



Growing space requirement and height growth rate-related mortality risk in three fast-growing tree species of Delhi Forest

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Summary

Identifying both exogenous and endogenous drivers of tree mortality is a big challenge for forest ecologists, particularly in times of climate change. The survival and mortality trends of fast-growing and slow-growing species (two distinct functional groups in nature) has been eloquently addressed and discussed in the past. This article compares height-growth rate-related mortality risk in three fast-growing Delhi- forest species viz. *Eucalyptus citriodora* (EC), *Acacia auriculiformis* (AA) and *Acacia nilotica* (AN). The survival curves for the three species were generated using the Kaplan-Meier function in R. Cumulative hazard curves were also built simultaneously. Results indicated that the survival probability of *E. citriodora* was low during most of its height development. Likewise, the cumulative hazard curve demonstrated a maximum value for EC (1.58), followed by AA (1.44) and AN (1.01). Moreover, Cox Proportional Hazard model also indicated a high risk of mortality in EC in contrast to the other two species. Covariates such as tree height suggested a high relative risk in EC as compared to the other two species. However, when crown diameter was incorporated as a predictor variable, it had a negative impact on the risk of mortality for EC in comparison to the other two species in question. With increasing crown diameter, the risk of mortality (relative risk) in EC dropped by about 32% and 11% in contrast to AA and AN, respectively, during the 11- year study period. In addition, the growing space requirement of a tree was also correlated to stem diameter, tree height, and height - to - diameter ratio (h/d). Both stem diameter and tree height had a positive correlation with the growing space requirement. h/d ratio sharply decreased with tree age and growing space having high values (> 1) in the beginning, which stabilized at later stages of growth. The investigation demonstrated that among three species evaluated, EC had the highest hazard and lowest survival time than AA and AN despite the fact that EC had attained maximum height (9.15 m) during the span of 11 years in contrast to AA (7.10 m) and AN (5.74 m).

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Introduction

Tree growth is specifically related to both resource availability and a tree's ability to utilize the available resources. However, available resources are a complex cocktail of many ecological factors and are difficult to quantify in natural ecosystems. As a result, two-dimensional measures of "growing space" are commonly applied as a proxy for the suite of factors that make up "available resources". Thus, determining the growing space requirement of a tree is a central concern to forest managers. Understanding the relationship between growing space and tree growth has economic as well as ecological significance.

Tree mortality is one of the most critical phenomena for the scientific community under rapid climate change (McDowell & Allen 2015; Dhaka & Prajapati 2022). Expected rise in the intensity and frequency of droughts and extreme weather events may contribute to the intensification of tree mortality across the world (Allen

et al., 2015; Seidl et al., 2017). Delhi has a semi-arid climate due to poor rainfall (66.6 cm annually), though the area once received significant rainfall in the monsoon. Currently, the city is also facing frequent and abrupt rainfall patterns due to climate change, leading to drought-like conditions, which is influencing the growth of forest flora as well, particularly fast-growing trees. The early detection of tree vulnerability to mortality is essential for the sustainable management of forest ecosystems and forecasting the capacity to provide ecosystem services over different time horizons (O'Brien et al. 2017). Therefore, approaches for the assessment of forest susceptibility to mortality have increasing importance in forest management.

Tree mortality arises from the interaction of characteristics of the species and the tree with the environment, resulting in physiological failure or structural damage leading to death (McDowell et al. 2018). Physiological failure may be caused by senescence, stress-related (i.e. light competition, moisture stress, pathogen attack) loss of physiological vigour (Chao et al. 2008) or by the impairment of water

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transport as a consequence of hydraulic failure (McDowell 2011; Rowland et al. 2015; Shedage et al. 2023). Structural failure happens as a consequence of storms and tree falls, leading to stem breakage or uprooting (Chao et al. 2009).

While the increase in tree size has been shown to predict tree death (Lines et al. 2010; Lida et al. 2014), recent studies have emphasized the importance of individual growth rate as a potential mortality risk factor (Gora et al. 2020). Tree height is one of the most relevant predictors of mortality in drought-like conditions (Stoval et al., 2019). Much evidence that large and fast-growing trees are most vulnerable to climate change-driven mortality was also highlighted previously (Allen et al. 2015; Brien et al. 2020). The fast growth rate of trees is generally associated with high mortality and reduced longevity (Korner 2017), probably due to highly stressed tree physiological systems, making it more vulnerable to environmental stresses and pathogen outburst, eventually leading to high hazard and low survival times. Thus, a growth rate of trees has also been found to be a valuable indicator of susceptibility to mortality (Cailleret et al., 2017). Faster-growing trees have shorter lifespans; therefore, the widespread increase in global forest mortality may also be related to growth rates (Searle & Chen 2018; Brien et al. 2020). All studies in the context of forest mortality have analysed radial growth. To the best of my knowledge, the effect of relative height increment on the mortality risk of a tree has not yet been studied to date. The article thus deals with predicting survival and mortality trends in three fast-growing tree species of Delhi urban forest viz. *E. citriodora*, *A. auriculiformis* and *A. nilotica*, by taking relative height increment as a basis to create binary codes (0 = relative height growth high and 1 = where relative tree height is low or no change). The survival and cumulative hazard curves were generated applying Kaplan- Meier function. Modeling results are described and interpreted in the present manuscript.

Material and Method

Study Area

Data was procured from Yamuna Biodiversity Park (YBP), which is located in the region of Delhi, extended from 28°25'N to 28°53'N and 76°50'E to 77°22'E. YBP is located at an elevation of 682 ft above sea level and spread over an area of 176.8 ha on the flat alluvial floodplain of the river Yamuna. The park features two major areas i.e., the Visitor Area and the Nature Reserve Area, and provides almost 30 different biotic communities.

Climatic conditions and soil physio-chemical characteristics

The climate of the area is semi-arid due to poor rainfall (66.6 cm annually). However, it once received significant rainfall in monsoon. Temperature ranges from 5 - 40°C, and the annual mean temperature is 25°C. The soil in this part of the city is mostly fertile and alluvial in nature. The physio- chemical properties of soil is as follows: Soil temperature = 17.8°C; Moisture content = 11.6%; pH = 7.13; Salinity = 0.10 ppt; Electrical Conductivity = 164 μScm^{-1} ; Organic matter = 2.81%; $\text{NO}_3 - \text{N}$ = 11.5 mg per100 gm; $\text{PO}_4 - \text{P}$ = 19.0 mg per100 gm Vegetation is

mostly thorny scrub (tropical forest) which is peculiar to arid and semi-arid region (Champion and Seth, 1968).

Experimental design and tree measurement

The data was collected from Yamuna Biodiversity Park between 2013 - 2024. The saplings of three fast growing species viz. *A. nilotica*, *A. auriculiformis* and *E. citriodora* were raised and monitored for 11 consecutive years and each year stem diameter, tree height and crown diameter was measured (Table 1). The experiment was laid down in Randomized Complete Block Design (RCBD) with three replicates each. The tree spacing was kept at 5.5 X 5.5 m. Initially, Circumference at Breast Height (CBH in cm) was measured at 1.37 m from the ground using a measuring tape. All CBH values were later converted to corresponding DBH values by dividing CBH by π (3.14). Tree height was measured using marked poles (for trees up to 5 m) and a clinometer for trees > 5 m tall. Crown diameter (CD) was measured in two directions (North – South and East - West) and an average was calculated (Chaturvedi and Khanna, 1982). The growing space of a tree was calculated by using the formula: Growing space = πr^2 , where r is the crown radius (in m) obtained from crown diameter. For generating both survival and cumulative hazard curves, Kaplan- Meier function was applied (Figures 1 and 2). Moreover, Cox- Proportional Hazard Model (CPHM) or Cox Regression model was also built to demonstrate whether *E. citriodora* had a high risk of mortality in contrast to other two species (Table 3). Other covariates included tree height and crown diameter.

Correlating growing space with stem diameter and tree height

Eventually, tree dbh and height were linked to tree growing space requirement by applying a 3- parametric Richard's function. The expression of the cumulative growth function was as follows:

$$Y = a(1 - e(-bX))^c$$

Where "Y" is the response variable (stem diameter and tree height), "X" is the predictor variable i.e. "Growing Space", a, b, and c are model parameters, and e is the exponential. Mean – bias or systematic error (Ochal et al., 2017) criteria was used for model evaluation. A model with the least mean - bias values was considered to perform the best (Table 4). Statistical significance (cross validation) of model parameters was determined through Jack- Knife resampling technique (Harris 1998). The values of the model parameters obtained after data fitting were further used to calculate stem diameter and tree height by keeping the growing space requirement constant for all three species (Table 5). Later, height- to-diameter ratio (h/d) were also calculated from freshly obtained H-D values and eventually compared. Moreover, relative diameter (ΔD) and relative height (ΔH) increment was also obtained for each species and simultaneously compared.

Survival analysis was all implemented in R -version 4.4.1 (R Development Core Team, 2024). Packages used were "Survival" (for generating Kaplan- Meier survival tables), "ggplot2" (for data visualization) and "minpack. lm" (for nonlinear curve fitting). "Survfit" code was used to build survival models and "coxph" code was used to develop

Cox Proportional Hazard Model. Richard's function was used to construct nonlinear models by applying "nlsLM" code.

Table 1. Stem diameter, tree height and crown diameter monitored for 11 consecutive years * AA = *Acacia auriculiformis*; AN = *Acacia nilotica*; EC = *Eucalyptus citriodora*; ($\pm$ SE)

Year	Tree variables	AA	AN	EC
1 st year of growth	Stem Diameter (cm)	0.35 $\pm$ 0.63	0.45 $\pm$ 0.89	0.38 $\pm$ 0.95
	Tree Height (m)	0.82 $\pm$ 0.54	0.78 $\pm$ 0.51	0.97 $\pm$ 0.69
	Crown Diameter (m)	0.19 $\pm$ 0.17	0.33 $\pm$ 0.36	0.15 $\pm$ 0.66
11 th year of growth	Stem Diameter (cm)	9.55 $\pm$ 0.49	9.41 $\pm$ 0.75	11.16 $\pm$ 0.97
	Tree Height (m)	7.1 $\pm$ 0.17	5.74 $\pm$ 0.43	9.15 $\pm$ 0.84
	Crown Diameter (m)	3.94 $\pm$ 0.25	4.98 $\pm$ 0.81	4.55 $\pm$ 0.81

Results and Discussion

Survival and mortality trends in three fast-growing species viz. *A. auriculiformis*, *A. nilotica* and *E. citriodora* was investigated applying a Kaplan-Meier survival function. Results highlighted that *E. citriodora* had lowest survival during most of its height development as compared to other two species (Table 2 and Figure 1a). Moreover, the cumulative hazard curve (Figure 1b) also demonstrated the trend: EC (1.58) > AA (1.44) > AN (1.01) i.e., EC had the highest cumulative hazard and AN

had the lowest. In addition, Cox Proportional Hazard model (Table 3) suggested that risk of mortality in EC was 6.3 times higher than AA and 12.6 times higher than AN, respectively. Moreover, the fast growth rate of tree height indicated a high risk of hazard in EC in contrast to AA and AN (Table 3). However, crown diameter responded positively to tree survival, i.e., as the crown diameter increased with age and growing space, the risk of mortality (hazard/failure rate) in EC dropped by 33% and 39% in contrast to AA and AN, respectively.

Table 2. Survival probabilities for the three species* EC = *Eucalyptus citriodora*, AA = *Acacia auriculiformis*, AN = *Acacia nilotica*

Groups= 1 EC				
Age (years)	n. risk	n. event	survival	SE
2	9	1	0.89	0.105
3	8	1	0.78	0.139
6	5	1	0.62	0.178
8	3	1	0.42	0.207
9	2	1	0.21	0.179
Groups= 2 AA				
Age (years)	n. risk	n. event	survival	SE
4	7	1	0.86	0.132
5	6	1	0.71	0.171
8	3	1	0.48	0.225
9	2	1	0.24	0.203
Groups= 3 AN				
Age (years)	n. risk	n. event	survival	SE
3	8	1	0.88	0.117
5	6	1	0.73	0.165
7	4	1	0.55	0.201
8	3	1	0.37	0.200

In addition, growing space requirement of trees was also correlated to stem diameter and tree height by using the model parameters obtained from Richard's function (Table 4). Both stem diameter and tree height correlated positively with the tree's growing space (Figure 2a and 2b). When a tree occupied an area of 10 m², the corresponding stem diameter for AA, AN and EC was 8.80, 7.79 and 9.58 cm, respectively (Table 5). When the tree crown eventually reached 20 m² of growing space, the complementary stem diameter for AA was 9.91 cm, AN was 9.49 cm and EC was 12.35 cm, i.e., when a growing space requirement of a tree increased from 10

m² to 20 m², then there was an 8.1% increase in stem diameter for AA, 13.6% for AN and 17.5% for EC respectively. Comparing between species, at 20 m², EC had a stem diameter increase of 14.1% against AA and 16.7% increase in contrast to AN (Fig 2a). Similarly, at 10 m² growing space, EC had the highest height (8.34 m) followed by AA (6.30 m) and AN (5.02 m). At 20 m², tree reached a height of 10.04 m for EC followed by AA (8.59 m) and AN (5.81 m). Between species, EC height increased by 10.1% in contrast to AA and 32.7% more in comparison to AN respectively when the growing space requirement reached 20 m².

Table 3. Cox Proportional Hazard model along with covariates (predictor variables)

EC Vs AA	coefficients	exp(coef)	se(coef)	z	Pr(> z)
Groups	1.843	6.317	1961	0.940	0.347

TH (m)	0.782	2.186	0.962	0.813	0.416
Crown Diameter (m)	-0.405	0.667	1.836	-0.221	0.825
EC Vs AN	coefficients	exp(coef)	se(coef)	z	Pr(> z)
Groups	2.531	12.561	2.194	1.153	0.249
TH (m)	0.576	2.129	0.728	1.038	0.299
Crown Diameter (m)	-0.501	0.606	1.306	-0.383	0.701

Table 4. Fitting and evaluation statistics applying a 3- 3-parametric Richards' model * GS = Growing space requirement ($\text{m}^2\text{tree}^{-1}$); SD = Stem diameter (cm); TH = total height (m)

Tree Variables (X, Y)	Model Parameters	AA	AN	EC
GS (m^2) Vs SD (cm)	a	10.001 $\pm$ 0.055	9.901 $\pm$ 0.124	13.470 $\pm$ 0.143
	b	0.258 $\pm$ 0.078	0.164 $\pm$ 0.086	0.124 $\pm$ 0.117
	c	1.619 $\pm$ 0.043	1.109 $\pm$ 0.032	0.998 $\pm$ 0.054
	Mean Bias	0.268	0.048	0.394
GS (m^2) Vs TH (m)	a	49.125 $\pm$ 0.036	6.075 $\pm$ 0.231	12.324 $\pm$ 0.117
	b	0.001 $\pm$ 0.078	0.134 $\pm$ 0.046	0.043 $\pm$ 0.125
	c	0.451 $\pm$ 0.048	0.663 $\pm$ 0.077	0.370 $\pm$ 0.078
	Mean Bias	0.064	0.038	0.150

Height-to-diameter ratio (h/d) was found to be inversely correlated with the growing space requirement (Figure 3). Results indicated that all species had a high h/d ratio (> 1) when young, but the ratio decreased as the growing space requirement increased, beginning to stabilize around 8 – 10 $\text{m}^2\text{tree}^{-1}$. However, AA demonstrated a slightly different trend. The h/d ratio increased a bit once the tree had exceeded 10 m^2 limit of growing space (Fig 3), though the increase was negligible and the trees were relatively stable ($h/d < 1$) after an 11- year growth period. Of the species evaluated, AA (2.46) and EC (2.42) had by far the highest ratio when young in comparison to AN (1.34). The h/d ratio for AN was the lowest throughout its growth and development.

Relative diameter (ΔD) and relative height (ΔH), when plotted against growing space, demonstrated a negative relationship, i.e., as the growing space increased, ΔD and ΔH decreased exponentially. In the case of ΔD , the values dropped maximum for AA as well as EC and the minimum for AN. EC had by far the highest ΔD values during most of its diameter growth. Initially high ΔH values were observed in EC (1.07), followed by AA (0.82) and AN (0.80). Overall change in ΔH values followed the order AA > EC > AN. However, up till 5 m^2 growing space, EC was ahead of AA and AN. This article compares height growth- rate- related mortality risk among three fast- growing species. Fast growing species tend to have a low investment in wood structures, thus being more vulnerable to mechanical damage, leading to shorter life cycles (Wright et al., 2010). The survival probability for EC was found to be lowest during most of its height development despite the fact that it has reached maximum height (9.15 m) in the span of 11 years. This could be explained by the physiological

stress put on the tree to achieve rapid height gain, potentially compromising its overall health and resilience to environmental changes like pathogen attack and water stress. High risk of mortality in fast - growing species may be linked to a group of factors, including: competition for light, mechanical stress on tissues, resource allocation, hydraulic resistance, and carbon balance (McDowell et al. 2022).

In general, fast-growing species in dense forests are exposed to intensive competition for light and other resources and thus typically allocate a high proportion of carbon to height growth to reach the canopy top (Poorter et al. 2012). However, if wider initial spacing is available, such species still have the tendency to attain rapid height growth due to ample nutrient supply and minimal competition. Rapid production of new wood to achieve maximum height results in weak or less dense wood, making it more vulnerable for tall trees to get damage by strong winds and storms. Moreover, when a tree prioritizes rapid height growth, it allocates a larger proportion of its biomass to develop vertical stems, potentially neglecting root development or other essential functions for long term survival. In addition, water- stress can particularly intensifies the ill- effects of fast growth, as rapidly growing trees may have less water reserves to withstand dry periods. High growth rates may perhaps lead to an imbalance in the tree's carbon uptake and utilization, potentially causing stress and affecting its longevity (Brienen et al. 2020). The cumulative hazard curves also suggested high risk of mortality in EC as compared to AA and AN. Cox Regression too indicated that as the tree height increased, the relative risk of EC almost increased twice in contrast to AA and AN.

Table 5. Fresh values of stem diameter and tree height obtained from model parameter * AN = *Acacia nilotica*, AA = *Acacia auriculiformis*, EC = *Eucalyptus citriodora*

Growing Space (m^2)	Stem Diameter (cm)			Tree Height (m)		
	AA	AN	EC	AA	AN	EC
1	0.91	1.22	1.58	2.24	1.63	3.81
2	2.29	2.41	2.97	3.05	2.43	4.89

3	3.67	3.47	4.20	3.67	3.02	5.63
4	4.90	4.39	5.28	4.17	3.49	6.22
5	5.93	5.19	6.24	4.61	3.86	6.70
6	6.79	5.88	7.08	5.01	4.18	7.11
7	7.47	6.48	7.83	5.37	4.44	7.47
8	8.02	6.98	8.49	5.70	4.66	7.79
9	8.46	7.42	9.07	6.01	4.85	8.08
10	8.80	7.79	9.58	6.30	5.02	8.34
11	9.07	8.10	10.04	6.58	5.16	8.57
12	9.28	8.37	10.44	6.84	5.28	8.79
13	9.44	8.60	10.79	7.09	5.38	8.99
14	9.57	8.80	11.10	7.33	5.47	9.17
15	9.66	8.96	11.38	7.56	5.55	9.34
16	9.74	9.10	11.62	7.78	5.62	9.50
17	9.80	9.22	11.84	7.99	5.68	9.65
18	9.84	9.33	12.03	8.20	5.73	9.79
	9.88	9.41	12.20	8.40	5.77	9.92
20	9.91	9.49	12.35	8.59	5.81	10.04

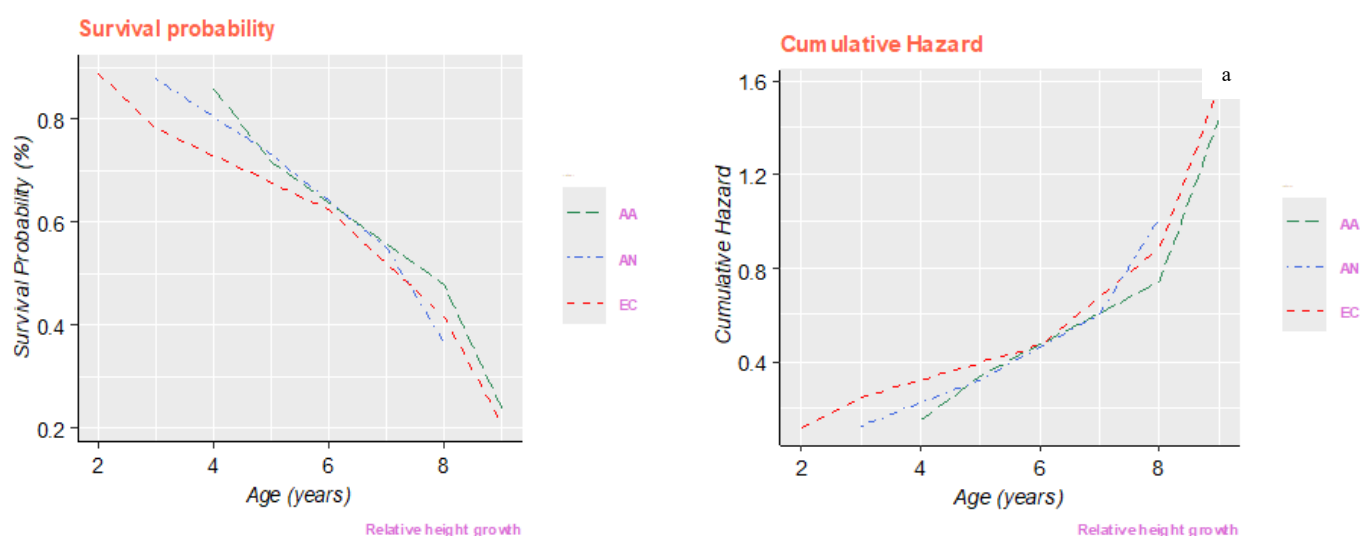


Figure 1 (a, b). Survival probabilities and cumulative hazard curves for three fast-growing species by applying a Kaplan-Meier function * AA = *Acacia auriculiformis*; AN = *Acacia nilotica*; EC = *Eucalyptus citriodora*

Tall trees like *E. citriodora* often face hydraulic resistance with accelerated growth rates. Taller trees had an advantage of effectively trapping the sunlight to perform photosynthesis (Fransson et al. 2020), which in turn also increases its crown diameter and photosynthetic efficiency as well during the early stages of growth. But as the tree becomes taller and the tree height exceeds a certain threshold limit, the hydraulic resistance and the friction within the xylem vessels also increase accordingly (Zaehle 2005; Venturas et al. 2017). Although, trees compensate for their increased size and fast growth by producing wider xylem elements with increased permeability (Prendin et al. 2018) to facilitate faster water transport, this was expected to be insufficient to prevent total resistance from increasing with height because as the height increases the large and wider xylem vessels becomes more vulnerable to cavitation, causing hydraulic failure under stress (Ryan &

Yoder 1997). With high growth rate, it becomes difficult for taller trees to maintain the transpiration pull within the xylem vessels as high water-stress (low water potential) in xylem causes cavitation (air bubble) in the vessel thus disrupting the "pull". This cavitation in turn forces stomata to close down early in the day to prevent xylem water potential from reaching a level that would lead to catastrophic failure of the transport system (Yoder et al., 1994; Brodribb & Hill 1999). Thus, stomatal closure reduces both loss of water (from the tree) and uptake of carbon-dioxide (from the environment) so that daily carbon assimilation by leaves falls and consequently, the mortality risk increases. If foliage on tall trees produces less photosynthate, then less wood growth will occur, because other carbon costs do not change much with tree height (Mencuccini & Grace 1996).

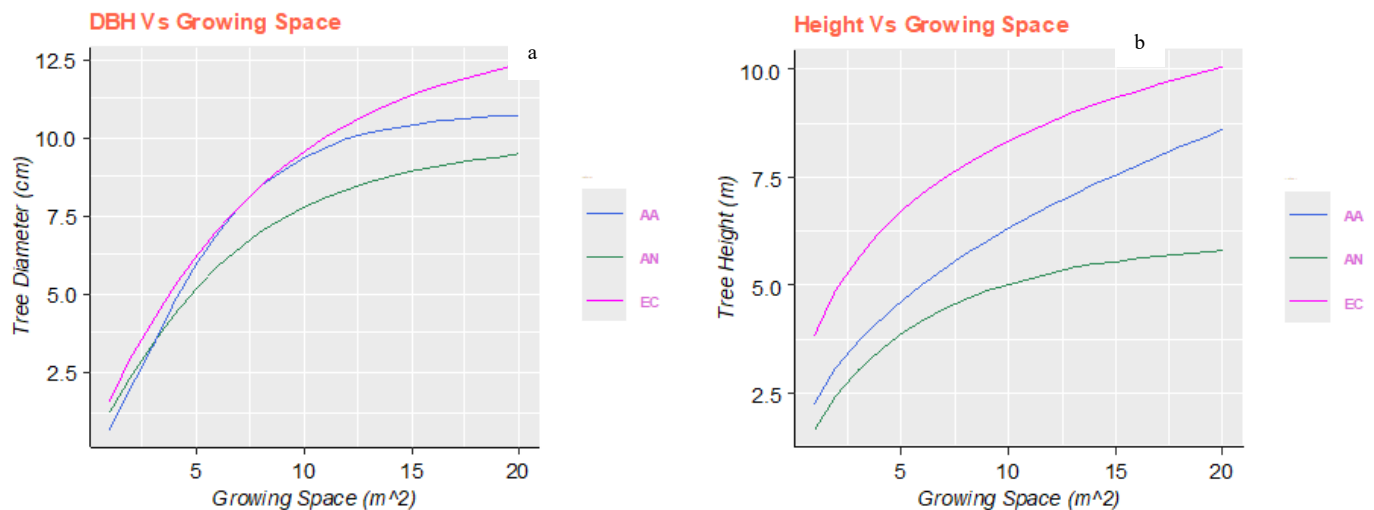


Figure 2 (a, b). Tree Diameter and Height Vs Growing space requirement for three species

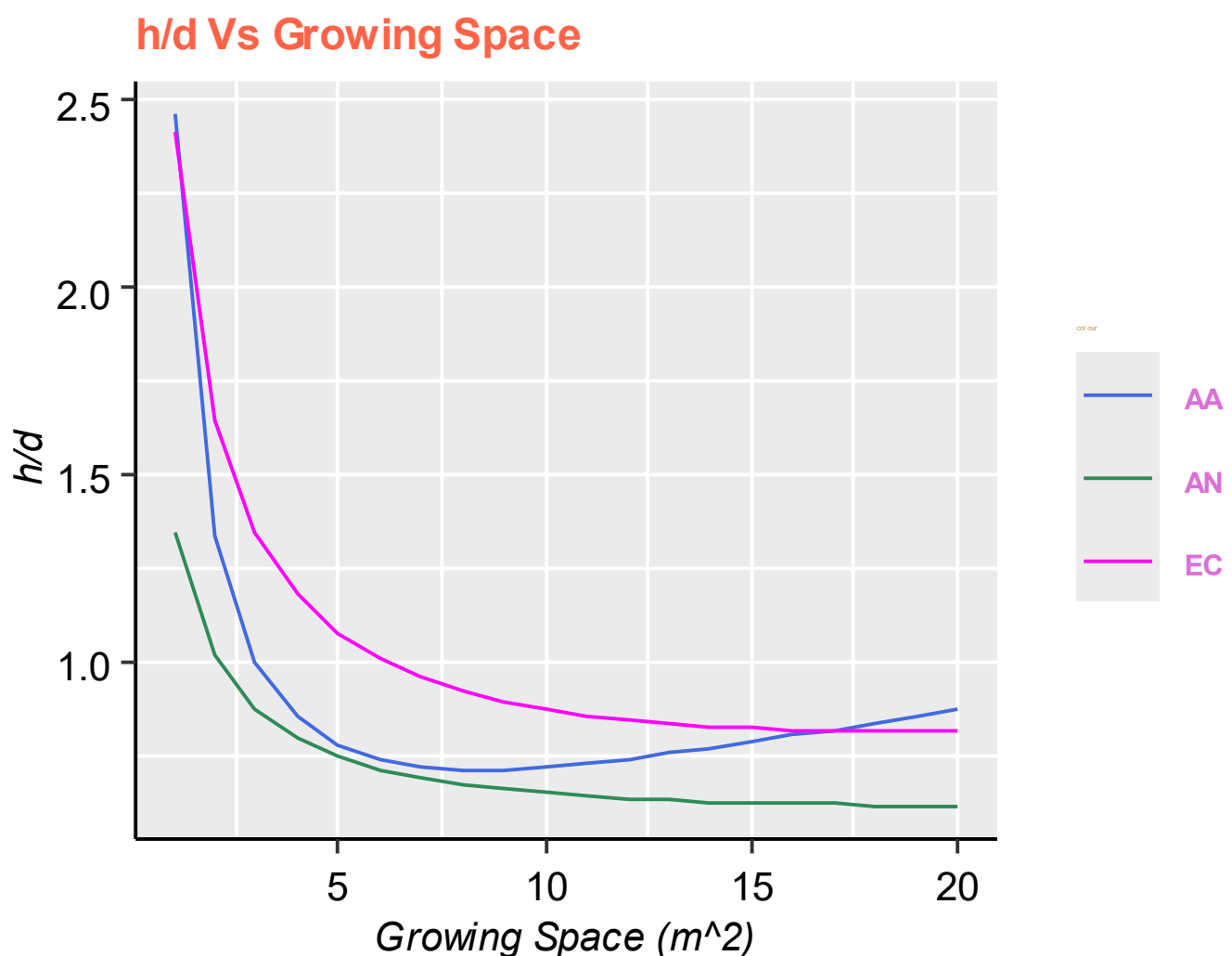


Figure 3. h/d Vs Growing space requirement for three species

In addition, as the crown diameter increased with growing space, the risk of mortality decreased by 33% and 39% for EC in contrast to AA and AN, respectively. Regardless of height, trees with sufficient initial spacing have nearly unrestricted access to solar energy and thus allocate a larger proportion of carbon to the lateral development of branches and radial stem growth (Thorpe et al. 2010). Thus, with the increase in crown diameter- crown projection area, crown volume and

packing of leaves within a crown in EC would also have increased accordingly, thus increasing the overall surface area of the crown for efficient light capture and enhanced photosynthesis. However, at later stages of growth tall trees of EC would have created hydraulic resistance, which probably would have escalated relative risk of mortality in EC in contrast to other two species. The height-to-diameter ratio (h/d) is yet another important parameter which is quite closely associated

with trees and stand stability (Opio et al., 2000). Trees with higher ratios (>1) are more prone to get damaged by high wind speed and storms than trees with lower ratios (Albrecht et al., 2010; Schmidt et al., 2010; Urata et al., 2010). Trees with high h/d values are always associated with increased risk of susceptibility to natural disasters (Castedo-Dorado et al. 2009; Wallentin & Nilsson 2014) and may be more vulnerable because their stems may not be adapted to conditions of higher mechanical strain (Moore 2000; Bosel'a et al. 2014). For all three species, the initial h/d values were high. The h/d ratio for AA and AN stabilized ($h/d < 1$) when the tree occupied a growing space of 3-4 m^2 . However, for EC, the h/d ratio dropped to < 1 , only when the tree had reached a growing space of 7 m^2 , in other words, EC trees had gained marginal stability ($h/d = 0.95$) after the growing space requirement reached 7 m^2 . In Indian subcontinent, the height-to-diameter ratio of fast-growing species is roughly 10:1 or 15:1, i.e., for every

unit increase in tree diameter, there is approximately 10 - 15 unit increase in tree height, depending upon the climatic conditions and water- nutrient availability.

The h/d ratio in young trees was usually high, which stabilized at later stages of growth (Figure 3). Large values of h/d ratios in juveniles may have two possible indications: (1) either trees are growing in a crowded stand with nutrient support from neighbouring trees or (2) trees are raised at wide spacing (open stand) where no significant competition existed (Wonn & O'Hara; 2001; Vospernik et al.; 2010). In our case, ample space was kept between saplings at the initial stages of growth. Moreover, the h/d ratio decreased at later stages of growth for all three species investigated. Perhaps, additional growing space provided through wider initial spacing (5.5 X 5.5 m) allowed the species to maintain rapid diameter growth, thus decreasing h/d ratio and increasing tree stability.

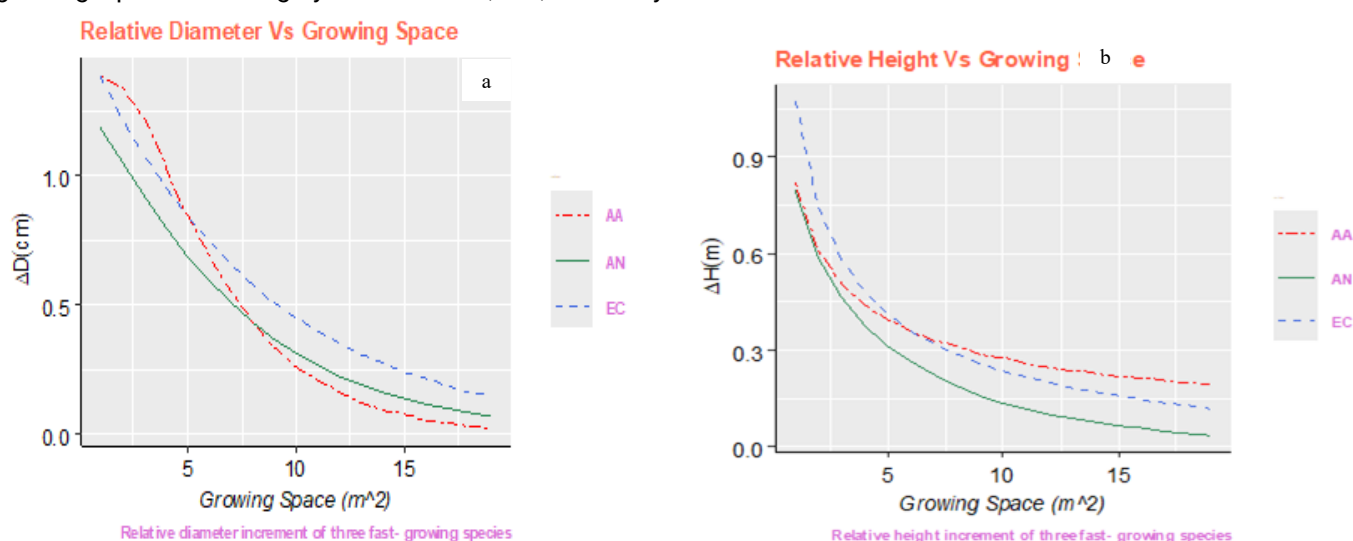


Fig 4 (a, b). Relative diameter (ΔD) and relative height (ΔH) increment Vs Growing space requirement for three species

A slightly different trend of h/d growth pattern was found in AA. The ratio started with a high value which subsequently decreased over time and as growing space of a tree. The h/d value decreased continuously when the tree reached 8-10 m^2 of growing space and later increased a little bit, though the value never exceeded > 1 at 20 m^2 . This probably happened due to changes in growth pattern where the tree initially prioritizes height growth to reach the canopy, then later shifts focus to increase diameter for stability as it matures. This shift resulted in a decrease in h/d ratio before it starts increasing again. There are variety of factors which can affect h/d ratio over time and growing space, which includes: competition, water stress, nutrient availability and exposure to sunlight which influences growth patterns of trees and stands and thus h/d ratios. Comparative analysis of h/d ratios for the three species suggested that AN was the most stable species ($h/d = 0.61$) at 20 m^2 growing space while for other two species the h/d ratio was close to 1. The highlight of this piece of work is taking relative tree height increment as a basis to create binary codes for survival analysis. As high growth rate in fast growing

trees coupled with climate change related drought has put considerable pressure on their survival so early detection of tree mortality can be helpful in sustainable management of tropical forests where fast growing species often dominates the flora.

Conclusion

Survival analysis was conducted on three fast-growing species of Delhi urban forest viz. *Eucalyptus citriodora*, *Acacia auriculiformis* and *Acacia nilotica* using a Kaplan-Meier function. Results demonstrated that the survival probability of *E. citriodora* was low during most of its height development. As the tree height increased with age and growing space, the mortality risk for EC also increased as compared to the other two species. With increasing crown diameter, the risk of mortality (relative risk) in *E. citriodora* dropped by about 32% and 11% in contrast to *A. auriculiformis* and *A. nilotica*, respectively, during 11 years study period. Both stem diameter and tree height had a positive correlation with the growing space requirement. h/d ratio sharply decreased with tree age and growing space having high values (> 1) in the beginning which stabilized at later stages of tree growth. The author believes that in times of climate change and

drought like conditions where tropical forests are potentially going to be impacted in the near future, tree mortality studies should be conducted by taking into account the plant hydraulics aspect in order to have a better understanding of the water transport system provided by xylem vessels to minimize catastrophic failure of taller trees due to hydraulic resistance and water stress.

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