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CROWN DIAMETER – STEM DIAMETER RELATIONSHIP IN SOME LIGHT DEMANDING TROPICAL TREE SPECIES OF KUMAUN FOOTHILLS

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ABSTRACT: There is a well - known but apparently less documented relationship between crown diameter (K) and stem diameter (d) of trees in forest and urban forest ecosystems. The investigation described in the manuscript was conducted to establish K-d relationships for seven fast- growing and light demandingtropical tree species of Bhabhar belt in Kumaun foothills viz. *Azadirachta indica* A. Juss. (Neem), *Syzigium cumini* L. (Jamun), *Neolamarckia Kadamba* Roxb. (Kadamb), *Acacia catechu* (L.f.) Willd. (Khair) *Mangifera indica* L. (Mango), *Populus deltoids* W. Bartram ex Marshall (Poplar) and *Tectona grandis* L.f. (Teak). In this study, K-d relationship was found to be linear, with $R^2_{adj.}$ value higher than equal to 0.77 ($R^2_{adj.} \geqslant 0.77$). Results indicated that all species had high K/d ratios when young, but the ratio decreased as stem diameter increased, beginning to stabilize around 30- 35 cm diameter. Of the species evaluated, Neem had by far the highest ratio when young, but other strong light - demanding species, such as Kadamb, Poplar and Mango had relatively low ratios. Use of knowledge of K/d ratios and their possible applications have also been discussed, including implications for decisions on tree spacings and predicting growing space requirement for individual trees at any mean dbh, basal area and stand density estimation, planning thinning regimes and in arboriculture for planting and management of urban trees.

Keywords: *Crown diameter, stem diameter, K/d relationship, urban forest, thinning regimes, arboriculture*

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INTRODUCTION

Tree crowns have always been very fascinating but oftennot much included intree measurements than their stems, perhaps due to their less commercial value. However, as crown size being closely related to photosynthetic capacity of a tree, is an important parameter in studies of the growth of stands due to close correlation between crown size and stem diameter, and the "packing" or density of trees in a stand. Forest trees display a characteristic relationship between their crown diameters (*K*) and stem diameters (*d*) (Lockhart *et al.* 2005; Blanchard *et al*. 2016; Song *et al*., 2024). The *K/d* knowledge of different species has multipurpose utilities including: planning and managing tree spacing in a plantation, predicting basal areas, devising thinning regimes, inclusion of height data for developing stand volume estimates etc.

Workers in different part of the world have identified *K/d* relationships and used the information to predict desirable spacings for species such as cheery, sycamore and ash (Thill, 1980), and have also calculated maximum basal area for species such as Douglas fir (Briegleb, 1952). Moreover, *K/d* relationships are particularly useful for determining crown competition (Coombes *et al*. 2019; Asigbaase *et al.* 2023), stand density and stocking relationships (Foli *et al*. 2003; Hemery *et al.* 2005) and tree growth (Pretzsch, 2021). Moreover, the *K/d* correlation is also useful in estimating stem diameters and basal areas from crown diameters measured by utilizing remote sensing techniques and aerial photographs which further helps in determining tree and stand volumes (Panagiotidis *et al*., 2016; Suhardiman *et al*. 2016; Xu *et al*. 2024). Volume determination is especially important with recent advances in remote sensing techniques that allow for rapid crown diameter measurement, conversion to dbh and then determination of tree volume. Inventory costs are thus greatly reduced compared to conventional tree dbh measurement in the forest.

This article thus demonstrates establishing allometric correlations between crown- diameter *(K)* and stem- diameter (*d)* and application of *K/d* ratios in monitoring tree/stand stability of seven fast- growing agroforestry species of Kumaun foothills. Moreover, possible applications of *K/d* ratios in predicting and planning thinning regimes, spacing between individuals at the time of planting, predicting tree growing space at any mean DBH and calculating basal areas and stand densities have also been discussed. All species are moderate to fast growing and light demanding tropical tree species and are popularly used for fuel, fodder, fruits, timber and medicines within the village community as well as for commercial purposes. Linear Regression models were built for all 7 species and the model parameters obtained were further used to calculate crown diameter values by keeping stem diameter as constant (i.e., 0.1, 0.15….0.6 m) for all species. Different workers may adopt the same approach for different species, in different habitats, soils and environmental conditions for appropriate results.

MATERIAL AND METHODS

STUDY SITE AND COORDINATES

The Bhabhar region in Kumaun Himalaya is spread over a geographical area of 51125 square kilometer (77°34' to 81°02' E longitude and 28°43' to 31°27' N latitude). The present investigation was restricted to Nainital district as Bhabhar belt is only represented by this district. The Bhabhar belt constitutes the Himalayan foothills, where the streams descend on to the plains. The sub-Himalaya geographically corresponds to the Siwalik range- foothills ranging in elevation from 250- 800 m. This zone is comprised of 10 km thick succession of sandstone and mudstone shed from the Himalayan mountains, and deposited by rivers, especially since the Miocene i.e., over the past 24 million years (Sorkhabi, 2010).The crown-diameter and stem- diameter data of individual trees belonging to seven different species was collected from two villages *viz*. Padampur and Fathepur, which were located in the Bhabhar belt, at the foothills of Kumaun Himalay in district Nainital. Distance between Padampur and Fathepur village was approximately 11 Km.

CLIMATIC CONDITIONS AND SOIL CHARACTERISTICS

Climate was monsoonal- sub tropical and characterized by marked seasonality. The year can be divided into 3 seasons *viz*. (a) summers (April-June), hot and dry weather where temperature reaching beyond 42°C, (b) rainy season (July- September), high humidity, may reach up to 95%, (c) winter season (November-February), where minimum temperature stoops down to 4°C with dense fog and humidity level drops to about 57%. February (winter- summer) and October (summer- winter) are two transitional months. Annual average quantum input (irradiance) was 27.81 $molm^{-2}day^{-1}$.The soil texture in Bhabhar belt was mostly loamy (sand 37- 60%, silt 29- 34% and clay 11-29%). General description of the tree species is provided in Table 1. Details of physio- chemical characteristic of soils of two villages has been presented in Table 2.

TREE VARIABLE MEASUREMENT AND BUILDING OF LINEAR REGRESSION MODELS

Crown- diameter and stem- diameter of individual trees were measured across species to build Linear regression models (Table 3). Initially, circumference at breast height (CBH in cm) for all trees were measured at 1.37 m from ground using a measuring tape. All cbh values were later converted to corresponding dbh values by dividing cbh by Π (3.14). Individuals with ⩾ 5 cm DBH were considered as trees and measured (MacDicken, 1997). Crown- diameter was measured in two directions (N-S and E-W) and an average was taken (Chaturvedi and Khanna, 1982). Growing space requirement of a tree was calculated by applying the equation G_S ($m^2 tree^{-1}$) = Πr^2, where Π = 3.14 and "*r*" is the crown - radius in meter.

Table 1. General description of the 7 species investigated

Botanical Name	Common Name	Hindi Name	Family	Habit/ Habitat	Uses
Azadirachta indica A. Juss.	Margosa	Neem	Meliaceae	T/W-C	Com, Medi, Fu,Ti
Syzigium cumini L	Jambul	Jamun	Myrtaceae	T/W-C	Ed,Fu,Ti
Neolamarckia Kadamba Roxb.	Burflower Tree	Kadamba	Rubiaceae	T/W-C	Ti,Medi,Fu,Fo
Acacia catechu (L.f.) Willd.	Cutch Tree	Khair	Fabaceae	T/W	Com, Fo, Fu, Ti, Medi
Mangifera indica L.	Mango	Aam	Anacardiaceae	T/C	Com, Ed, Fo, Ti, Fu, Medi
Populus deltoids W. Bartram ex Marshall	Popular	Popular	Salicaceae	T/C	Com,Fu
Tectona grandis L.f.	Teak	Sagon	Verbenaceae	T/W	Fu,Ti

*T= Tree; W-C = Wild and Cultivated; W= Wild; C= Cultivated; Com= Commercial; Medi = Medicinal; Fu= Fuelwood; Ti= Timber; Fo= Fodder; Ed = Edible

Crown – diameter was considered as a function of stem- diameter [*CD =f(SD)]* i.e., crown – diameter was taken as response variable and stem-diameter as predictor variable. Trees in this study were selected at random, with the constraint of sampling of a wide range of stem diameters, though there were often difficulties finding sufficient number of large trees. Those with severely deformed or asymmetric crowns were rejected, though such rejections were very rare.

Table 2. Physio-chemical characteristic of soils from two villages in Bhabhar belt from where data was collected

Physio-chemical characteristics	Padampur	Fathepur
Sand (%)	60.15±0.51	51.65±1.57
Silt (%)	28.72±0.55	30.33±0.73
Clay (%)	11.19±0.66	17.65±0.95
Bulk Density (g/cm^3)	1.54±0.03	1.31±0.05
Porosity (%)	42.39±0.78	50.33±0.51
Moisture (%)	5.51±0.09	7.81±0.05
WHC (%)	32.55±0.78	38.59±0.42
Temperature (°C)	22.25±0.04	21.46±0.04
pH	7.2±0.03	7.2±0.06
C (%)	0.67±0.02	0.81±0.04
N (%)	0.18±0.03	0.23±0.05
P (%)	0.013±0.07	0.012±0.02
SOM	1.18±0.02	1.42±0.06

Statistical analysis was all implemented in R - version 4.4.1 (R Development Core Team, 2024). Linear models were built with "*lm ()*" function. Data visualization was performed using *ggplot* (library/package: "*tidyverse*").

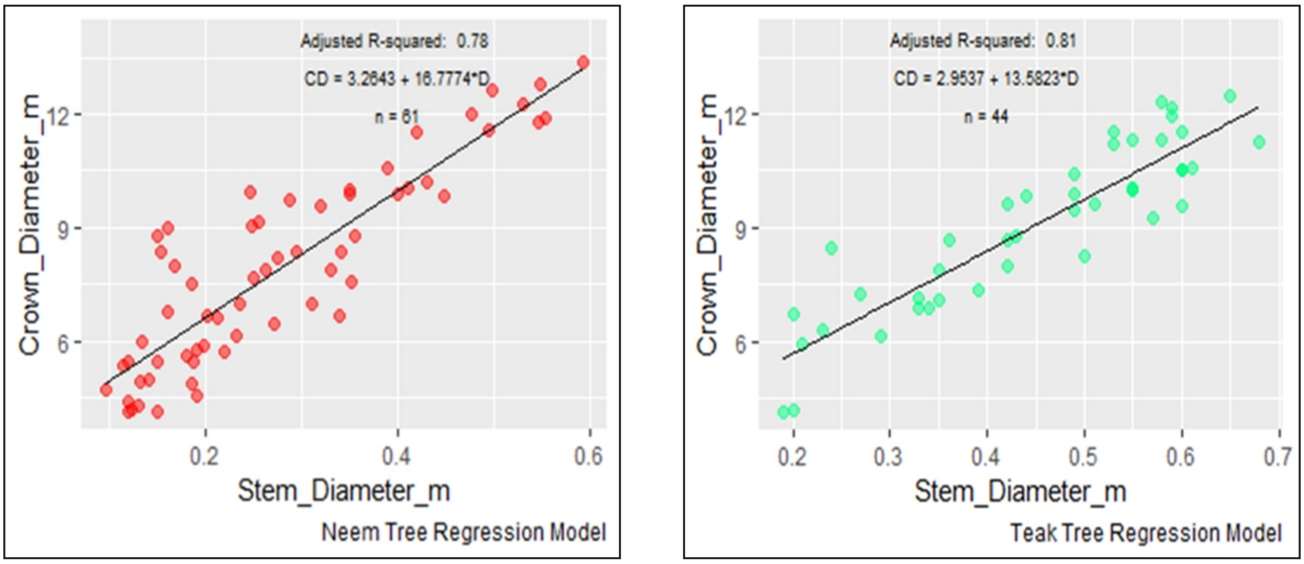

Fig. 1. Crown diameter- stem diameter (*K-d*) relationship for *Neem* and *Teak*

RESULTS

Linear regression models for predicting crown-diameters (*K*) from stem – diameters (*d*) have been depicted in Table 3, along with two examples of such regressions (Figure 1). Generally, the trends in *K/d* ratios for different tree species are not often presented. To demonstrate this trend between species, the regression models from Table 3 was applied to calculate *K/d* values in Table 4. When *K/d* ratios were plotted against increasing stem diameter (Figure 2 and 3), the variation between different species was evident, specifically at small stem diameters (dbh < 0.15- 0.20 m). *Neem* was included in Figure 3 as a basis for comparison. *Jamun*, *Khair* and *Teak* followed a similar pattern to *Neem* in that they had high initial values for *K/d* (and for *a*), but the ratio decreased as stem diameter increased, dropping by about 60% from 0.1 to 0.5 m dbh. *Neem K/d* ratio dropped by less than other species (52.83%), over the same range of DBH (Figure 2 and 3).

Table 3. Regression models for predicting crown- diameter (*K*) from stem- diameter (*d*) for seven light demanding tropical tree species of Kumaun foothills

Species	Number of observations	Predicting K from d		
		Intercept (a)	Slope (b)	$R^2_{adj.}$
Neem: *Azadirachta indica*	61	3.264	16.777	0.78
Jamun: *Syzigium cumini*	34	3.591	11.968	0.78
Kadamb: *Neolamarckia kadamba*	31	1.915	17.435	0.88
Khair: *Acacia catechu*	37	3.233	11.564	0.77
Mango: *Mangifera indica*	64	2.223	15.116	0.79
Poplar: *Populus deltoids*	33	1.904	17.721	0.87
Teak: *Tectona grandis*	44	2.954	13.582	0.81

Table 4. *K/d* ratios for seven tree species

D_m	Neem	Jamun	Kadamb	Khair	Mango	Poplar	Teak
0.1	49.42	47.88	36.58	43.89	37.34	36.76	43.12
0.15	38.54	35.91	30.20	33.12	29.93	30.42	33.27
0.2	33.10	29.92	27.01	27.73	26.23	27.24	28.35
0.25	29.83	26.33	25.09	24.50	24.01	25.34	25.40
0.3	27.66	23.94	23.82	22.34	22.53	24.07	23.43
0.35	26.10	22.23	22.91	20.80	21.47	23.16	22.02
0.4	24.94	20.95	22.22	19.65	20.67	22.48	20.97
0.45	24.03	19.95	21.69	18.75	20.06	21.95	20.15
0.5	23.31	19.15	21.26	18.03	19.56	21.53	19.49
0.55	22.71	18.50	20.92	17.44	19.16	21.18	18.95
0.6	22.22	17.95	20.63	16.95	18.82	20.89	18.51

It was only when most species reached stem diameters of 30 – 40 cm, that the ratios began to get stabilized, with declining becomes less rapid (Table 4). Most trees maintained a reasonably consistent *K/d* ratio, the ratio gets stabilized with increasing age and diameter but never increased. Thus, for instance, if *K/d* ratio was 25, a healthy tree of mean diameter "*d*", on an average, would have a crown- diameter of 25 x *d* across plantations, and of course the same mean spacing between trees if the crown was not to become constricted**.** *K/d* ratio is a significant indicator of tree and stand stability. A low ratio suggested more stability and vice versa.

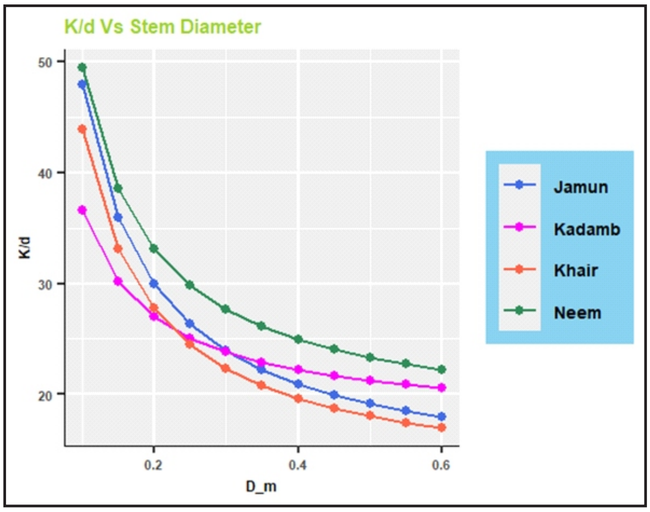

Fig. 2. ***K/d*** **ratios at different dbh for** ***Neem, Jamun, Kadamb*** **and** ***Khair***

At 50 cm mean diameter, *Neem* tree had the highest growing space requirement of 106.59 $m^2 tree^{-1}$ in contrast to *Khair* tree which had the lowest requirement of 63.80 m^2 $tree^{-1}$ (Figure 4a). The relationship between mean tree diameter and growing space requirement of a tree at 50 cm DBH across all species followed the trend: *Neem (106.59)* > *Poplar (90.96)* > *Kadamb (88.74)* > *Mango (75.10)* > *Teak (74.55)* > *Jamun (71.97)* > *Khair (63.80)* (Fig. 4a and b).

It was further assumed that *K/d* ratios for young *Neem*, *Kadamb*, *Mango* and *Poplar* trees would be more or less identical as all are light demanders and requires wide spacings to grow, but as Figure 2 and 3 demonstrated, this was not found to be true. The *K/d* ratios for *Neem* was substantially high (49.2) in contrast to *Kadamb* (36.58), *Mango* (37.42) and *Poplar* (36.76). In fact, the *K/d* ratios for *Kadamb*, *Mango* and *Poplar* displayed much similar patterns.

DISCUSSION

K/D RATIOS AND ITS APPLICATIONS

DECISIONS ON TREE SPACING AND PREDICTING GROWING SPACE AT ANY MEAN DIAMETER

It was possible to calculate from Table 3, the space occupied by the crown of each tree at any mean DBH, and assuming that no overlapping occurs, it was also feasible to obtain number of trees per hectare *i.e.*, stand density. An example is demonstrated in Table 5, for trees of 50 cm DBH. Table 5 suggested that more light demanding species *viz*. *Neem, Poplar* and *Kadamb* require comparatively more space to grow than others. However, young *Kadamb* and *Poplar* trees had relatively low *K/d* ratios (at 0.1 m DBH) than *Neem i.e.* less growing space requirement at initial stages of growth. Consequently, there are fewer than 113 trees ha^{-1} at 50 cm DBH (Table 5). *Khair, Jamun, Mango and Teak* required less light and growing space in contrast to *Neem, Poplar and Kadamb*, with number of trees per hectare exceeding 132, at 50 cm DBH (Fig 4).

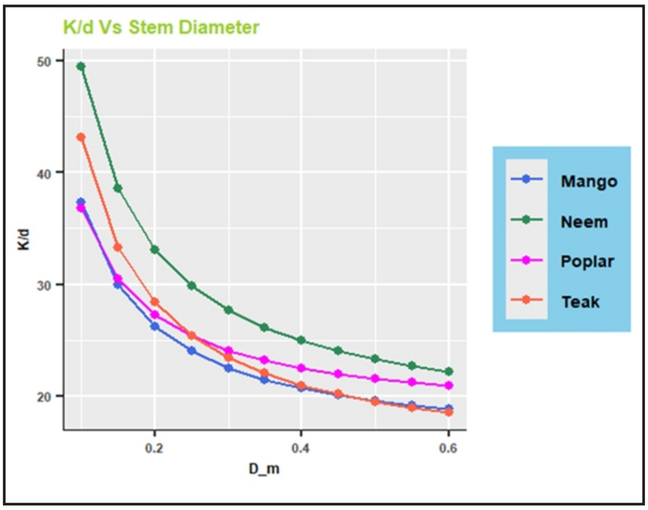

Fig. 3. ***K/d*** **ratios at different DBH for** ***Neem, Mango, Poplar*** **and** ***Teak***. ***Neem*** **is repeated from figure 2 for comparative purposes**

BASAL AREAS AND STAND DENSITY MEASUREMENT

From $K - d$ regression models, basal area per hectare (BA, m^2ha^{-1}) can be calculated (Dawkins, 1963):

$$BA, m^2ha^{-1} = 10^4 \times \frac{0.7854}{z^2}$$

Where, 10^4 is the area of 1 hectare in m^2, 0.7854 is the canopy density for circular touching crown at square planting and z is the K/d ratio.

The maximum number of trees per hectare (N) or stand density can be calculated as:

$$N = \frac{10^4}{K^2}$$

Where, 10^4 is the area of 1 hectare in m^2, 0.7854 is the canopy density for circular touching crown at square planting and z is the K/d ratio.

The maximum number of trees per hectare (N) or stand density can be calculated as:

Where, K is the crown diameter (in meter).

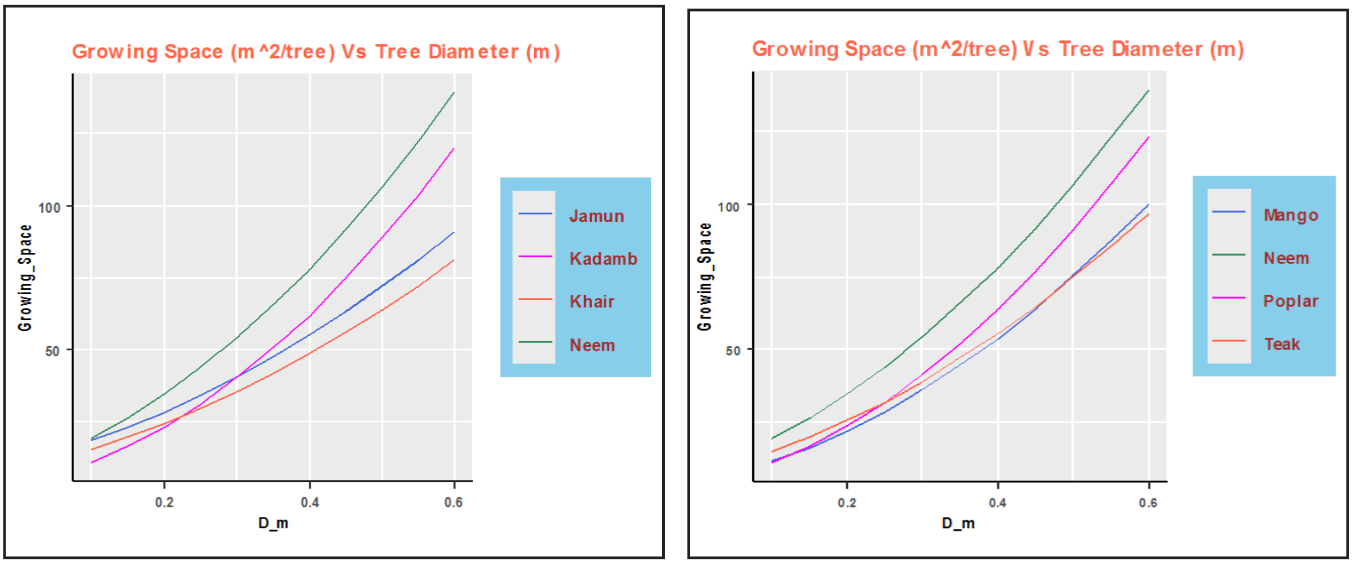

Fig. 4. (a, b) Growing space requirement at different mean diameter for seven light-demanding species, *Neem* is repeated for comparative purpose

For *Neem*, at 15 cm DBH, the basal area accumulation was 5.3 m^2ha^{-1} with a maximum of 299 trees ha^{-1}. At 50 cm DBH, the basal area accumulation increased from 5.3 to 14.5 m^2ha^{-1}, with a maximum of 74 trees ha^{-1} (Table 6). Similarly, when comparing between species, *Neem* at 50 cm diameter had the lowest basal area (14.5 m^2ha^{-1}) with a maximum of 74 trees ha^{-1} while *Khair* had the highest (24.2 m^2ha^{-1}) and a maximum of 123 trees ha^{-1}. The increasing trend in basal areas for all seven species at 50 cm DBH was: *Neem* (14.5) >*Poplar* (16.9) >*Kadamb* (17.3) >*Mango* (20.5) >*Teak* (20.7) >*Jamun* (21.4) >*Khair* (24.2). Thus, basal areas and stand densities can be obtained for other species as well and simultaneously compared (Table 7).

Table 5. **Growing space ($m^2 tree^{-1}$) and number of trees per hectare in fully occupied stands with no crown overlap when mean diameters are 50 cm, based on regressions in Table 3**

Species	*CD (m) at 50 cm D*	*Growing Space ($m^2 tree^{-1}$) at 50 cm D*	*No. of treesha⁻ at 50 cm D*
A. indica	11.65	106.54	94
P. deltoids	10.76	90.89	110
N. kadamba	10.63	88.70	113
M indica	9.78	75.08	133
T. grandis	9.74	74.47	134
S. cumini	9.58	72.04	139
A. catechu	9.01	63.73	157

Basal area (sum of cross-section area of trees at diameter at breast height) is a useful measure of stand density. A higher basal area indicates a larger total area occupied by tree trunks, indicating a dense stand and vice versa. The maximum stand basal area and maximum stand density index are often used to express stand carrying capacity of a forest stand.

Out of seven species investigated, *Mango* and *Teak* followed a more or less similar pattern of basal area accumulation at 50 cm DBH with a stand density of approximately 105 trees ha^{-1}*.* *Jamun* tree demonstrated the second highest value for basal area accumulation (after *Khair*) at 50 cm DBH. Basal area growth for *Jamun* tree reached 21.4 $m^2 ha^{-1}$ having a stand density of 109 individuals per hectare (Table 7). At 15 cm DBH, *Neem* tree had the lowest basal area (5.29 m^2 ha^{-1}) and highest growing space requirement (26.23 $m^2 tree^{-1}$) which suggested that the specie would mature into a large tree with a wider crown, requiring ample space for its canopy and root system to develop fully. Trees with high growing space requirement are more likely to be negatively impacted by competition from other species, particularly if stand density is high, which can eventually restrict its growth and development (Aleinikovas *et al.* 2014; Kholdaenko *et al.* 2022). Understanding the basal area and growing space requirement is significant in forest management as it helps determine appropriate stocking densities and thinning strategies to promote healthy growth and development of the desired tree species. Thus, a significant correlation between basal area accumulation, growing space requirement and stand density was observed in all species investigated.

Table 6. Stand density and basal area for *Neem* (*Azadirachta indica*) stands based on 100% canopy closure and square planting

D (m)	CD (m)	z ratio (K/d)	N (max. trees ha^{-1})	BA ($m^2 ha^{-1}$)
0.1	4.94	49.42	409	3.2
0.15	5.78	38.54	299	5.3
0.2	6.62	33.10	228	7.2
0.25	7.46	29.83	180	8.8
0.3	8.30	27.66	145	10.3
0.35	9.14	26.10	120	11.5
0.4	9.98	24.94	100	12.6
0.45	10.81	24.03	86	13.6
0.5	11.65	23.31	74	14.5
0.55	12.49	22.71	64	15.2
0.6	13.33	22.22	56	15.9

THINNING REGIMES

Thinning regimes can be planned by applying the *K-d* regression equations, that ensured the relationship between basal area growth and the number of stems per hectare remained within the realistic limits (Philip, 2004). Such regimes should be based on mean stem diameter to be achieved, rather than the typical age- dependent tables (Savill, 1991). For instance, the expected crown-diameter (m) of *Poplar* for any mean stem diameter can be calculated as follows:

$$CD = 1.904 + (17.721 \times dbh)$$

Here, both crown diameter and stem diameter are in meters. Therefore, if suppose DBH is 30 cm (0.30 m), the crown-diameter would average 7.2 m, and the crown would occupy an area of 40.7 m^2, indicating that if competition between crowns is to be avoided at the time the stem reaches 30 cm DBH, there should be no more than 10,000/40.7 = 245.7 stems ha^{-1}. Similarly, if the trees are then thinned to a final crop spacing, and clear-felled when average DBH is 60 cm, the average crown- diameter would be:

$$CD = 1.904 + (17.721 \times 0.60) = 12.5\ m$$

The area occupied by a crown of 12.5 m diameter would be 122.7 or 123 m^2, and therefore the number of trees remaining after thinning would be 10,000/122.7 = 81.5 stems ha^{-1}, at an average spacing of 11.09 × 11.09 m.

Table 7. ***Crown Diameter, z- ratio, Stand density and basal area*** **of seven light demanding species at 50 cm diameter**

Species	CD (m)	z- ratio	Stand Density (trees ha^{-1})	BA (m^2ha^{-1})
Neem	11.65	23.3	73.68	14.47
Jamun	9.58	19.16	108.96	21.39
Kadamb	10.63	21.26	88.50	17.38
Khair	9.02	18.04	122.91	24.13
Mango	9.78	19.56	104.55	20.53
Poplar	10.77	21.54	86.21	16.93
Teak	9.75	19.5	105.19	20.65

ARBORICULTURE AND URBAN FOREST MANAGEMENT

The Crown-diameter-stem diameter relationship can be effectively applied in the field of arboriculture too for designing plantation programs, planning of growing space requirement and management of urban trees. The *K-d* knowledge helps the urban forest managers to maximize the delivering of ecosystem services while balancing the cost of management and possible negative effects of competition (Aryal *et al*. 2021). Globally, ample studies on urban trees allometry suggest that the findings could be useful for urban planners in determining growing space requirement for trees (Pretzsch *et al*. 2015; Monteiro *et al*. 2016). However, most of the studies do not specifically address the issue of competition and spacings in street plantings, nor provide subsequent recommendations or spacing standards. Indeed, the focus is often on the space requirement of trees based on crown dimensions, and not changes in crown dimensions at different spacings.

Stem diameter plays a significant role in balancing the overall weight of a tree- crown as the tree matures. The stem diameter, tree height and crown diameter grow at different rates. Fast - growing young trees have a larger crown diameter and tree height relative to their stem diameter. This is the reason that the *K/d* ratio is higher in young trees, and it decreases as the stem diameter increases with age, thus maintaining tree/stand stability. Therefore, in young trees, the *K/d* ratio drops very fast and later gets stabilized when the tree attains maturity. Under natural conditions, a weak stem would probably break and the tree would collapse as it would not be able to bear the weight of the crown. Moreover, storms and high wind speed may also do the damage in young trees because of fragile stem structure. Knowledge of *K/d* ratios is thus crucial for monitoring the stability of young trees and tracking the maturity of older ones. In addition, this relationship can further be utilized to plan, monitor and manage mono culture as well mixed species plantations applying similar approach.

CONCLUSION

The highlight of this piece of work is building *K-d* models and using this information*(K/d)* to plan growing space requirement of a tree and thinning regimes. Moreover, basal areas and stand densities estimation along with its application in the field of arboriculture for effective management of urban trees are some goals which can be achieved using *K-d* knowledge. The limitation of this piece of work is that site and species-specific crown diameter - stem diameter data is required to build linear regression models as for such models, the model parameter values might change with habitat, environmental conditions and soil physio-chemical characteristics which might influence *K-d* predictions as well. In future, more and more species with different functional groups under different habitats and environmental conditions should be investigated and their *K/d* pattern should be interpreted for better management of trees and to maximize ecosystem benefits.

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