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RESEARCH

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Effects of the urban heat island and climate change on the growth of *Khaya senegalensis* in Hanoi, Vietnam

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Abstract

Background: Recent projections expect that Vietnam will be affected most severely by climate change with higher temperatures, more precipitation and rising sea levels. Especially increased temperatures will worsen the situations in cities, amplifying the urban heat island effect. Green infrastructures, i.e. urban trees are a common tool to improve the urban micro-climate for humans. Vital and well growing trees provide greatest benefits such as evaporative cooling, shading, air filtering and carbon storage. However, urban tree growth is often negatively affected by urban growing conditions such as high soil sealing with compacted tree pits providing small growing spaces with limited water, nutrient and oxygen supply, further warm temperatures and high pollution emissions. This study analyzed the growth of urban and rural African mahogany (*Khaya senegalensis* (Desr.) A. Juss.) trees in the city of Hanoi, Vietnam and the effects of the surrounding climate conditions on tree growth.

Results: The results showed that rural African mahogany trees grew better than trees situated in the city center, which is contrary to other results on tree growth of temperate and subtropical cities worldwide. Moreover tree growth was similar regardless of the time of growth. Other results regarding stem growth of African mahogany located in different areas of Hanoi (east, west, north, city center) revealed a better growth in the northern and western outskirts of the city compared to the growth of trees in the city center.

Conclusion: African mahogany trees in the urban centers of Hanoi showed a decreased growth compared to rural trees, which was likely induced by a low ground-water level and high pollution rates. In view of climate change and global warming, the decreased tree growth in the city center may also affect tree service provision such as shading and cooling. Those climate mitigation solutions are strongly needed in areas severely affected by climate change and global warming such as Vietnam.

Keywords: African mahogany, Dendrochronology, Ecosystem services, Urban tree growth

Background

Heat and heat-induced problems are important issues for arid and subtropical regions, in particular for highly urbanized areas (IPCC 2014; Klemm et al. 2015). Due to the urban heat island effect (Oke 1987; Coburn 2009), urbanized regions can be significantly warmer than the surrounding rural regions (Ballester et al. 2010; Seto et al. 2011; Klemm et al. 2015). In the next decades heat problems in urban areas will likely worsen due to increased urbanization and climate change effects. In subtropical regions, high temperatures together with high humidity can dramatically affect the thermal comfort and hence human-wellbeing in urban regions (Daanen et al. 2013; Santamouris 2014). As Schmidt-Thomé et al. (2015) points out, Vietnam will be affected by climate change most severely; It has been considered as a country suffering tremendously from increasing temperatures (annual average temperature has increased by 0.5 °C nationwide), changed precipitation (annual precipitation has decreased in the North and increased in the South) and rising sea

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water levels (IPCC 2001; Schmidt-Thomé et al. 2015). Mitigation measures and adaptation strategies to buffer the impacts of climate change on Vietnam are therefore extremely essential (Schmidt-Thomé et al. 2015). Possible solutions for climate change adaption and mitigation measures are urban green infrastructures, especially urban trees, which are getting increased attention due to their effects of ameliorating their surrounding micro-climate (Dimoudi and Nikolopoulou 2003; Foster et al. 2011; Roy et al. 2012). Urban trees influence the climate of a city by e.g. evapotranspiration and hence air cooling (Rahman et al. 2017a, 2017b) as long as water availability allows, shading (Akbari et al. 2001; Lee et al. 2013), air purification (Bell et al. 2011), wind buffering (Nowak and Dwyer 2007), carbon storage (Nowak and Crane 2002; Davies et al. 2011), reduction of rainwater-runoff (Armson et al. 2013), biodiversity preservation (de Groot et al. 2002; TEEB 2011) and esthetic features for recreation means (Tyrväinen et al. 2005).

However, ecosystem services provided by urban trees are highly related to the growing conditions of a tree, the individual tree size and age, tree vitality, species and specific species features such as wood anatomy and water stress behavior (Yoon et al. 2013; Konarska et al. 2015; Moser et al. 2015; Moser et al. 2016a; Rahman et al. 2017a). For example, anisohydric species react on drought stress with significant decreases of their leaf water potential, providing continued transpiration and hence air cooling as well as growth. Contrary, isohydric species maintain a consistent minimum leaf water potential (reduced transpiration) during drought stress to minimize water loss, however inducing higher latent heat exchange from the ground (Klein 2014; Sjöman et al. 2015). Moreover, broad-leaved species with full crowns provide more shading than species with small leaves and sparse crowns, as well as older and more vital trees (Moser et al. 2015).

Vitality and growth, though, are also highly related to the specific influences an urban tree is exposed to at its growing site. Often urban trees suffer from soil compaction (Bühler et al. 2007; Bartens et al. 2008) and small planting pits with limited water supply and nutrient availability as well as reduced aeration and growing space (Morgenroth and Buchan 2009; Rahman et al. 2013). Additionally the urban heat island can affect urban tree growth due to higher temperatures (higher temperatures can hinder photosynthesis and respiration, lead to membrane destruction (Akbari et al. 2001; Moser et al. 2016a; Rennenberg et al. 2006), higher CO_2 concentrations and higher air pollution (Bussotti et al. 2014).

However, despite the often very negative effects of the urban climate on tree growth, several studies worldwide found an enhanced urban tree growth compared to rural trees (see for example Pretzsch et al. (2017) and Searle et al. (2012)). The study of Pretzsch et al. (2017) included dendrochronological samples of more than 1000 trees of ten metropolises worldwide, spanning from boreal cities to temperate and Mediterranean and subtropical cities. The resulting tree-ring chronologies reflect the past growth of urban trees, dating back more than 100 years, revealing the effects of global climate change and the urban heat island effect on urban tree growth worldwide.

Our study in Hanoi, Vietnam focuses on the urban tree species African mahogany (*Khaya senegalensis*) and its current and past growth in urban and rural areas. African mahogany was introduced to Hanoi; it is native in Africa and occurs along a broad range from Western Africa to Central Africa to Eastern Africa. It is one of the most important timber species in Africa, used e.g. for furniture, railroads and boats. Trees are growing to a maximum height of 30 m (Gaoue and Ticktin 2007). Due to its origin, African mahogany is adapted to moist regions with high rainfall though due to its deep root system it is very drought resistant. African mahogany is a common urban tree species worldwide, especially in tropical and subtropical regions such as Vietnam. Hanoi, with a population of 6.5 million inhabitants the second largest city of Vietnam, will also be affected most severely by climate change due to increased temperatures and precipitation levels (IPCC 2001; Schmidt-Thomé et al. 2015). This study analyzed the growth of a common urban and forest tree species in a subtropical city, highly affected by climate change. The results show how urban trees will be influenced by the urban heat island effect and climate change, helping to find common and practical solutions for mitigation measures to climate change with vital and benefitting green infrastructure. The underlying research questions of this study are:

- How is the general growth trend of *K. senegalensis* trees in Hanoi, Vietnam?
- Is the stem growth of urban *K. senegalensis* trees similar to the stem growth of rural trees?
- Do the past and the current stem growth rates of urban and rural *K. senegalensis* in Hanoi differ?
- How does the climate of Hanoi influence urban tree growth?

Methods

Climate of Hanoi

The climate of Hanoi (Hà Nội), Vietnam is characterized by warm humid subtropical conditions with plentiful precipitation especially in summer, but a distinctly cool and dry season (DWD 2017) (Fig. 1). The cool season starts in November and lasts until April with temperatures of minimum 17 °C, while the warm season spreads from May to

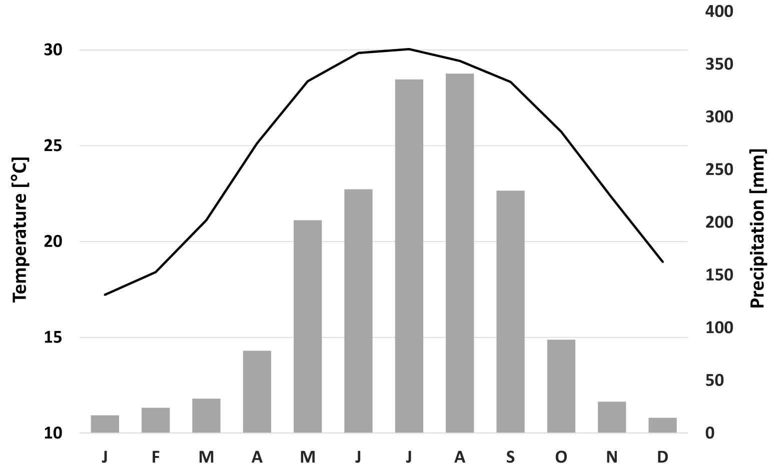

Fig. 1 Monthly temperature (Temp, black line) and precipitation (Prec, grey bars) in Hanoi, Vietnam from 1970 to 2007. Data source: DWD (2017)

October with maximum temperatures of 30 °C. The long-term mean annual temperature is 24.6 °C and the corresponding average precipitation amounts to 1626 mm per year (1970–2009). Over the past 50 years (1958–2007), the annual average temperatures of Vietnam have increased by about 0.5 °C to 0.7 °C. The annual average precipitation does not show a clear trend across the country, however in northern regions a decrease of precipitation has been observed (FAO 2011). In Hanoi, temperatures increased about 0.44 °C in this period, while the precipitation decreased by about 113 mm (DWD 2017).

Data collection

In the city of Hanoi, 149 African mahogany trees were sampled randomly. Data collection was conducted at several sites mostly along streets throughout the city to include variation in site microclimate, urbanity and direction (Fig. 2, Table 1).

The degree of urbanity at each site was assigned to one of three categories: urban, suburban and rural. Trees in the inner city center were classified as urban (map numbers 8, 12–16), while trees in the outer city center were marked as suburban (numbers 7, 9–11) and trees growing in the outskirts of the cities were sampled as rural trees (numbers 1–6). Moreover, based on their location in terms of cardinal directions seen from the city center, the sampled trees were divided into the groups center (numbers 8–11, 14), northern (numbers 1, 2, 6, 7), eastern (numbers 12, 13, 15, 16) and western (numbers 3–5) growing trees. The sampling locations differed also in terms of ground water availability. Phi and Strokova (2015) analyzed the ground-water level in Hanoi and found high water levels northern of the Red river for sampling locations 1, 2, 6 and 7 as well as for the sampling spots 3, 4 and 5. In the inner city center (locations 8, 9) the ground-water level is very deep, however increasing towards the Red river and at the southern and western parts of the city (Phi and Strokova 2015).

Data collection included increment core collection, recording of tree structural data such as diameter at breast height (*dbh*), tree height (*h*), height to the crown base (*cb*), crown radii in four cardinal directions (North, East, South, West) following basic forestry inventory methods (Pretzsch 2010) and prevalent site conditions including tree position (coordinates and altitude).

Based on these collected tree data, the quadratic mean crown radius (*cr*) and crown projection area (*cpa*) were calculated as following

$$\mathrm{cr} = \sqrt{\left(r_{\mathrm{N}}^2 + r_{\mathrm{S}}^2 + \ldots + r_{\mathrm{W}}^2\right)/4} \tag{1}$$

with r_{N} as the widest measured crown extension in the northern direction,…, r_{W} the widest crown extension in the western direction.

$$cpa = cr^2 \times \pi \tag{2}$$

with *cr* as the crown radius and π as pi.

Increment core collection was conducted at each tree with extraction of two wooden cores in opposing directions (north, east) at a height of 1.3 m aimed at the center of the tree. The increment corer was 5 mm in diameter (Manufacturer: Haglöf, Sweden).

Core and data processing

All cores were mounted on grooved boards with glue and sanded using progressively finer sand papers. The first sanding was applied to flatten the cores, whereas the subsequent sanding episodes polished the cores for better visualization of the cross-sectional area (Speer 2012). The

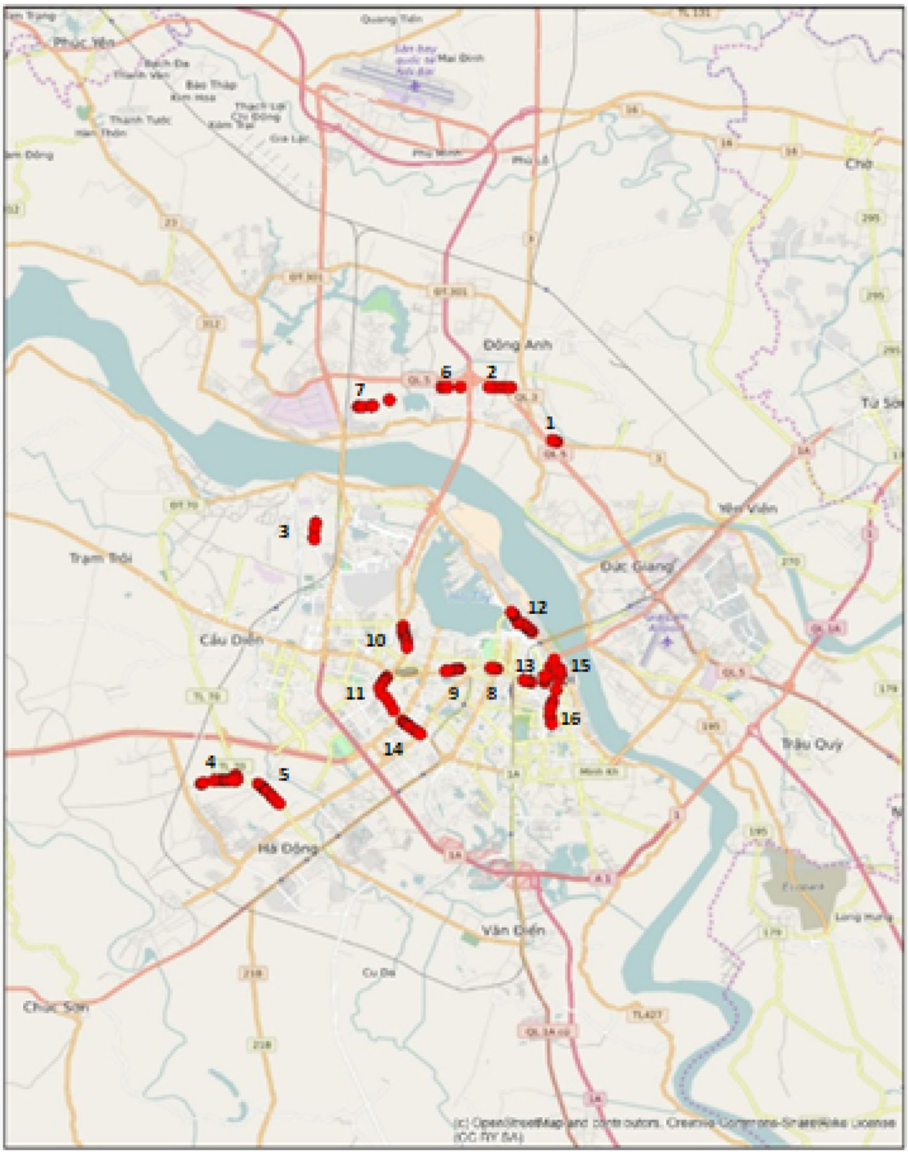

Fig. 2 Selection of African mahogany (*K. senegalensis)* in Hanoi, Vietnam with numbers indicating categories urban, suburban and rural as well as cardinal direction north, east, west and center

annual tree-ring widths of the cores were measured using a Lintab digital positioning table with a resolution of 1/100 mm (Rinn 2005). For cross-dating of the time-series, the software package TSAP-Win (Rinn 2003) was used and hereby checked for possible missing growth rings or measurement errors. Further analyses were carried out in R (R Core Team 2018) using package dplR (Bunn et al. 2015). With dplR, all tree-ring series were indexed using a double detrending process: first, modified negative exponential curves were applied followed by cubic smoothing splines (20 years rigidity, 50% wavelength cutoff). The detrending was conducted to remove low frequency trends, which are age associated (Holmes et al. 1986; Gillner et al. 2014). The resulting detrended series were averaged using Tukey's biweight robust mean to build a final chronology and chronologies for each category (all trees; urban, suburban, rural; center, north, east, west). As a result of detrending, standardized chronologies with a yearly ring width index (RWI) averaging around 1 were obtained. Values smaller than 1 indicate growth below normal, while values greater than 1 indicate growth higher than normal. For chronology building, the autocorrelation of every individual series was removed (maximum order: 3). This procedure of detrending ensured a removal of all long-term growth trends, thereby obtaining a chronology containing only tree ring variability with climate fluctuations (Cook and Holmes 1986; Gillner et al. 2013). The statistical validity of the chronologies was assessed using the expressed

Table 1 Information on sampling site, urbanity grade classification, cardinal direction of sampling site and ground water level of the sampled African mahogany (*Khaya senegalensis*) trees in Hanoi

No.	Name of site	No. of trees	Urbanity grade	Cardinal direction	Ground water level[a]
1	Dong Ang	18	rural	North	high
2	Dong Ang	5	rural	North	high
3	Dan Phuong	4	rural	West	high
4	Hoai Duc	12	rural	West	high
5	Hoai Duc	13	rural	West	high
6	Dong Ang	5	rual	North	high
7	Dong Ang	11	suburban	North	high
8	City center	5	urban	Center	low
9	CIty center	10	suburban	Center	low
10	City center	11	suburban	Center	low
11	City center	11	suburban	Center	low
12	City center	9	urban	East	high
13	City center	11	urban	East	high
14	City center	5	urban	Center	low
15	City center	15	urban	East	high
16	City center	14	urban	East	high

[a] Based on Phi and Strokova (2015)

population signal (EPS) for the common period of the time series of all analyzed tree individuals.

Trend analysis (long term trends)

Using the R package lme4 (Bates et al. 2015), three linear mixed models of the following forms 4, 5 and 6 were developed to assess the influence of the tree age (*age*), the time of growth (before 1960/since 1960; *time of growth*), urbanity (urban/rural; *grade of urbanity*) and further climate (M) on the annual basal area (response variable) derived by increment cores.

To assess the climate influence on tree growth, we calculated the index of de Martonne (1926) M on the basis of the precipitation (in mm) and mean temperature (in ° C) for each month from 1970 to 2012:

$$M = Prec \,/\, (Temp_{\mathrm{mean}} + 10) \tag{3}$$

with M as the de Martonne index, $Prec$ as precipitation in mm and $Temp_{\mathrm{mean}}$ as mean temperature in °C.

$$\log\left(ba_{ij}\right) = a_0 + a_1 \times time\ of\ growth_{ij} + (b_0 + b_1 \times time\ of\ growth_{ij}) \times \log(age_{ij}) + c_{ij} + \varepsilon_{ij}, \tag{4}$$

with ba_{ij} as the basal area for the jth of n_i observations, a_0 as the intercept, a_1 as the intercept of $time\ of\ growth_{ij}$, $time\ of\ growth_{ij}$ as the growth periods before 1960 or since 1960, b_0 as fixed effect, b_1 as fixed effect of $time\ of\ growth_{ij}$, age_{ij} as the age of each tree, c_{ij} as random effects and ε_{ij} as errors.

$$\log\left(ba_{ij}\right) = a_0 + a_1 \times grade\ of\ urbanity_{ij} + (b_0 + b_1 \times grade\ of\ urbanity_{ij}) \times \log\,(age_{ij}) c_{ij} + \varepsilon_{ij}, \tag{5}$$

with ba_{ij} as the basal area for the jth of n_i observations, a_0 as the intercept, a_1 as the intercept of $grade\ of\ urbanity_{ij}$, $grade\ of\ urbanity_{ij}$ as urban or rural, b_0 as fixed effect, b_1 as fixed effect of $grade\ of\ urbanity_{ij}$, age_{ij} as the age of each tree, c_{ij} as random effects and ε_{ij} as errors.

$$\log\left(ba_{ij}\right) = a_0 + a_1 \times grade\ of\ urbanity_{ij} + (b_0 + b_1 \times grade\ of\ urbanity_{ij}) \times \log\,(age_{ij}) + (b_0 + b_1 \times grade\ of\ urbanity_{ij}) \times \log(M_{ij}) + c_{ij} + \varepsilon_{ij} \tag{6}$$

with ba_{ij} as the basal area for the jth of n_i observations, a_0 as the intercept, a_1 as the intercept of $grade\ of\ urbanity_{ij}$, $grade\ of\ urbanity_{ij}$ as urban or rural, b_0 as fixed effect, b_1 as fixed effect of $grade\ of\ urbanity_{ij}$, age_{ij} as the age of each tree, M_{iJ} as the de Martonne index, c_{ij} as random effects and $\boldsymbol{ij}$ as errors.

To summarize the variables of the equations, $\boldsymbol{a}_1$, ..., $\boldsymbol{a}_n$ and, $\boldsymbol{b}_1$, ..., $\boldsymbol{b}_n$ are the fixed effects with the "*a*" parameters are components of the intercept and the "*b*" parameters are components of the slope, respectively. The two dummy variables *time of growth* and *grade of urbanity* were introduced to differentiate between the two growth-trend relevant periods (before 1960/since 1960) and urbanity classifications (urban/rural). If a_1 in eq. 4 differed significantly from 0, this would mean that the age-basal area relationship before 1960 had a different intercept than since 1960. In eq. 5 this would indicate that the intercept of urban trees is not the same as for rural trees. The parameter b_1 in both equations has an analogous meaning for the slope. The "*c*" parameters are random effects, which are assumed to be normally distributed. These random effects cover statistical dependencies which are due to the nested data structure. The errors $\boldsymbol{ij}$ are assumed to be independent identically distributed.

Results

In Table 2 the measured characteristics of all analyzed trees are presented with found minimum, maximum and average measured values together with standard deviation. The average age of all sampled trees was 33 years with a minimum of 10 years and a maximum of 73 years. The smallest African mahogany had a *dbh* of 44.1 cm, while the largest tree had a *dbh* of 123.1 cm and the average *dbh* was 73.4 cm with 16.0 cm standard deviation for all trees. The average height of African mahogany was 22.6 m (14.1 m minimum and 36.0 m maximum). Further, the average yearly growth rate was 5.9 mm.

Figure 3 displays the average undetrended radius increment, basal area increment and age-detrended growth of African mahoganys in Hanoi, Vietnam from 1947 to 2012. The first order autocorrelation was 0.3 and the resulting detrended chronology of all trees (Fig. 3c) had an EPS value of 0.64.

Overall, the analyzed trees showed a very steady growth increase, as in particular the BAI displays. There were no exceptionally good and bad growth years in the last years, 2010, 1998 and 1994 are examples of years with growth above the average, while 1992, 1997 and 1999 were years with growth below the average.

Trends in relation to the growing site

In a next step, the growth over the past years was analyzed regarding the growing site in a finer scale (urban, suburban, rural). Overall tree structures, growth and age varied depending on growing location (Table 3). Age, *dbh*, tree height, crown radius, crown length and *cpa* of urban trees were in average greater than of suburban and rural trees. EPS values of all three chronologies were lower than 0.85 (Wigley et al. 1984). The autocorrelation before the detrending process was highest for the suburban chronology and lowest for the rural chronology.

The radius increment, basal area growth and ring width index (RWI) of rural, urban and suburban trees displayed clear differences (Fig. 4). While the radius increment and the basal area increment of rural trees showed a higher growth rate than urban and suburban trees, the indexed growth values were more uniform. Though between 2002 and 2007, rural trees displayed greater RWI as well, albeit the growth of suburban and urban trees was more enhanced from 2010 on.

To further analyze the growth of African mahogany in Hanoi, sampled trees were classified based on the cardinal direction (seen from the city center) in which they were found. Table 4 displays the tree characteristics of trees based on this classification. Center and east growing trees showed greatest tree structures, while northern trees were youngest and had smallest tree structures. EPS values of all four chronologies were lower than 0.85 with highest values for the eastern chronology and lowest values for the center chronology of African mahogany. Moreover, autocorrelation of the undetrended chronologies varied between 0.22 for the northern trees and 0.37 for the center trees.

Figure 5 displays the radius increment, basal area growth and indexed ring width values of African mahogany trees based on the cardinal direction they were growing. Radius increment and basal area highlight a better growth of northern trees with smallest growth in the center and eastern region. Ring width index RWI, however, shows an acceleration of the center and eastern trees during the more recent years.

Table 2 Minimum, average, maximum and standard deviation (SD) of age, diameter at breast height (*dbh*), radius increment (*RI*), tree height (*h*), crown radius (*cr*), crown length and crown projection area (*cpa*) of the analyzed African mahogany (*Khaya senegalensis*) trees in Hanoi

	Age	*dbh* (cm)	*RI* (mm)	*h* (m)	*cr* (m)	Crown length (m)	*cpa* (m^2)
Min	10.0	44.1	0.2	14.1	3.1	9.1	29.3
Avg	33.3	73.4	5.9	22.6	6.5	16.9	141.1
Max	73.0	123.1	46.9	36.0	11.6	27.0	424.7
SD	13.5	16.0	5.8	5.1	1.7	4.3	77.6

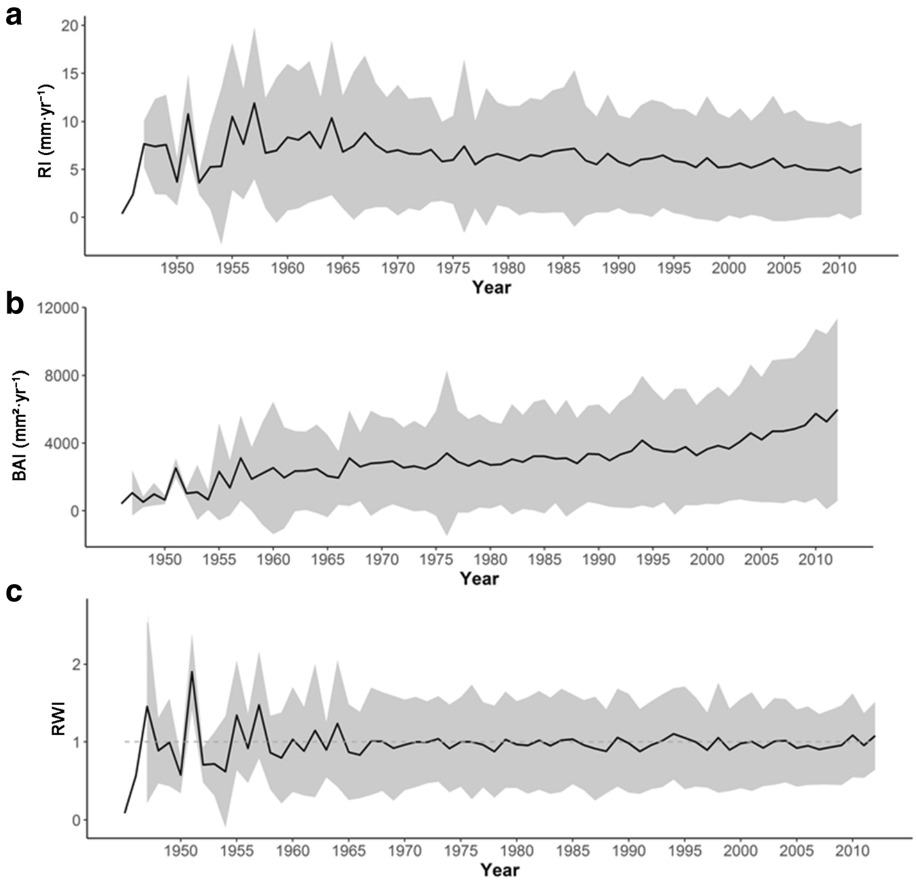

Fig. 3 Radius increment (**a**), basal area increment (**b**) and detrended ring width index (**c**) of all sampled African mahogany trees (*K. senegalensis*) in Hanoi with according standard deviation (grey areas)

Long-term growth trends

Figure 6 displays the growth of African mahogany in Hanoi in comparison to the averaged growth of urban trees in 10 metropolises worldwide from the study of Pretzsch et al. (2017). When analyzing the growth trends from 1960 to 2012 and before 1960, a similar growth of African mahogany in these two periods was found. The growth of African mahogany was similar regardless of the time of growth, only minor differences were found (Fig. 6a, colored lines). Furthermore, rural African mahogany trees were growing better than trees in rural areas. Only very young urban trees grew slightly better than rural trees (Fig. 6b, colored lines).

The results of the statistical models in Fig. 6 are presented in Table 5 (a and b). A lower AIC value of the model in Table 5b indicates a better fit compared to the model presented in Table 5a. In both models, age positively influences growth, therefore as also illustrated in Fig. 6 older African mahogany trees in Hanoi tend to be greater in size than younger trees. Time of growth was negatively correlated with growth, however together with age this effect was reversed. Urbanity classification (urban

Table 3 Number and average with standard deviation of age, diameter at breast height (dbh), tree height (h), crown radius (cr), crown length and crown projection area (*cpa*) as well as the Expressed Population Signal (EPS) and the Autocorrelation (AR) of the analyzed African mahogany (*K. senegalensis*) in Hanoi in the categories urban, suburban and rural

	n	Age(a)	*dbh*[m]	*h*(m)	*cr*(m)	Crown length(m)	*cpa* (m^2)	EPS[a]	AR
urban	37	40.5 ± 12.7	82.2 ± 9.7	26.8 ± 4.3	7.3 ± 2.1	20.1 ± 4.1	179.3 ± 98.1	0.73	0.31
suburban	48	39.0 ± 10.6	76.4 ± 9.7	22.9 ± 3.4	6.0 ± 1.5	16.8 ± 3.5	120.2 ± 65.8	0.4	0.39
rural	57	22.5 ± 8.5	62.9 ± 12.0	18.4 ± 2.6	6.1 ± 1.1	14.0 ± 2.4	121.7 ± 45.3	0.8	0.21

[a] Based on the ring width index of tree ring chronologies for the common period, obtained by double detrending of the tree ring series

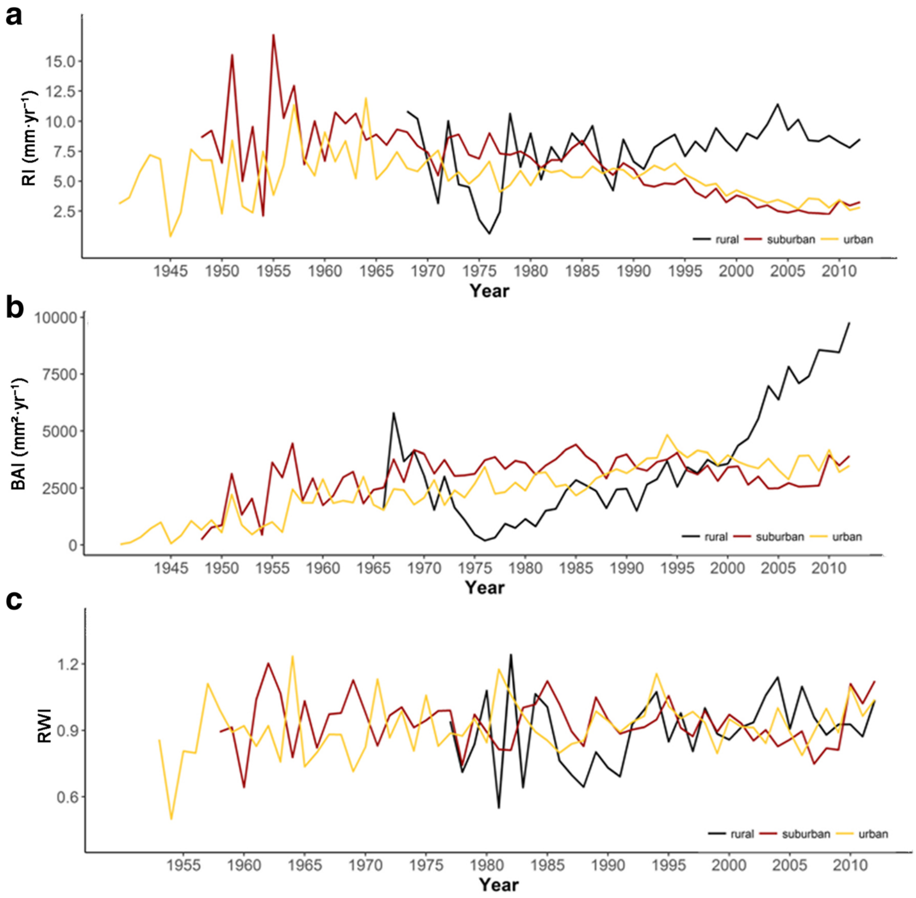

Fig. 4 Radius increment (**a**), basal area increment (**b**) and ring width index RWI (**c**) of African mahogany (*K. senegalensis*) in Hanoi growing at forest, rural, suburban and urban sites

to rural) had the strongest effect on the growth rate, with rural trees showing higher basal area growth than urban trees, however during very young age this effect was reversed.

Climate-growth relationships

The influence of climate, i.e. water supply as the index of de Martonne on growth in relation to the grade of urbanity and growing direction were further tested (Table 6). A mixed model revealed a positive influence of more favorable water status on growth, albeit the relationship was not significant. In interaction with the grade of urbanity, a better climate had negative influences on urban tree growth. However the effect size was small and not significant.

The found effects were also revealed in a finer scaling of urbanity (urban, suburban, rural), with suburban tree growth displaying similar correlations with climate as was shown above for urban trees. The growing site in terms of cardinal direction had no significant influence on tree growth and interactions with climate were also non-significant.

Table 4 Number and average with standard deviation of age, diameter at breast height (*dbh*), tree height (*h*), crown radius (*cr*), crown length and crown projection area (*cpa*) as well as the Expressed Population Signal (EPS) and Autocorrelation (AR) of the analyzed African mahogany (*K. senegalensis*) in Hanoi based on cardinal direction of sampling site (north, center, east, west)

	n	Age (a)	*dbh* (m)	*h* (m)	*cr* (m)	Crown length (m)	*cpa* (m^2)	EPS[a]	AC
North	35	22.9 ± 12.1	60.2 ± 10.5	18.1 ± 2.5	5.5 ± 0.8	13.6 ± 2.0	98.6 ± 28.9	0.71	0.22
Center	44	38.6 ± 10.1	80.0 ± 14.7	24.9 ± 4.6	6.2 ± 1.7	18.3 ± 4.5	130.7 ± 70.0	0.50	0.37
East	41	41.1 ± 13.3	78.9 ± 14.3	26.8 ± 3.9	7.2 ± 2.1	20.1 ± 3.8	177.2 ± 102.1	0.72	0.31
West	40	30.0 ± 10.1	71.6 ± 13.1	20.0 ± 2.8	6.5 ± 1.2	15.2 ± 2.6	138.8 ± 49.0	0.60	0.29

[a] Based on the ring width index of tree ring chronologies for the common period, obtained by double detrending of the tree ring series

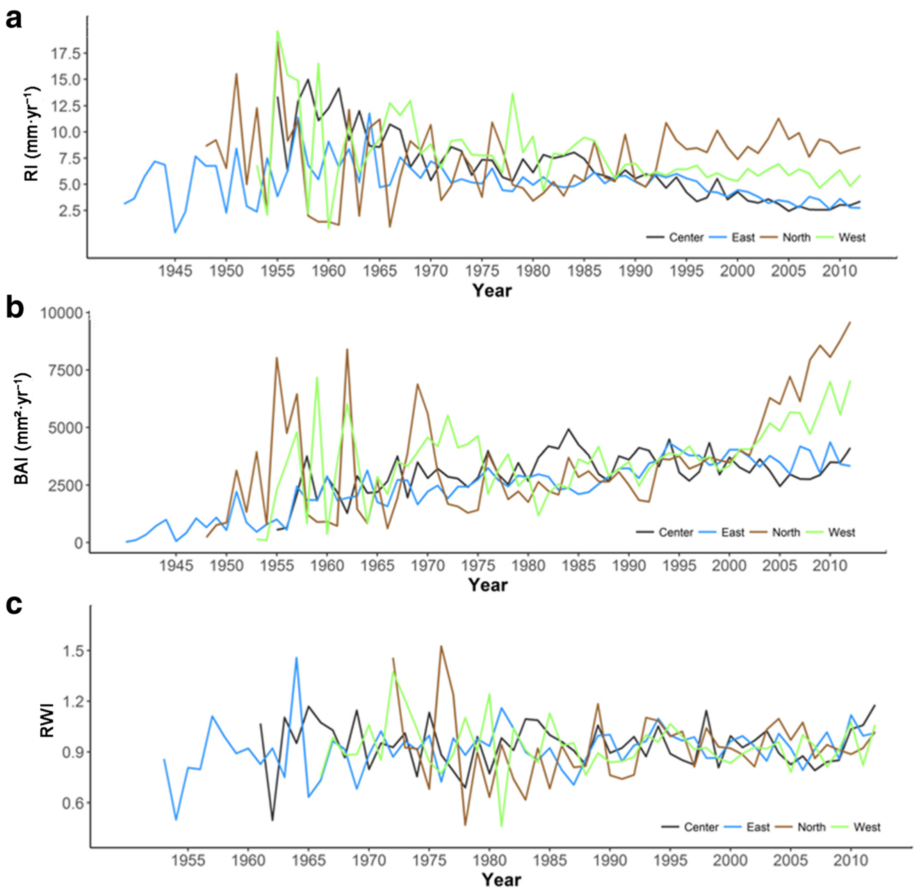

Fig. 5 Radius increment (**a**), basal area increment (**b**) and ring width index RWI (**c**) of African mahogany (*K. senegalensis*) in Hanoi growing in the center, in eastern, northern and western direction

Discussion

Growth of *K. senegalensis*

The growth potential of the studied African mahogany is hardly known, due to a lack of long-term experimental plots, physiological and dendrochronological studies of this species (Arndt et al. 2015). The scarcity of dendrochronological studies might also be related to the difficulties of tree ring distinction of African mahogany. Tarhule and Hughes (2002) even classified mahogany as a problematic species for dendrochronological approaches

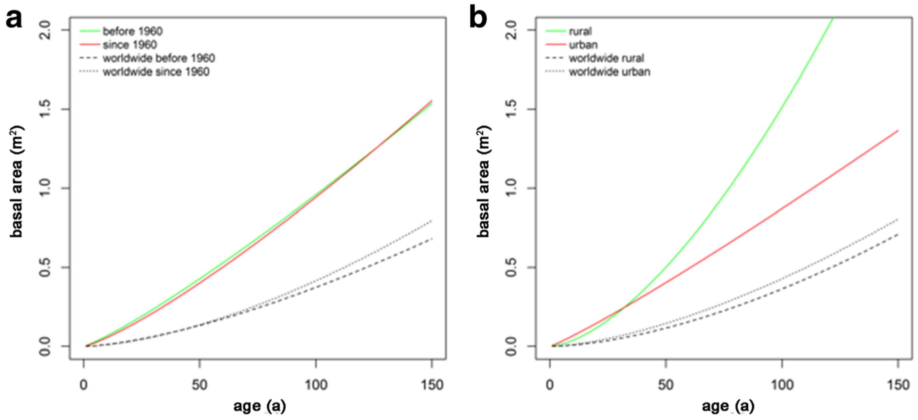

Fig. 6 The size growth in terms of basal area growth of *K. senegalensis* in Hanoi and the worldwide found growth trends of Pretzsch et al. (2017) for (**a**) the period before 1960 compared to the period since 1960 and (**b**) urban trees compared to more rural growing trees

Table 5 (a) Linear mixed model on the annual basal area increment ($mm^2 \cdot yr.^{-1}$) of all analyzed trees (response variable) with the individual tree code as random effect and fixed effects logarithmized age related to the factor time of growth (period before 1960 and period since 1960), SD: Standard deviation, AIC: Akaike Information Criterion

Parameter	Fixed effect	Value ± SE	*p*
a	Intercept	− 5.40 ± 0.14	< 0.001
log(age_{ij})	Age	1.16 ± 0.04	< 0.001
$time\ of\ growth_{ij}$	Time of growth	−0.34 ± 0.13	0.01
b x $time\ of\ growth_{ij}$ x log(age_{ij})	Age x Time of growth	0.07 ± 0.04	0.06
Random effect d_{ij}		0.47	–
ε		0.19	–
AIC		− 1664.82	–

Levels of Time of growth: 2 (Before 1960 and Since 1960)

because of unclear tree ring formation. The low EPS values of the presented chronologies confirm these problems in wood core analyses of African mahogany. The EPS values were mostly lower than the threshold of 0.85 for dendrochronological analyses set by Wigley et al. (1984). However, the studied African mahogany trees were in average only 30 years old, which increases difficulties in chronology building due to the low number of rings (Speer 2012). Moreover the selected trees cover a wide variety of conditions in terms of the grade of urbanity, water supply and other urban settings (pit size, pollutant input) affecting tree ring formation, which also makes chronology building more difficult (Speer 2012; Moser et al. 2016b; Campelo et al. 2018; Vieira et al. 2018).

We calculated annual stem radius growth rates of around 6 mm on average for African mahogany in Hanoi. Perera et al. (2012) analyzed the growth rate of three mahogany specimen and found similar growth rates of around 3–8 mm per year. However, in comparison with other urban tree species studied (e.g. Gillner et al. (2014), Dahlhausen et al. (2016), Moser et al. (2017)) this growth rate is exceptionally high. Pretzsch et al. (2017) for example found in their worldwide metropolis study of urban trees average stem radius growth rates of 3.2 mm per year. These high growth rates, especially in a stressful environment such as urban areas might be due to the high resilience against drought and heat stress, as Arndt et al. (2015) found out for this species.

Influence of site conditions and the city climate on tree growth

An analysis of the growth of African mahogany in Hanoi showed a distinctly better undetrended growth and basal area increment of rural trees in comparison to suburban and urban tree. However, the current higher growth rate of rural trees can also be influenced by the younger age of trees growing in the rural surroundings of Hanoi, since younger trees mostly exhibit higher growth rates than older trees (Esper et al. 2002). The studied rural trees were on average around 25 years younger than the urban trees, followed by a markedly smaller *dbh* of urban trees compared to suburban and urban trees. This was confirmed by a more uniform growth of urban, rural and suburban trees after age-trend removal. Nevertheless, rural trees were marked by a very high basal area increment compared to urban and suburban trees, exceeding the growth of urban and suburban trees at a similar age by far. Possible reasons for this high basal area increment of rural trees can be a better water supply by a high ground-water level (Phi and Strokova 2015) and lower pollution inputs (Kim Oanh et al. 2006).

Table 5 (b) Linear mixed model on the annual basal area increment ($mm^2 \cdot yr.^{-1}$) of all analyzed trees (response variable) with the individual tree code as random effect and fixed effects logarithmized age related to the growing site (urban and rural), SD: Standard deviation, AIC: Akaike Information Criterion

Parameter	Fixed effect	Value ± SE	*p*
a	Intercept	−6.92 ± 0.08	< 0.001
log(age_{ij})	Age	1.59 ± 0.02	< 0.001
$urbanity\ grade_{ij}$	Grade of urbanity	1.68 ± 0.10	< 0.001
b x $urbanity\ grade_{ij}$ x log(age_{ij})	Age x Grade of urbanity	−0.48 ± 0.02	< 0.001
Random effect d_{ij}		0.52	–
ε		0.17	–
AIC		− 2356.13	–

Levels of Urbanity: 2 (Urban and Rural)

Table 6 Linear mixed model on the annual basal area growth ($mm^2 \cdot yr.^{-1}$) of all analyzed trees (response variable) with the individual tree code as random effect and fixed effects growing site (urban and rural) and the de Martonne index with interactions, SD: Standard deviation, AIC: Akakike Information Criterion

Parameter	Fixed effect	Value ± SE	*p*
A	Intercept	−7.14 ± 0.16	< 0.001
log(*age*)	Age	1.61 ± 0.01	< 0.001
$Urbanity\ grade_{ij}$	Grade of Urbanity	1.89 ± 0.19	< 0.001
$\log(M_{ij})$	De Martonne Index	0.04 ± 0.03	0.27
$b \times \log(urbanity\ grade_{ij}) \times \log(age)$	Grade of Urbanity x Age	−0.50 ± 0.02	< 0.001
$b \times urbanity\ grade_{ij} \times \log(M_{ij})$	Grade of Urbanity x de Martonne Index	−0.03 ± 0.04	0.38
Random effect d_{ij}		0.52	–
ε		0.17	–
AIC		− 2451.83	–

Levels of Urbanity: 2 (Urban and Rural)

Further analyses of African mahogany growth revealed a better development of trees located in the northern areas of Hanoi than of trees studied in other directions. In particular trees in the center and in eastern regions showed far less growth rates than western and northern trees. These findings might be influenced by higher humidity and moisture in the north due to the fact the "Red River" crosses city from the north to the east. Results of Phi and Strokova (2015) describe a lower ground water level in the city center of Hanoi compared to the northern, eastern and western parts of the city, confirming this assumption. However, trees of eastern region did not show an enhanced growth. This can be attributed to the study design of African Mahogany trees, since trees in the northern region were also mostly rural trees and eastern trees were all urban trees. Therefore the underlying trend was probably also influenced by the urbanity classification.

Long-term growth trends and climate-growth relationships

Findings in forests of different climate zones (Fang et al. 2014; Kauppi et al. 2014; Pretzsch et al. 2014) and in cities worldwide (Searle et al. 2012; Pretzsch et al. 2017) illustrate accelerated growth rates of trees in recent decades as well as a better growth of urban trees in city centers compared to rural trees. These findings raise the question of tree responses in forests and cities to climate change and changed environmental conditions. Due to the urban heat island effect (Oke 1987; Coburn 2009), urban areas might reflect future conditions induced by climate change and the resulting consequences for trees (Bussotti et al. 2014; Farrell et al. 2015). For example, the study of Pretzsch et al. (2018) showed that forest trees can grow faster by climate change, but the annually growing wood has gradually becoming lighter, by up to eight to 12% since 1900. The causes might be temperature increased and prolonged vegetation periods caused by climate change as well as nitrogen inputs by agriculture, traffic and industry (Pretzsch et al. 2018). This effect of lighter wood might be even stronger in case of urban trees. Lighter wood is less solid, it has a lower calorific value and lower contribution to carbon sequestration. Less solid wood in living trees also increases the risk of damage events such as breakage due to wind or snow, which is of high importance in urban areas.

In fact, the worldwide study of Pretzsch et al. (2017) on 10 urban tree species include analyses of boreal, temperate, Mediterranean, and subtropical climate conditions and revealed that across all climate zones urban tree growth has significantly enhanced during the past decades. On average trees in the city centers also grew significantly quicker than trees in the city's rural surrounding (Pretzsch et al. 2017). Possible reasons for this trend are based on the global climate change leading to higher temperatures (IPCC 2014) with higher N-deposition rates and higher CO_2 concentrations (Churkina et al. 2010) along with prolonged growing seasons (Chmielewski and Rötzer 2001).

In contrast to the results found for other urban tree species in cities worldwide (Searle et al. 2012; Pretzsch et al. 2017) no accelerated basal area growth was found over time for African mahogany in Hanoi. Moreover, contrary to the observed worldwide trend, mahogany trees growing in urban settings showed smaller basal area growth than rural trees. Rural African mahogany trees with age over 30 years grew significantly better than urban trees. Very young aged urban trees, however, displayed better basal area growth than rural trees. Due to the age differences, though, the age-detrended RWI results can provide further insight to the growth of urban and rural African mahogany trees in Hanoi. Here, similar growth rates were found, when analyzing the age detrended RWI development of urban and rural trees, though, rural trees showed low-growth episodes (1985–1992, 2009–2012) compared to urban trees.

Having a closer look at the results of Pretzsch et al. (2017) slightly different results can be derived when urban trees of the subtropical climate are compared to the worldwide average: Subtropical rural trees showed a very high growth acceleration since 1960. Whether a tree in the city centers grew better compared to trees in the rural surrounding is highly dependent on the city analyzed. Moser et al. (2017) showed a trend of better urban growth in recent years for trees in the city of Houston, Texas, a subtropical city. The contrasting results found for the subtropical city of Hanoi might also be due to the critical effects of climate change in Vietnam (IPCC 2001; Schmidt-Thomé et al. 2015), but also high air pollution (Kim Oanh et al. 2006) and low ground-water levels in the city center (Phi and Strokova 2015).

Using a mixed model approach a positive though not significant influence of climate on tree growth in Hanoi was found. Moreover, urban trees showed less growth with better climate conditions (higher de Martonne-Index), albeit this correlation was also not significant. As discussed before, the negative influences of the urban environment in Hanoi (low ground water level, high air pollution) counteract positive influences affecting trees in urban areas such as higher temperatures (IPCC 2014) and a longer growing season (Chmielewski and Rötzer 2001).

This study illustrates that the relationships of tree growth in urban and rural areas is a complex interaction of factors such as urbanity grade, planting age and design as well as climate variables (e.g. city location with according climate, climate change effects, pollution). More studies are necessary to understand worldwide urban tree growth, in particular under conditions changed by climate change.

Conclusion

Vietnam and in particular Hanoi will be affected most severely by climate change. Urban trees such as the here studied urban tree species African mahogany can mitigate the negative effects of climate change and the urban heat island effect, e.g., through shading and cooling. However, African mahogany trees in the city center of Hanoi showed less growth than rural trees. This might be due to changing environmental conditions, however more likely is a worse water supply by a lower ground -water level and higher pollution loads. Rural trees were significantly younger and displayed higher growth rates, in particular basal area growth in recent years was enhanced. Since the climate mitigation services trees can provide are highly related to tree vitality and growth, the living conditions of urban trees in cities like Hanoi need to be improved provide sustainable ecosystem services for better human living conditions, especially in urban regions highly affected by global warming.

Abbreviations

AIC: Akaike information criterion;; AR: Autocorrelation;; BAI: Basal area increment;; cb: Height to crown base;; cpa: Crown projection area;; cr: Crown radius;; dbh: Diameter at breast height;; EPS: Expressed population signal;; h: Tree height;; M: de Martonne index;; RI: Radius increment;; RWI: Ring width index;; SD: Standard deviation;; urb: Urbanity.

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Availability of data and materials

The materials described in the manuscript including all relevant raw data will be freely available upon request from the corresponding author.

Authors' contributions

HP, EU, TR, PB and TC initiated the study and conceptualized the study design. PB, TC and NTT conducted the field work. AMR conducted the data analysis and wrote the draft version of the manuscript. PB supported the statistical analysis and revised the manuscript together with TR, EU and HP. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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