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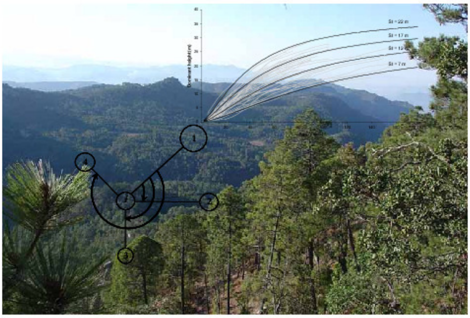

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1. Introduction

1.1. Description of the study area

Altogether 55.3 million hectares or 28 percent of the total national territory of Mexico is covered by forests. These forests are very diverse, produce a wide range of economic benefits, and are critical to the well being of rural Mexican communities (WWF, 2002; FAO, 2005). The Mexican forests are spread along the Mexican Pacific Slope and are one of the main sources of biodiversity on earth. Mexican Pine and Oak Forests cover large portions of the states of Durango, Chihuahua, Michoacan, Jalisco, Guerrero and Oaxaca. The pine-oak forests are most abundant. They cover 16% of the national territory, comprising 31.8 million hectares in total, and occur throughout the major mountain ranges of the Sierra Madre Oriental, the Sierra Madre Occidental, the Sierra Madre del Sur and the Transvolcanic Belt (Rzedowski, 1978).

Mexico is not only home to 50% of all the known pine species, but also gives refuge to a remarkable 135 species of oak compared to the 87 found in the United States and Canada together (WWF, 2002). About 80% of the forest area is managed and owned by about 8,000 rural communities and Ejidos while 15% of the forest land is in private ownership. The remaining 5% belongs to the Federal Government, out of which 3.7% is classified as Protected Areas. Most of the rural communities living in the forest are composed of indigenous people (Thoms and Betters, 1998). These rural lands are known as *Ejidos* and *Comuninades* where communal groups live and manage their natural resources with some level of governmental control. This arrangement is similar to the tribal lands in the United States (Thoms and Betters, 1998; Velazquez et al., 2001).

The most productive forest states are Durango, Chihuahua, Michoacan, Guerrero, Jalisco and Oaxaca. In these states every year a total of approximately 5.7 million m^3 of pine (by far the most logged species group in the country) timber is harvested, which represents 74% of the national timber production.

This study was conducted in forest region of El Salto, Durango, which is located in the Eastern Sierra Madre between 23° 30' to 24° 15' latitude and 105° 15' to 105° 45' longitude, 100 km to the southwest of Durango City (Figure 1). It covers an area of approximately one million hectares and is very important for the country's timber production, biodiversity, and essential protective functions. In this region the timber harvest amounts to about 920,000 m^3 yearly, which is 44% of the total production in Durango State (SEMARNAT, 2006).

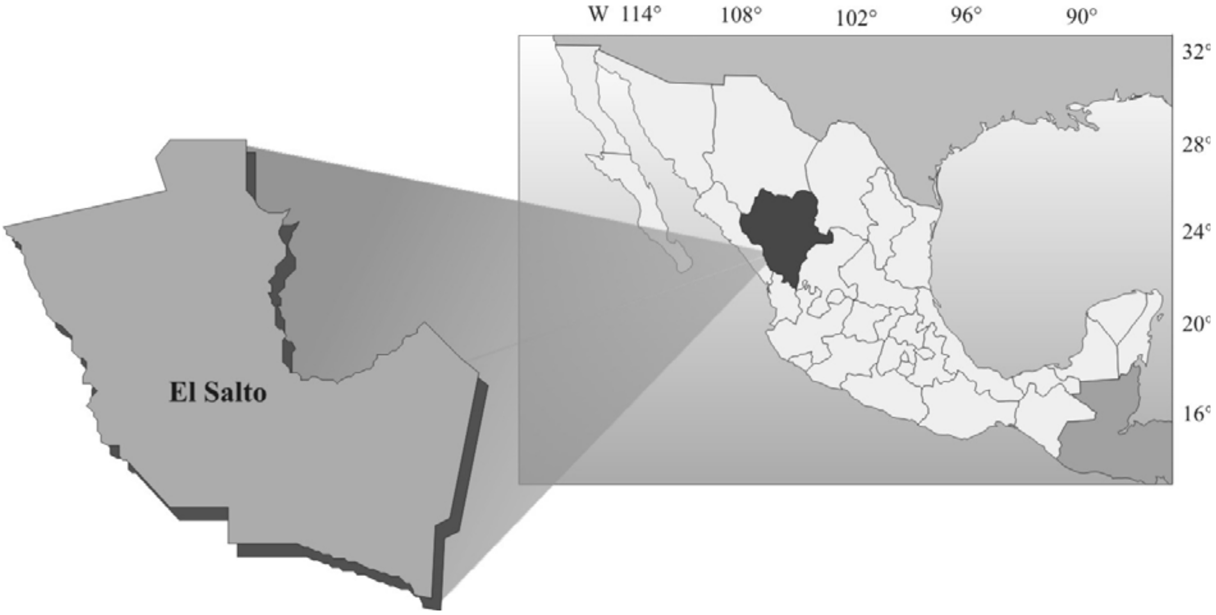

Fig. 1. Location of the study area: The forest region of El Salto is in Durango State in the northern part of Mexico.

The species of greater commercial value, due to the technological characteristics of the wood and the distribution range as well as their harvested timber volume, are the following pine species listed in the order of their importance: *Pinus cooperi* Blanco, *P. durangensis* Martínez, *P. leiophylla* Schl et Cham, *P. engelmannii* Carr, *P. cooperi* var ornelasi, *P. teocote* et Cham, and *P. herrerae* Martínez. Other pine species of less commercial value, distribution and abundance are *P. ayacahuite* Ehrenb, *P. lumholtzii* Rob et Fern, *P. douglasiana* Martínez, *P. michoacana cornuta* Martínez, *P. oocarpa* Schiede. In addition, some oak species and other coniferous and hardwood species, including the genera *Arbutus*, *Juniperus*, *Pseudotsuga*, *Abies* and *Picea* are also utilized.

The mixed pine-oak natural forests of El Salto, Durango have important ecological and social functions, such as prevention of soil erosion and the protection of valuable water reservoirs. They also provide recreation areas for the society and represent the major economic activity for the communities. Accordingly, sustainable forest management has to be adopted as a standard approach for effective conservation of the natural resources and for timber production. Sustainability can only be achieved if the forest management decisions are based on a sound understanding of forest structure and growth potential.

1.2. Objetives of the study

Accurate predictions of tree growth and yield are needed for determining sustainable harvests and to evaluate how stand and tree parameters change over time and inresponse to silvicultural interventions. Moreover, the characterization of spatial forest structures can help to understand the history, function, and future of a forest ecosystem and the knowledge of variation in forest structure over time and space can serve as the basis for forest management strategies that seek to sustain a broad array of forest goods and services (Spies et al., 1991; McComb et al., 1993; Spies, 1998). Therefore, the main goals of this study are: (i) the development of accurate growth models to predict both stand and individual tree growth and yield for mixed and uneven-aged forests, and (ii) to investigate the performance of useful spatio-statistical indices for the description of the spatial structure of a forest.

For publications (I-V), the following objectives may be defined:

(1) To develop specific site index models for the major pine species

(2) To identify an effective competition index to be incorporated into further individual tree basal area growth models

(3) To develop a compatible volume system for the major pine species

(4) To develop species-based equations for predicting both *dbh* and volume from stump diameter.

(5) To describe and evaluate the performance of two indices for characterizing the geometric pattern of tree locations in a forest.

1.3. Forest management systems practiced within the study area

The forest management in El Salto Durango involves the organized application of some particular silvicultural procedures to regulate and control harvest yields and to ensure restocking of harvested areas to achieve pre-determined objectives. The region of El Salto is managed with a 10-years management plan. The plan is based on a forest inventory using information of previous inventories, permanent sample plots, stem analysis and periodic remeasurements.

We may distinguish two methods of forest management which are used in the forest region of El Salto, Durango:

1. The Continuous-Cover Forestry System (known in Mexico as *The Mexican Method of Irregular Forest Regulation* (*MMIFR*)): this method is characterized by selective harvesting,

natural regeneration, and the assumption that growth projection follows an exponential behaviour, expressed by the compound interest equation (Rodriguez et al., 1960; SARH, 1984). This formula establishes that the annual harvest volume should not exceed the initial volume plus the volume product of the net growth of the forest, which is assumed to grow at a constant rate on the volume during the cutting cycle. The *MMIFR* is a volume-control method and the application of the formulas to calculate allowable cut is very simple, the growing stock is obtained in a conventional forest inventory and only additional data of mean annual increment in volume are necessary.

2. The Rotation Forest Management System (known in Mexico as *The forestry development method* (*FDM-system*)): this silvicultural system is applied in subcompartments constituted mainly by pines and consists in the determination of a rotation of 60 years normally. This period of production is divided in a period of growth (intermediate cuts) and one of regeneration, during which the silvicultural treatments that include a pre-thinning, thinnings (normally three), and a regeneration cut (with some nurse trees left standing) are applied. In the second forest regulation a pre-thinning is applied simultaneously with a liberation cut (Musalem, 1976; Cano, 1977; Musalem, 1979; Rosales et al., 1982). The objective of the *FDM-system* is to obtain a normal age class distribution after one rotation, using a method of regulation by area.

1.4. Forest growth models

Tree growth manifests itself by the elongation and thickening of roots, stems, and branches. Growth causes trees to change in weight and volume (size) and in form (shape). Generally, the growth of a tree is a function of different factors, such as age, tree size, competition and site quality. Total and merchantable height growth, diameter growth at breast height, and diameter growth at different points up the stem are elements of tree growth traditionally measured by forest researchers and managers. All these elements may be determined accurately in the field, analysed and then predicted, using growth models.

Forest growth models predict growth of a target forest stand using sites characteristics and management options as input variables, and constitute important tools for decision making in sustainable forest management. Most of these models are empirical and can be organized around three types representing a broad continuum of model classes: *whole stand models*, *size class models*, and *individual tree models* (Vanclay, 1994; Gadow and Hui, 1999; Davis et al., 2001).

Whole stand models require stand parameters (e.g. age, density, site quality, basal area, volume, etc.) as inputs and predict with a greater degree of detail, how these parameters change over time. Examples of *whole stand models* are yield tables and yield functions. The basic modelling unit in a s*ize class model* is a representative tree impersonating a number of trees within a size class or cohort. Size class models, requiring even more detailed information than stand models, are probably the most common type for simulating alternative silvicultural programs. *Individual tree models* utilize individual tree data as inputs. Changes in the attributes of individual trees (e.g. *dbh*, total height, diameter growth, etc.) are predicted and stand level attributes are obtained by summing information of the individuals. They may be distance-independent or distance-dependent. The distance-independent ones do not require tree coordinates, since they are simple functions of stand-level variables or of the initial dimensions of the subject tree, while distance-dependent models require the dimensions and the relative locations of several neighbours for the computation.

Two other classes of models are process and succession models. Process models attempt to model the processes of growth, taking as inputs the light, temperature and soil nutrient levels, and modelling photosynthesis, respiration and allocation of photosynthesis to roots, stems and leaves (e.g. Langerberg, 1986; Mäkelä, 1992). These models are also known as mechanistic versions of physiological models. Process models help to provide a better understanding of growth and stand dynamics, but have yet not been successfully used for predicting timber yield for forest management.

Succession or "gap" models attempt to model species succession, but are generally unable to provide reliable information on timber yields (e.g. Shugart, 1984; Botkin; 1993).

1.5. Stand structure

Mexican pine-oak forests are very complex and diverse in composition, structure and functions. Since informed decisions are basic to good management practice, sustainable forest management requires quantitative information on such aspects. Most frequently, forest conditions have been conventionally interpreted by the stand structure, which is thought to be both a product and a driver of ecological process and biodiversity. In addition, there has been a long history of traditional practice in forestry that variation in forest structure is typically manipulated for timber output maximization. Thus, structure has both ecological and economic implications for sustainable management. However, the term "*forest structure*" includes many things and can be described in numerous ways. It needs to be described for simplifying the process of measuring, understanding, and manipulating forests and hence making objective decisions in management planning.

Stand structure is related to the spatial and temporal arrangement of individual trees in the forest stand. The spatial structure defines the organization of the trees in space while temporal structure refers to successional patterns over time. The spatial structure of a forest stand plays a key role in its dynamics (i.e. regeneration, competition, survival, establishment, development, etc.). Accordingly, three critical aspects have been taken into account in describing the structure of a forest stand: the spatial distribution of the tree position (i.e. spatial distribution), the spatial arrange of the tree dimensions (i.e. size differentiation), and the particular mingling patterns of the different tree species (i.e. mixture; see Stoyan and Penttinen., 2000; Gadow and Hui, 2002; Pommerening, 2002; Aguirre et al., 2003).

1.6. Review of growth modelling and stand structure in Mexico

With the increase in readily available, high-powered personal computers, the development and complexity of forest growth models and parameters for the description of the spatial structure of stands have increased.

Growth models help forest researchers and managers in many ways. Some important uses include the ability to predict future yields and to explore silvicultural options. Models provide an efficient way to prepare resource forecasts, but a more important role may be their ability to explore management options and silvicultural alternatives. For example, foresters may wish to know the long-term effect on both the forest and on future harvests, of a particular silvicultural decision, such as changing the cutting limits for harvesting. With a growth model, they can examine the likely outcomes, both with the intended and alternative cutting limits, and can make their decision objectively. The process of developing a growth model may also offer interesting new insights into stand dynamics.

The spatial tree distributions provide indications of the underlying biological processes and of the ecosystem management techniques (Stoyan and Penttinen, 2000). The spatial distribution of trees is an important characteristic of forest stands reflecting their history (Moeur, 1993), but also contribuiting to the formulation of more effective future management practices. More specifically, the spatial distribution affects (1) the sampling design of a forest inventory, (2) timber production, and (3) the need for silvicultural treatments in a stand (Tomppo, 1986).

In Mexico the first studies on growth modelling were developed for pure even-aged forest stands. However, these ecosystems are not common in Mexico, and therefore many of these modelling approaches do not apply in forest stands with trees of many ages or many species that cover most of the Mexican forests.

Probably one of the first forest growth studies in Mexico was realized by Musalem (1973) who published a paper in which he explores the possibility to use yield tables in pure even-aged forest stands. Manzanilla (1974) recommended to manage *Abies religiosa* forests considering its irregular stand structure, proposing the application of selective cuts instead of the *Rotation Forest Management System*. This was indeed the first attempt to use a *Continuous-Cover Forestry System* in Mexico. Garzón (1976) developed a normal yield table for *Pinus hartwegii* in Zoquiapan, Mexico. Cano y Nevárez (1980) published a study on growth simulation over time for some parameters of *Pinus douglasiana*. Torres (1984) presents a methodology to estimate growth and yield for *Pinus hartweggi* in Zoquiapan, Mexico. Aguirre (1989) published a standard method to develop yield tables using data from permanent sample plots, stem analysis and measurements on individual trees. Torres and Brodie (1990) developed a dynamic model to predict growth and yield for *Pinus hartweggi* using the Weibull growth function.

In the forest region of El Salto, Durango, only a few studies on growth modelling have been carried out in the last years (Aguirre, 1987; Corral and Radilla, 1996; Corral and Manzano, 1998; Návar et al., 1998; Valles et al., 1998; Corral, 1999; Corral et al., 1999;Valles and Islas, 2000). Of these studies the study by Corral (1999) stands out since he tested several volume equations, taper and site index models, growth and increment functions for some pine species as well as modelled the diameter structure of mixed and uneven-aged forest stands using the Weibull distribution function.

Regarding to stand structure, it has hardly been investigated in this forest region. Only two papers dealing with spatial forest structure have been published until now. They correspond to the studies by Aguirre et al. (1998 and 2003) which present relatively new approches for the analysis of the stand structure.

2. Data

Most of the experimental data used in this analysis come from a forest inventory carried out in 1997 by the *Técnica Informática Aplicada* of the Forestry Department of Durango City in the forest region of El Salto. In publication II, data from permanent sample plots were used to evaluate the performance of competition indices (see Tab. II-1, p. 52)[1].

The goal of the forest inventory was to describe the growing stock and the forest structures present in this area. The sampling design was stratified random, covering most of the conditions of productivity and silviculture in the forest. The sample for the complete forest inventory included 1,131 circular sample plots covering 1000 m^2 each and representing a sampling intensity of 1.5% of the total area. The data included growing stock and ecological information, tree health, density, volume distribution and tree growth. A subsample of 135 plots was selected to represent the range of site quality and density conditions in the area for the most important pine species. For each plot one dominant, one co-dominant and one suppressed tree were selected for stem analysis. These were the sample trees used to develop most of the growth models in this study. In Publication I, the stem analysis of 160 dominant pine trees of five different species was used (47 *Pinus cooperi*, 37 *P. durangensis*, 34 *P. engelmannii*, 17 *P. leiophylla* and 25 *P. teocote* trees; see Tab. I-1, p. 29). In Publications III and IV, data from 459 trees of *Pinus cooperi*, 413 of *P. durangensis*, 375 of *P. engelmannii*, 380 of *P. leiophylla*, and 284 of *P.teocote* were used to test the statistical performance of the taper, diameter and volume functions (see Tab. III-1 p. 76 and Tab. IV-1, p. 104). Most of the experimental data used in Publication V were generated by computer simulations. In addition, sixteen Mexican permanent sample plots of quite different forestry characteristics are used to evaluate the performance of two spatio-statistical indices, the *Uniform Angle Index* and the *Mean Directional Index*, for characterizing the geometric pattern of tree locations in a forest. The tree distributions of the first eight permanent plots come from Corral-Rivas et al (2005) and can be visually considered as regular tree patterns. They are located in the forest region of El Salto, Durango on mature and even-aged stands of *Pinus cooperi* Blanco, each covering an area of 0.5 ha. The remaining 8 data sets were visually selected as the most aggregated ones from a network of 66 permanent sample plots located in a forest Ejido known as Ejido San Diego de Tenzaenz, in Durango (Mexico). These plots are established in uneven-aged and mixed forest stands, each covering a square area of 30x30m. The tree patterns result from natural regeneration, competition of trees and forester's work. The main plot characteristics are presented in Tab V-4, p. 123.

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[1]The data come from eight permanent plots located in mature and even-aged stands of *Pinus cooperi* Blanco, each covering an area of 0.5 ha.

3. Discussion and conclusions

Growth models for five major pine species were developed in this study. In addition, two spatio-statistical indices were evaluated using simulation studies. The growth models represent qualitative tools that can be used by the forestry departments of El Salto, Durango for determining sustainable harvests and to evaluate how stand and tree parameters change over time. Differences in growth patterns between selected pine species were found and hence species-based models are recommended to be implemented as new forest management tools.

This thesis also evaluates the performance of two structural indices, the *Uniform Angle Index* and the *Mean Directional Index*, for characterizing the geometric pattern of tree locations in different forests of Durango. When these indices are used as summary characteristics, they help to classify given tree patterns as regular, random or clustered. The ability to describe forest spatial structures, and their modifications through timber harvesting, is of prime importance for the sustainable management of these mixed and uneven-aged woodlands.

In publication I, taking into account that the *nonlinear extra sum of squares method* indicates differences in dominant height growth among the selected pine species, a species specific site index model was developed for the forest region of El Salto, Durango. The use of this species-based site index equation is recommended instead of a single site index model which was proposed by the *Técnica Informatica Aplicada* forestry department (UCODEFO No 6, 1997) for all pine species combined. Based on the results of publication I, the species specific site index model developed in this study has already been implemented in *BWINPro* version *El Salto, Durango*[2], a computer program designed to analyze and predict growth and yield in mixed forest stands. It is parameter-parsimonious, polymorphic and base-age invariant with multiple asymptotes and provides compatible site index and height-growth estimates.

The effect of competition on individual tree basal area growth was evaluated in publication II using different competition indices. It was found that the best distance-independent competition indices performed as well as the best distance-dependent competition indices. These findings are consistent with several studies that point out that distance-dependent indices are seldom better that distance-independent indices in predicting

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[2] The *BWINpro* version El Salto, Durango is being adapted by Benedicto Vargas, a doctoral student under the supervison of Prof. Dr. J. Nagel at the Forest Research Station of Lower Saxony in Göttingen.