MODELS FOR THE SUSTAINABLE MANAGEMENT OF PINE PLANTATIONS OF DURANGO, MEXICO

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ABSTRACT

The are covered by forest plantations is rapidly expanding in Mexico. However, models to predict taper, biomass, diameter structures, growth and yield, & carbon sequestration of forest plantations are scarce in the Mexican scientific literature. This report presents several empirically models developed with pine forest plantation data collected for stem analysis, biomass studies, and stand measurements of a chronosequence of forest stands measured in Durango, Mexico. The results present models for estimating taper functions, biomass components, diameter structures, growth and yield, and carbon stocks in aboveground standing biomass. These models are required for the sustainable management of pine plantations of Durango, Mexico.

RESUMEN

El área cubierta por plantaciones forestales se esta expandiendo rápidamente en México. Sin embargo, existe poca información en la literatura científica Mexicana sobre el modelaje del perfil fustal, los componentes de biomasa, las estructuras diamétricas, el incremento y rendimiento y el almacenamiento de carbono en plantaciones forestales. Este reporte presenta varios modelos empíricamente desarrollados con datos provenientes de plantaciones forestales para análisis fustales, estudios de biomasa, mediciones de rodales establecidos en diferentes tiempos en Durango, México. Los resultados presentan los modelos para estimar el perfil diamétrico, los componentes de biomasa, las estructuras diamétricas, el incremento y rendimiento y los almacenes de carbono en la biomasa aérea. Estos modelos son necesarios para el manejo sustentable de plantaciones de pino de Durango, México.

Key words: *P. durangensis*, *P. cooperii*, *P. engelmannii*, stem volume, taper, diameter structures, growth and yield, biomass components, carbon dioxide.

INTRODUCTION

The Federal Government is promoting the establishment of forest plantations in Mexico through projects such as Proderplan (Promotion for the Establishment of Forest Plantations) and Pronare (Mexican Program of Reforestation). Therefore, for the period between 1997 and 2003 approximately 47,000 ha are being planted in the country (Semarnap, 1999). However, since early last century small-scale forest plantations had been established across the country. In the state of Durango, Mexico, the coniferous forests of the western Sierra Madre mountain range are extensively managed to provide several economic benefits. Yet, natural and human disturbances such as forest fires, pest and diseases, overgrazing, harvesting, and road construction are degrading forest stands. Land managers are trying to restore plant cover on degraded stands by planting native coniferous species. Thus, there is a wide range of small-scale forest plantations scattered over the landscape of the Sierra. For the period between 1993 and 1998 approximately 5000 hectares were annually planted to restore plant cover and diminish land degradation processes (Semarnap, 1999).

The sustainable management of forest plantations requires modeling techniques that address several traditional and environmental services. Growth and yield models had been developed for the management of native coniferous forests of Mexico. Aguirre-Bravo (1987) developed growth & yield, taper, site index, and density models for native, monocultures, even-aged forests of *P. cooperii*. Torres-Rojo and Brodie (1990) showed the need to develop growth and yield models to manage native forest stands of *P. hartwegii.* Navar et al. (1996) used a different approach to model growth and yield of chronosequences of native, mixed, uneven-aged coniferous forests of Sinaloa, México, based primarily on fitting the Weibull distribution and predicting parameters. Zepeda and Domínguez (1998) and Zepeda and Acosta (2000) used the Clutter (1963) approach to model growth and yield of native coniferous forests of Chihuahua and Puebla, México. Regardless of this effort, there is no information to model several conventional and environmental services provided by forest plantations of Durango, Mexico. Therefore, the aim of this report is to present models empirically developed for the sustainable management of pine plantations of Durango, Mexico.

MATERIALS AND METHODS

This research was conducted in forests managed by the Unidad de Conservación y Desarrollo Forestal No 6, UCODEFO No 6, of the western Sierra Madre mountain range of Durango, Mexico. Forest plantations of several community-based land ownership, *ejidos*, including 'La Campana', 'San Pablo', 'La Ciudad', 'Los Bancos', 'La Victoria', were sampled. These ejidos are located in the municipality of Pueblo Nuevo, Durango, Mexico, within the coordinates 105º36'19''W and 105º51'48''W and 24º19'05''N and 24º30'16''N and exist between 2000 and 2900 meters above sea level, masl. The area is characterized by a cold-temperate climate with average annual long-term precipitation and temperature of 900 mm and 15^{O}C, respectively.

Methodology. Stem analysis on 75 trees, biomass components of 56 trees of three pine species *P. durangensis*, *P. cooperii*, and *P. engelmannii*, and dasometric information on a chronosequence of 23 forest stands planted with five different pine specie were measured. In each of the 23 forest plantations, at least two trees were selected for stem analysis and biomass measurements. Trees were felled and separated into biomass components leaf, branch and stem. Biomass components were weighed fresh, and samples of 15% of each component were collected for ovendry analysis. For the stem analysis and taper functions, diameter measurements at several stem lengths were conducted on cross cuttings were selected. In addition, twenty-three quadrats of 20 m x 30 m were randomly sampled by measuring attributes of all trees. Quadrats covered a wide range of site conditions and species planted. In a sample plot, each tree was measured for basal diameter (D), top height (H), and canopy cover (CT). Average statistics of tree attributes measured for developing taper functions, stem analysis, and additive biomass equations are presented in Table (1). Since most trees harvested for stem analysis and biomass measurements come from the same plantations with ages from 6 to 21 years, basal diameter and top height are quite small for pine trees. However, size of small trees is of paramount importance to compute carbon sequestration in the early stages of growth. Most biomass tables have been developed for fully-grown trees and they do not fit well for small trees.

Table 1. Average characteristics of 75 sample trees used for developing taper functions, stem analysis, and additive biomass equations for three pine species planted in Durango, Mexico.

Species	Tree Parameters

	Age (years)		Basal Diameter (cm)		Top Height (m)		Cover (m^2)	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Pinus cooperi	13.95	5.80	12.44	3.87	6.27	3.02	4.19	2.52
Pinus durangensis	14.12	4.85	13.46	4.18	5.91	2.32	5.39	2.78
Pinus engelmannii	14.82	5.25	12.52	3.81	4.44	1.27	5.02	3.45
All Species	14.30	5.30	12.81	3.95	5.54	2.20	4.87	2.92

Std Dev= Standard Deviation

The goodness of fit statistics to select the single and best regression equation were the coefficient of determination, r^2, the standard error, Sx, and the coefficient of variation, CV. The goodness of fit statistics were estimated for each model or equation separately. The goodness of fit statistics of the log-transformed linear square procedures is not compatible with the linear procedures of fitting parameters. Baskerville (1972) suggested a correction factor when using transformations of data. In this report, when variables were log-transformed, first parameters were estimated with the log-transformation procedure and then parameters were computed by the commonly used correction factor ($y=\exp^{(g(y)+s2/2)}$), where s2 is the variance of the log-transformed regression). Observed and computed parameters in original units provided information to estimate the goodness of fit statistics in compatible units. Least square techniques in nonlinear, linear, multiple regression, multiple regression with dummy variables, linear and log-transformed system of equation procedures was used to compute parameters. The method of Newton in SAS was employed in the nonlinear procedures.

RESULTS

1. Taper functions

Table 3. The taper functions with parameters estimated by least square techniques in regression analysis.

Taper Equation		
No	Researcher	Equation
1	Biging (1984)	Di=Dap*(1.0083*log(1-(1-exp(-1.0083/0.3569*X)));
2	Newnham (1992)	Di=DAP*exp(-1.4197+(X*2.4234)+(X2*-1.2868)+(X3*0.0688)+ (X4*-0.00107)+ (X5*0.0000117)+ (dh2*-0.09432)+(dh3*0.02297)+(X2DH*0.2085)+ (XDH3*-0.01037)+(x3dh3*-0.000436)+(dhh2*-0.23703109))

P=(hi/ht); x=((ht-h)/(Ht-1.3)); z=(h/ht); ps=√(p); zs=√(z); xk=((1-zs)/(1-ps)); lx=log(x); rd=(d/dap); lrd=log(rd); k=(lx/lrd); k=log(k); rhs=(ht-h); lrhs=log(rhs); x2=(x**2); x3=(x**3); x4=(x**4); x5=(x**5); x6=(x**6); x7=(x**7); x8=(x**8); dh=(dap/ht); dh2=(dh**2); dh3=(dh**3); xdh=(x*dh); x2dh=(x2*dh); x3dh=(x3*dh); xdh2=(x*dh2); xdh3=(x*dh3); x2dh2=(x2*dh2); x2dh3=(x2*dh3); x3dh2=(x3*dh2); x3dh3=(x3*dh3); rh=(1/ht); sh=sqrt(ht); hh=(ht/sh); dhh=(dh/ht); dhh2=(dh/sh); rh2=(1/sh); dhh3=(dh/rh2).

Goodness of fit tests indicated that the equations of Biging and Kozak2 had the highest coefficients of determination. However, the equations of Kozak and Clutter recorded the smallest standard errors. The equation of Newnham had intermediate goodness of fit statistics. Residual analysis, goodness of fit tests on validating data, performance on estimating stem volume for trees of validation indicated that the taper equations of Newnham and Biging resulted in the best models to predict stem profiles of these trees. The taper equations of Newnham and Biging had also been reported as those with the highest precision for *P. hartwegii* (Návar et al., 1997) and *P. teocote* (Contreras, 1997; Tapia and Návar, 1998).

2. **Biomass Components**

The seemingly-unrelated regression clearly is the method of choice for fitting additive biomass component equations since it circumvents the contemporaneous correlations, achieves lower variance and, therefore, it is a more efficient estimator (Parresol, 1999). The seemingly unrelated regression is an extension and improvement of additive procedure (i) and (ii). It has been widely recommended because it is more flexible and it accounts for statistical dependencies among sample data by setting constraints on the coefficients (Cunnia and Briggs, 1985; Parresol, 1999). However, this procedure is the most difficult additive method to calculate in this analysis, and predictions beyond the characteristics of measured trees are uncertain. This is also a feature of all regressions developed in this study. The parameters of the seemingly unrelated regression equations are reported below:

P.durangensis: $y_{leaf} = -0.6008 + 0.4378D - 0.3874\ln D^2H$
$y_{branch} = 0.1075 + 0.003094D^2H$
$y_{stem} = 0.1331 + 0.00866D^2H$
$y_{total} = -0.3601 + 0.4378D - 0.3874\ln D^2H + 0.01175D^2H$

P.cooperii: $y_{leaf} = -6.0039 - 0.00163D^2H + 1.6945\ln D + 0.8461\ln D^2H$
$y_{branch} = 4.0317 + 0.9047D - 4.8079\ln D$
$y_{stem} = 0.0388 + 0.0090D^2H$
$y_{total} = -1.9332 + 0.00739D^2H - 3.1133\ln D + 0.9047D + 0.8461\ln D^2H$

P.engelmannii: $y_{leaf} = 7.0332 + 1.3704D - 3.3470\ln D^2H$

3. Fitting and Predicting the Weibull Distribution

The equations to predict the Weibull distribution are reported in Table 2.

Table 2. Equations to predict the three-parameter Weibull Distribution for forest stands planted with five pine species in Durango, Mexico.

Equation	Goodness of Fit Tests		
	R2	Sx	Sx(%)
$\beta=e(0.1567+.946*\ln(D)+0.033375*\ln(Ho))$	0.99	0.22	1.6
$\alpha= e(-0.198+21.0157*\ln(\beta)- 20.89\ln(Dq)-.1364\ln(H))$	0.92	1.59	48.7
$\varepsilon=e(0.911-44.66\ln(\beta)+31.485\ln(D) + 14.03\ln(Dq) + 0.351099\ln(D))$	0.97	3.87	46.3

D= Average basal diameter (cm); H= Height (m); Dq= Average quadratic diameter; Ho= Height of dominant trees (m); α, β, ε = Form, shape, and scale parameters of the Wibull distribution.

The null hypothesis, with an error of 0.05 is accepted in 11 out of 18 times when using the x^2 test. When using the K-S test, the number of null hypotheses increases up to 100%. That is, the Weibull distribution is a good model to fit the diameter structures of the pine plantations of Durango, Mexico. The validation tests on the remaining five stands showed that the null hypothesis was accepted in 2 out of 5 and 3 out of 5 when predicting the diameter structures with equations provided in Table 5. That is, the prediction equations are appropriate to predict the diameter structures with the measurement or prediction of stand attributes.

4. Growth and Yield Models and Carbon Sequestration.

Model (1) was developed with a strong theoretical basis (Clutter, 1963; Clutter et al., 1983) and provides robust volume estimates (Table 3). When adapted to forecast carbon stocks it also increases precision in contrast to the other methods tested. It requires the estimation of only nine parameters and it is somehow independent of stand density. Some disadvantages of this model are that it requires basal area data on a full set of data or forecast this parameter using independent methods when information does not meet all the full range of projections. It is slightly biased and requires empirically derived biomass estimates of crowns (leaf and branches). Leaf and branch volume are difficult to estimate and the conventional procedures of piling branches may result in errors of one order of magnitude (Contreras, 1997).

$$C = (Bf + Bc) \cdot Cf ; Bf = Vf \cdot \rho f ; \rho f = \frac{Bf}{Vf} ; Bc = f(Vf) \qquad [1]$$

$$\ln(Vf) = B_0 + B_1 SI + \frac{B_2}{t} + B_3 \ln(BA) \qquad [2]$$

$$\frac{\partial Vf}{\partial t} = Vf \left[-\frac{B_2}{t^2} + \frac{B_3 \frac{\partial BA}{\partial t}}{BA} \right] \qquad [3]$$

$$\ln(Vf_2) = B_0 + B_1 SI + \frac{B_2}{t_2} + B_3 \left(\frac{t_1}{t_2} \right) * \ln(BA_1) + c\left(1 - \frac{t_1}{t_2} \right) \qquad [4]$$

$$\ln \frac{\partial BA}{\partial t} = \ln(BA_2) = \left(\frac{t_1}{t_2} \right) * \ln(BA_1) + c_1 \left(1 - \frac{t_1}{t_2} \right) \qquad [5]$$

$$SI = H_{max} (1 - EXP(-B_0 t))^a \qquad [6]$$

Model (3) predicts carbon stocks with the highest precision as seen by the goodness of fit statistics (Table 3). It requires only seven parameters and two variables (basal area and site index) to project volume and carbon stocks at the stand scale. This model meets several of the theoretical assumptions of the model (1) of Clutter et al., (1983), although it was empirically derived. The disadvantages of this model are that carbon stock estimates are slightly biased and require reliable basal area projections. This type of model should be further explored by adding more explanatory variables such as mean top height, a wood density parameter, and a carbon factor to provide more physically-based estimates and to use it in forest management planning for carbon sequestration. Mean stand top height was not statistically related to carbon stocks and therefore it was not included into de model. Hence, more information is required to statistically test the significance of the additional variables.

$$\ln(C) = \alpha + B_1 \ln(BA) + B_2 SI + \frac{B_3}{t} \qquad [7]$$

$$BA = SI \cdot \alpha (1 - e(-B_1 t))^{B_2} \qquad [8]$$

Table 3. Goodness of fit statistics of three models to estimate carbon in aboveground standing biomass of forest plantations of Durango, Mexico.

Statistic of Goodness of Fit		Models				Conventional Procedure
		1	2	3	4	5
R^2		0.85	0.56	0.92	0.47	0.57
Sx (Mg C ha^{-1})		6.3	14.7	4.5	13.2	9.9
CV (%)		26	62	19	55	42
Biass (Mg C ha^{-1})	Total	38	-8	-2	125	-130
	Mean	1.6	-0.3	-0.1	5.4	-5.6

CONCLUSIONS

Equations to estimate stem profiles, biomass components and total, the diameter structures, growth and yield, and carbon stock projections in aboveground standing biomass were developed for pine species typical of small-scale forest plantations of the coniferous forests of the western Sierra Madre mountain range of Durango, Mexico. The equations were tested and some of them validated to understand potential sources of variation. Therefore, these equations are recommended for the sustainable management of forest plantations of Durango, Mexico.

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