49–55
- Long RP, Davis DD (1999) Growth variation of white oak subjected to historic levels of fluctuating air pollution. *Environ Pollut* 106(2):193–202. doi:10.1016/S0269-7491(99)00077-9
- Malik I, Danek M, Marchwińska-Wyrwał E, Danek T, Wistuba M, Krapić M (2012) Scots pine (*Pinus sylvestris* L.) growth suppression and adverse effects on human health due to air pollution in the upper Silesian Industrial District (USID), southern Poland. *Water, Air, Soil Pollution* 223(6):3345–3364. doi:10.1007/s11270-012-1114-8
- de Mattos PP, Braz EM, Domene VD, Sampaio EVDSB, Gasson P, Pareyn FGC, Araújo EDL (2015) Climate tree growth relationships of *Mimosa tenuiflora* in seasonally dry tropical forest, Brazil. *Cerne* 21(1):141–149. doi:10.1590/01047760201521011460
- de Mattos PP, dos Santos AT, de Oliveira YMM, Rosot MAD (2007a) Dendrocronologia de espécies da Floresta Ombrófila Mista do Município de Candói, PR. *Pesquisa Florestal Brasileira* 54:153–156
- de Mattos PP, dos Santos AT, Rivera H, de Oliveira YMM, Rosot MAD, Garrastazu MC (2007b) Crescimento de *Araucaria angustifolia* na Reserva Florestal Embrapa/Epagri, Caçador, SC. *Pesquisa Florestal Brasileira* 55:107–114
- de Mattos PP, Oliveira MF, Agustini AF, Braz EM, Rivera H, de Oliveira YMM, Garrastazu MC (2010) Aceleração do crescimento em diâmetro de espécies da Floresta Ombrófila Mista nos últimos 90 anos. *Pesquisa Florestal Brasileira* 30(64):319–326. doi:10.4336/2010.pfb.30.64.319
- McLaughlin SB (1985) Effects of air pollution on forests - a critical review. *Journal of the Air Pollution Control Association* 35(5):512–534. doi:10.1080/00022470.1985.10465928
- McLaughlin SB, Shortle WC, Smith KT (2002) Dendroecological applications in air pollution and environmental chemistry: research needs. *Dendrochronologia* 20(1):133–157. doi:10.1078/1125-7865-00013
- McLaughlin SB, Bräker OU (1985) Methods for evaluating and predicting forest growth responses to air pollution. *Experientia* 41(3):310–319. doi:10.1007/BF02004491
- McPherson EG, Peper PJ (2012) Urban tree growth modeling. *ArboricULT Urban For* 38(5):175–183
- Muzika RM, Guyette RP, Zielonka T, Liebhold AM (2004) The influence of O<sub>3</sub>, NO<sub>2</sub> and SO<sub>2</sub> on growth of *Picea abies* and *Fagus sylvatica* in the Carpathian Mountains. *Environ Pollut* 130(1):65–71. doi:10.1016/j.envpol.2003.10.021
- Nascimento RGM, do Amaral Machado S, de Figueiredo DJ, Augustynczyk ALD, Cavalheiro R (2010) Relações dendrométricas de *Araucaria angustifolia*. *Pesquisa Florestal Brasileira* 30(64):369–374 doi: 10.4336/2010.pfb.30.64.369



- Nowak DJ, McHale PJ, Ibarra M, Crane D, Stevens JC, Luley CJ (1998) Modeling the effects of urban vegetation on air pollution. In: Air pollution modeling and its application XII. Plenum Press, New York, pp 399–407
- Oliveira JM, Roig FA, Pillar VD (2010) Climatic signals in tree-rings of *Araucaria angustifolia* in the southern Brazilian highlands. *Austral Ecology* 35(2):134–147. doi:10.1111/j.1442-9993.2009.02018.x
- Oliveira JM, Santarosa E, Pillar VD, Roig FA (2009) Seasonal cambium activity in the subtropical rain forest tree *Araucaria angustifolia*. *Trees* 23(1):107–115. doi:10.1007/s00468-008-0259-y
- Paraná (2006) Resolução/SEMA/Nº 054 de 22 de dezembro de 2006. <http://www.abic.com.br/publico/meda/res05423191.pdf> Accessed 08 november 2016
- Pope CA 3rd (1989) Respiratory disease associated with community air pollution and a steel mill, Utah Valley. *Am J Public Health* 79(5): 623–628. doi:10.2105/AJPH.79.5.623
- Rinn, F (1996) TSAP, ver. 3.0. Reference manual: computer program for tree ring analysis and presentation. TSAP, Heidelberg 263 pp.
- Santana E, Cunha K, Ferreira A, Zambon A (2012) Padrões de qualidade do ar: experiência comparada Brasil, EUA e União Européia. Instituto de Energia e Meio Ambiente 81 pp
- Santarosa E, de Oliveira JM, Roig FA, Pillar VD (2007) Crescimento sazonal em *Araucaria angustifolia*: Evidências Anatômicas. *Revista Brasileira de Biociências* 5(S1):618–620
- Scolforo JRS (2005) Biometria florestal: modelos de crescimento e produção florestal. UFLA/FAEPE, pp 393
- Seitz RA, Kanninen M (1989) Tree ring analysis of *Araucaria angustifolia* in southern Brazil: preliminary results. *IAWA J* 10(2): 170–174. doi:10.1163/22941932-90000485
- Serengil Y, Augustaitis A, Bytnerowicz A, Grulke N, Kozovitz AR, Matyssek R, Paoletti E (2011) Adaptation of forest ecosystems to air pollution and climate change: a global assessment on research priorities. *iForest-Biogeosciences and Forestry* 4(2):44–48. doi:10.3832/ifer0566-004
- da Silva MN (2006) Indústria e produção do espaço urbano em Araucária. *Raega-O Espaço Geográfico em Análise* 12:73–91. doi:10.5380/raega.v12i0.5142
- Sjöman H, Nielsen AB (2010) Selecting trees for urban paved sites in Scandinavia – a review of information on stress tolerance and its relation to the requirements of tree planners. *Urban For Urban Green* 9(4):281–293. doi:10.1016/j.ufug.2010.04.001
- Souza SL (2006) Doenças respiratórias em Araucária/PR (2001 a 2003) – condicionantes socioambientais e poluição atmosférica (Master's thesis, Universidade Federal do Paraná) Curitiba PR Brazil
- Stepka TF, Figueiredo Filho A, de Mattos PP, Machado S Do A (2014) Idade e dendrocronologia em árvores nativas de araucária, cedro e imbuia no Sul do Brasil. In: Sanquetta CR, Dalla Corte AP, Rodrigues AL, Mognon F (2014) Floresta com araucária: pesquisas ecológicas de longa duração. Curitiba: Multi-Graphic:117–163
- Stravinskiene V, Erlickyte-Marčiukaitiene R (2009) Scots pine (*Pinus sylvestris* L.) radial growth dynamics in forest stands in the vicinity of “Akmenes cementas” plant. *Journal of Environmental Engineering and Landscape Management* 17(3):140–147. doi:10.3846/1648-6897.2009.17.140-147
- Stravinskiene V, Bartkevicius E, Plausinyte E (2013) Dendrochronological research of Scots pine (*Pinus sylvestris* L.) radial growth in vicinity of industrial pollution. *Dendrochronologia* 31(3):179–186. doi:10.1016/j.dendro.2013.04.001
- Tolunay D (2003) Air pollution effects on annual ring widths of forest trees in mountainous land of Izmir (Turkey) water. *Air and Soil Pollution: Focus* 3(5–6):233–250. doi:10.1023/A:1026017515151
- Vanclay JK (1994) Modelling forest growth and yield: applications to mixed tropical forests. School of Environmental Science and Management Papers 537 pp
- Wilczyński S (2006) The variation of tree-ring widths of Scots pine (*Pinus sylvestris* L.) affected by air pollution. *Eur J For Res* 125(3):213–219. doi:10.1007/s10342-005-0106-2