Tree Crown Structure Indicators in a Natural Uneven-Aged Mixed Coniferous Forest in Northeastern Mexico

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Abstract — Characterization of tree crown structure provides critical information to assess a variety of ecological conditions for multiple purposes and applications. For biomass growth, for example, tree crowns have basic physiological functions: assimilation, respiration, and transpiration. How tree crowns spatially interact and grow can bring about a seamless landscape of unique features and microclimatic conditions that are highly relevant to biological diversity, soil processes, productivity, wildlife habitats, ecosystem health and sustainability. Approaches to measuring tree crown structure and variability within multiple diameter distributions are particularly important in uneven-aged, multispecies natural stands. Results of using the "Weibull bimodal probability distribution function" to model diameter distributions of multi-storied stands and various crown index measurements to describe their respective tree crown attributes and properties are presented and discussed. Specific patterns of values of these indices were found which suggest they have potential for use as indicators of crown structure complexity and variability across a wide spectrum of forest conditions and types. In light of these results, we also address the relevance of these results for forest inventory and monitoring programs. Funding for this research was provided by Mexico's National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnologia (CONACYT; Project 333919-B) and Universidad Autónoma de Nuevo León.

Introduction

The main functions of a tree crown are assimilation, respiration and transpiration. Assimilation, which is known as photosynthesis in green plants, can be described as the process by which light energy is trapped by chlorophyll and used to produce sugar from carbon dioxide and water. Respiration refers to the process by which the energy stored in reduced carbon compounds during photosynthesis is released by oxidation in a form that can be used in assimilation and growth, and in maintenance of cell structure and function. Transpiration is the process of taking water from the soil through plant roots and the loss of this water into the atmosphere as water steam through the leaves (Kozlowski and others 1991).

The tree crown is one complement of net primary production and its dimensions reflect general tree health. Dense and large crowns are associated with potential growth rates. Sparse and small crowns can prove responsive to unfavorable site conditions (competition, moisture, diseases). Tree crowns are highly variable. Their general shape varies from relatively dense conoid crown-shapes for conifers of an excurrent habitat to wide open shapes for many broad-leaved trees of a deliquescent habitat (Husch and others 2003). Tree crown research contributes to several key forest ecosystem attributes: biodiversity, productivity, forest management, forest environment, and wildlife. Crown characteristics are useful in predicting growth responses in spacing and thinning, and in relating growth to soil moisture availability. These studies emphasize the close relationship between the crown size and the amount of the photosynthetically active foliage (Laar and Akca 1997).

The surface area of forest trees is a useful measurement for the study of precipitation interception, light transmission through forest canopies, forest litter accumulation, soil moisture loss, and transpiration rates (Husch and others 2003). The size of a tree crown is strongly correlated to tree growth. The crown displays the leaves to allow the capture of radiant energy for photosynthesis. Thus, measurement of a tree crown is often used to assist in the quantification of tree-growth. The crown biomass and the quantity and quality of branch material, however, are also of direct interest to ecological studies and research into the effects of trees on pollution. Nowadays, the knowledge concerning to the tree crown structure is important, in the sense that trees use this tree component as a source of absorption of carbon dioxide.

Now, the length of the live crown is determined as the height of the first branch or the first live branches (Bachmann, 1998; Nagel and Biging, 1996; Kramer and others 1999). Taking into consideration the crown as a primary element in the vegetation development, several scientific studies relating to tree crown confirmation and growth have been undertaken to determine tree growth through models for tree crown profiles (Kellomäki and Kurttio, 1991; Biging and Gill, 1997; Gadow, 1999; Gill and others 2000).

Objective

The objective of this research is to develop a method to characterize tree crown structure in uneven-aged, mixed coniferous forests, through the application of tree dimensions (dbh, total height, basal area), diameter distribution (bimodal Weibull distribution) and crown indexes (crown width, crown thickness index, crown spread ratio, crown projection area and crown surface area).

Study Site and Methods

In recent decades, Mexico has promoted the protection of natural forests through the creation of protected areas and national parks (Jiménez and Kramer 1991, Aguirre and others 2001). Accordingly, in 1998 the Cerro El Potosí was decreed as protected area, containing natural forests of high biological value and being located in the highest peaks (3,675 masl) of Northeastern Mexico. This mountainous area is located in the Sierra Madre Oriental.

The study area is located in Cerro El Potosí, in a mixed coniferous forest composed by *Abies vejari*, *Pseudotsuga menziesii*, *Pinus hartwegii* and *Pinus ayacahuite*. This uneven-aged stand contains 504 trees, with a mixture of species in a marked differentiation of strata. For each tree the diameter (dbh), height (h), age (t), and basal area (g), as well as its spatial distribution, were measured. The area is located at an altitude of 3,100 meters above the sea level (figure 1).

To obtain the diametric distributions per species, the Weibull distribution was employed, being one of the most used in the forest area because of its relative flexibility, as well as being better adapted to uneven-aged and mixed forest (Zarnoch and Dell, 1985; Killki and others 1989; Maltamo and others).

$$f(x) = \frac{c}{b} * \left(\frac{x-a}{b}\right)^{c-1} * e\left(\frac{x-a}{b}\right)$$

Where:

x=dbh, a=Location parameter, b=Scale parameter, and c=Shape parameter.



Figure 1. Location of the study area.

Crown radius is needed in certain kinds of competition measurements (Gill and others 2000) and is defined in this study as the distance between the center of the bole and the four cardinal points. Crown diameter or crown width assessment is based on the measurement of two or four radii, and is usually defined as twice the radius. Crown length or live crown length (Biging and others 1990) is defined as the distance between the apex of the tree and the base of the live crown (CL = tree height – crown base). Live crown length is the distance between the apex and the light crown.

After tree crown parameters were measured, the following crown indexes were calculated: Crown percentage (CR%), Light crown percentage (LCP%), Crown thickness index (CTI), Crown spread ratio (CSR), Crown projection area (CPA), and Crown surface area (CSA).

Crown percentage is the length of the light crown length calculated as a percentage of the total tree height (CR% = 100 * CL/h). Light crown percentage is the percentage of light crown length and crown length $(LCP\%=100*LCL/_{CL})$. Crown thickness index is the ratio of the crown diameter and crown length (CTI=CD/CL). Crown spread ratio is the ratio between the crown diameter and the tree height and it is used when attempting to determine the shape of the crown (CSR = CD/h). The crown projection area is the surface occupied by the crown and is usually used as a measurement of stand density (*CPA*= $\pi/_{\mathcal{A}}$ **CD*). The crown surface area is defined as the external surface area of the live crown. Normally it is assumed that the conifer crown can be represented either as a cone or as a paraboloid (Kramer, 1998; Laar and Akca, 1997; Jiménez and others 2002)

Results and Discussion

Size Structure

From the table 1 we found that the numbers of individuals, as well as the basal area per hectare are very different. There is a similarity between the individual number of most species: Pinus ayacahuite (124 stems/hectare), Abies vejari (120 stems/hectare) and Pseudotsuga menziesii (102 stems/hectare), most of them except Pinus hartwegii (60 stems/hectare). However, an affinity was discovered in the values of the basal area for Pinus ayacahuite, P. hartwegii and Pseudotsuga menziesii. Despite the fact that Abies vejari showed a higher tree number, its basal area only represents a total of 12 percent of the total basal area percentage per hectare. In general, there is a high variability between all the species with respect to age (14-126 years), diameter (5-65.4 cm) and height (2.2-22.4 m). This high variability in age, height, and diameter of the species is due to the fact of the mixed and uneven-aged stand.

Diameter Distribution

In order to determine the diametric distribution applicable to all species we used the Weibull distribution, which is frequently observed in young even-aged stands before the first thinning, and in age-varied forests (Laar and Akca1997), but it was observed that in its natural state, the forest showed a bimodal type distribution, resulting in a typical structure with two subpopulations. In table 2 it is demonstrated that *Abies vejari*, *Pseudotsuga menziesii* and *Pinus hartwegii* present a higher number of individuals in the minor categories. However, *Pinus*

hartwegii shows a similar bimodal distribution, as much in the minor as well as in the major diametric categories. It is important to note that at the site level, 73 percent of the trees are located in the lower strata and only 27 percent of them in the higher strata. This demonstrates a clear bimodal distribution.

This study employed a method for describing bimodal diametric distributions using estimates of a maximum and minimum stand diameter (Hessenmöller and Gadow 2000). Thus, for the mixed conifer forest the following bimodal Weibull distribution ensues:

$f(x) = g^* f_u(x) + (1 - g)^* f_o(x)$

Where $f_u(x)$ and $f_0(x)$ describe the respective diametric functions regarding the higher and lower forest strata and g is the linking parameter between both functions.

Figure 2 shows the Weibull distribution of the four species found in the study area. It is observed that there exists a good adjustment of the bimodal Weibull distribution in the diametric categories.

It was observed that the method employed by Hessenmöller and Gadow (2000) showed a greater precision when the parameters of distribution were calculated separately, equally for the upper as well as the lower strata. By using the diametric bimodal Weibull distribution method, we concluded that the forest proved to be uneven-aged and mixed, presenting two strata in vertical structure.

Crown Analysis

Following the diametric analysis, it proceeded to separate the trees into Height Zones. The study site was divided into two strata: Height Zone I and Height Zone II. Table 4 shows the trees by species and by Height Zones, 75 percent

Table 1. Size structure of the uneven-aged stand per hectare.

Tree species	Age (years)	N stems	Basal Area (m²)	Diameter (cm)	Height (m)
Abies vejari	32	120	1.86	12.5	7.9
Pseudotsuga menziesii	38	102	3.65	17.1	8.9
Pinus ayacahuite	40	124	5.10	18.8	8.1
Pinus hartwegii	51	60	4.62	26.5	10.6
Stand	38	406	15.10	17.6	8.6

Table 2. Tree distribution in relation to two diametric categories.

Tree species	Diametric Category 5- 20 cm	Diametric Category >21 cm	Total
Abies vejari	133	16	149
Pseudotsuga menziesii	97	29	126
Pinus ayacahuite	107	47	154
Pinus hartwegii	33	42	75
Total	370	134	504



Figure 2. Bimodal Weibull distribution for Abies vejari, Pseudostuga menziesii, Pinus hartwegii, and Pinus ayacahuite.

(376) corresponding to the individuals in Height Zone II, and only 25 percent (128) in Height Zone I.

In the predominant and dominant trees stratum (Height Zone I), Pinus ayacahuite and Pinus hartwegii show a remarkable similarity in their stem dimensions (d, h, d)t). With respect to the relation $\frac{dbh}{h}$, we observed that they present a lower value (41-42), which is evidence of the stability of the species in this site. Abies vejari and *Pseudotsuga menziesii* show a greater variability in their dendrometrical parameters, as well as an increase in their stabilizing values (51-61). This is due to the fact that they are shade-tolerant species, and for this reason their development is slower in their primary phases and with greater competition, which is why a positive stable relationship does not exist. However, in Height Zone II, the shade-tolerant species show a greater similarity in diameter, height, and age values, thus observing a greater stability.

The definition of the base of the live crown is important to calculate the crown length, crown percentage, crown thickness index and crown surface area. In this case, the base of the live crown was defined as the height of the last live branch. Table 3 shows in a global way that, in the upper stratum, the crown percentage covers 53 percent of the tree, while in the lower stratum it covers 73 percent. At a species level, it was observed in Height Zone I that crown percentage decreases while the age increases (*Pinus hartwegii t* = 73; *CR*% = 45 percent, *Abies vejari t* = 47; *CR*% = 62). This is due to the fact that crown percentage decreases while the tree keeps growing. However, in Height Zone II there exists a great similarity between the age (28-31 years) and CR% (71-78 percent) values, presenting no difference between the species because they are located underneath the canopy of Height Zone I.

In order to characterize the light crown length (*LCL*) the height of the widest part of the crown was measured, and to calculate the light crown percentage (*LCP*%) a relation between the light crown length and the crown length (*LCP*%=100**L*^C*L*/*CL*) was performed. In general, there is no differentiation of the *LCP*% (75 percent) between the two Height Zones. At the species level, *Abies vejari* presents the highest *LCP*% (I = 96 percent; II = 90 percent), meaning, practically, that a high percentage of the light crown belongs to the complete crown. *Pseudotsuga menziesii* also presents a high percentage of light crown (87 percent). This is explained if we consider that both species are tolerant to light. However, in both pine species, there exists a lesser percentage of *LCP*% (I = 60-67 percent; II = 61-65 percent).

Table 3. Stand crown characteristics according to the height 201	Table 3.	Stand cr	own charad	cteristics a	according	to the	height z	one
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Species	n (ítem)	dbh (cm)	h (m)	t (year)	dbh/h	CL (m)	CR%	LCP (m)	LCP%
Height Zone I (predomin	ant and don	ninant trees)							
Abies vejari	21	23.9	13.	47	61	8.4	62	8.2	96
Pseudotsuga menziesii	35	33.6	15.2	63	51	8.9	58	7.9	87
Pinus avacahuite	33	39.3	15.5	72	42	8.2	53	4.9	60
Pinus hartwegii	39	39.6	15.3	73	41	6.7	45	4.4	67
Strata	128	35.3	15.2	66	47	8.0	53	6.1	75
Abies vejari	128	10.7	6.9	29	68	4.9	72	4.3	90
Height Zone II (suppress	sed trees)								
Pseudotsuga menziesii	91 ´	10.8	6.5	28	67	4.8	76	3.6	75
Pinus avacahuite	121	13.2	6.1	31	50	4.2	71	2.8	65
Pinus hartwegii	36	12.2	5.6	28	50	4.2	78	2.6	61
Strata	376	11.7	6.4	29	58	4.6	73	3.5	75

CL= Crown length, CR%= Crown percent, LCP= Light crown length, LCP%= Light crown percent.

Conclusions

In accordance with the heterogeneous structure of this mixed and uneven-aged stand, it was observed that there is a great variability in stem dimensions and crown parameters, not only at a site level, but also in the species that are found in the ecosystem. *Abies vejari* is the species showing the lowest average age (32 years) and *Pinus hartwegii* is the one presenting the highest average age (51 years). Despite this, *Pinus ayacahuite* shows a wider dispersion range (15-126), which indicates that the ecosystem is uneven-aged. In turn, *Pinus hartwegii* is considered the one having the widest average diameter (55 cm), but *Pseudotsuga menziesii* has the widest range of variability (CV%=77.2 percent). Regarding the greatest height, *Pinus hartwegii* holds 10.6 m on average, and a range that varies between 2.3-22.4 m.

A large discrepancy was observed in tree distribution per species. The shade-tolerant species - *Abies vejari* and *Pseudotsuga menziesii* - respectively 74 percent and 66 percent of their individuals in the 10 cm diametric categories; while the light-tolerant species – *Pinus ayacahuite* and *Pinus hartwegii* – have only a 55 percent and 47 percent of their trees in this diametrical category.

There is a bimodal type Weibull distribution for the tree species of the ecosystem. *Abies vejari*, *Pseudotsuga menziesii* and *Pinus ayacahuite* show a higher slope in the curve in the first diametric categories, due to a greater amount of trees, while *Pinus hartwegii* shows a similar tendency among the higher and lower diametric categories, which results in a similar curve slope. In general, it is observed that there is a good adjustment in the bimodal Weibull distribution for all species.

One of the important objectives in this investigation was the analysis of the crown parameters. Towards this end, the crown diameter, light crown length, and the base of the crown defined as the height of the last live branch, were used. With these variables, the crown indexes were defined: crown length, crown percentage, light crown length, and light crown percentage. It was concluded from tables 4 and 5 that there exists a great heterogeneity in the values corresponding to the crown indexes in Height Zone I and Height Zone II; the discrepancy among the species within each of Height Zones is even greater.

The final conclusion of this study is that uneven-aged, mixed forests present a specific structure, in accordance with its stem parameters, diameter distribution, and crown parameters and indexes, proving that this evaluation methodology can be reliably used. These tree crown structure indicators have a high value in forest ecosystem management, where the forest structure is considered a high priority.

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