ARTÍCULO DE INVESTIGACIÓN

Carbon stocks and fluxes in reforestated sites of Durango, Mexico

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ABSTRACT

In this research, we present predictions of carbon sequestration by pines growing in reforested sites of Durango, Mexico. Four methodologies to predict carbon stocks in standing aboveground biomass were tested. Two models at the whole stand scale and two hybrid models between whole stand, stand class, and individual trees were fitted. A chronosequence of 23 small-scale reforested sites and stem analysis conducted on 60 trees were used to fit model parameters and estimate goodness of fit statistics. A stand class model produced a better fit to measure carbon stocks in aboveground standing biomass. Reforested sites with native pine species are sequestering carbon at differential rates partially explained by density, species, micro site, climate and age of pines. Society is benefiting from the environmental services provided by carbon sequestration and conservation of native coniferous forests.

KEY WORDS:
P. cooperii, *P. durangensis*, *P. engelmanii*, Small-scale reforestation sites, Volume and Basal Area Growth & Yield Models, Western Sierra Madre.

RESUMEN

En esta investigación, se presentan las proyecciones de secuestro de carbono por pináceas que crecen en proyectos de reforestación de Durango, México. Cuatro metodologías para proyectar los almacenes de carbono en tiempo en la biomasa aérea fueron probados. Fueron ajustados dos modelos al nivel del rodal y dos modelos híbridos que combinan variables predichas al nivel del rodal, al nivel de clases y al nivel de árboles individuales. La fuente de datos consistió de una cronosecuencia de 23 sitios reforestados y análisis troncales realizados en 60 árboles provenientes de la misma reforestación. Un modelo al nivel del rodal produjo las mejores estimaciones en la biomasa aérea y el carbono almacenado. Del modelo se concluye que la vegetación de los sitios reforestados está secuestrando bióxido de carbono a tasas diferenciales explicadas por la densidad, las especies, el micrositio, el clima y la edad. Sin embargo, en general, la tasa de secuestro es mayor en los sitios reforestados que en los bosques nativos. Por consiguiente la sociedad se está beneficiando por este servicio ambiental que prestan los sitios reforestados.

PALABRAS CLAVE:
P. cooperii, *P. durangensis*, *P. engelmanii*, Sitios reforestados, Modelos de Incremento y Rendimiento en Volumen y Area Basal, Sierra Madre Occidental.

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INTRODUCTION

Afforestation and reforestation practices are being extensively conducted in Mexico by several government initiatives. In the Sierra Madre Occidental mountain range of Durango, Mexico, for the period of 1993-1998, on the average, 2500 ha are planted every year (Semarnap, 1999). Previous to 1992, the annual reforestation rate was between 500-1000 ha. Regardless of this effort to restore plant cover, in northern Mexico there are currently extensive areas with low plant densities that require additional silvicultural treatments to improve stocking. Official reports indicate that there are approximately 4 Mha in the states of Durango and Chihuahua with less than 60 $m^3 ha^{-1}$ of standing volume. In particular the eastern slopes of the Western Sierra Madre mountain range are lacking natural regeneration and stocking is quickly diminishing by human-related disturbances, including grazing practices and forest fires, as well as to subtle climatic changes. Landowners require economic incentives to promote reforestation practices to conserve plant cover through sustainable forest management. The long-term economic and environmental benefits of these forestry activities may speed conservation efforts in the region.

The emerging international greenhouse market and the payment for environmental services provided by the federal government of Mexico may provide economic incentives to fully restore plant cover of the Western Sierra Madre mountain range. The United Nations Framework Convention on Climate Change recognizes the importance of accounting for net carbon flux when it refers to emissions by sources and removals by sinks. The Kyoto Protocol endorses emission offsets by removal of CO_2 via reforestation and afforestation practices. The Clean Development Mechanisms, CDM, envisages the establishment of multilateral mechanism to provide economic incentives by carbon-conservation and sequestration practices such as reforestation and afforestation. However, studies providing estimates of carbon sequestration by reforestation practices are lacking in northern Mexico.

In this study we address the carbon sequestration services provided by reforestation practices carried out in Durango, Mexico by testing several methodologies of estimating carbon stocks and fluxes in aboveground biomass. We contrasted results with the conventional procedure of carbon stock estimation CO2 fix, as well as with the modeled carbon sequestration rate using existing regional growth and yield models for native coniferous forests.

MATERIALS AND METHODS

This research was conducted in reforestation sites of the Sierra Madre Occidental mountain range of Durango, Mexico. Reforestation sites 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 cold-temperate climates with average annual long-term precipitation and temperature of 900 mm and 15 $^{\circ}$C, respectively.

Native coniferous forests of the Western Sierra Madre Mountain range are quite diverse. At the ejido scale forests are a mixture of approximately 41 arboreal species recorded in the last forest inventory (Graciano, 2001; Návar y Contreras, 2000). Therefore, there is a wide range of species adapted for reforestation and afforestation practices. Common native pine species used to restore plant cover include *P. durangensis, P.cooperi, P. teocote, P*., and *P. engelmannii.* Other conifer and broadleaf species found in these forest ecosystems are *P. herrerai, P. lumholtzii, P. oocarpa, P. duglasiana, P. michoacana, P. chihuahuana and P. maximinoi, Juniperus spp, Cupressus spp, Pseudotsuga menziesii, Picea chihuahuana,* and *Abies durangensis, Q. crassifolia, Q. cupreata, Q. mexicana, Q. prinopsis, Arbutus spp, Alnus firnifolia, Fraxinus spp,* and *Populus wislizenii.*

METHODOLOGY

Sample data consisted of selecting a random chronosequence of 23 quadrants reforested with five pine species distributed in five ejidos, La Ciudad, San Pablo, Los Bancos, La Victoria, and La Campana. The age of pines reforested varied from 6 to 21 years. In each quadrant of commonly 20m x 30 m in size, measurements of basal diameter, *Db*, top height, *H,* and canopy cover, *Ct*, were conducted on each standing tree. Age was estimated as the date of the forest plantation plus one year seedlings had at the time of the plantation. Measurements of biomass component and stem analysis were conducted on 55 trees of *P. durangensis* (24), *P. cooperi* (19), and *P. engelmannii* (11). In each forest plantation, at least two trees were selected for biomass measurements and stem analysis. Trees were felled and

separated into biomass component leaf, branch and stem. Biomass components were weighted fresh, and samples of 15 % of each component were collected for ovendry analysis. Stem analysis was conducted on stem cross cuttings taken from the base, 0,5 m, 1,0 m, 1,30 m, 1,5 m, 2,5 m, and every 1,0 m afterwards. Tree inventory of the 23 quadrants, biomass, and stem analysis data provided sufficient information to develop volume, biomass component, diameter, top height, and site index equations. The chronosequence data provided a wide range of individual tree and stand characteristics such as basal area, *BA*, stand density, *N,* stand stem volume, *Vf*, stem biomass, *Bf*, stand total biomas, *St,* total carbon in aboveground standing biomass, *C,* site index, *SI*, stand biomass components, *SBC*, diameter growth, *DG*, and top height growth, *THG*. The characteristics of trees sampled in 23 plots are described in Table 1.

Aboveground stand carbon estimates

Models to project carbon stocks are being developed and reported in the scientific literature. Mohren and Klein Goldewijk (1990) developed and Mohren *et al*., (1999) modified CO_2 fix, a dynamic model intended to quantify the carbon budget at the stand level on an annual basis for multiple rotations. Black (2003) developed Century, a model used to estimate changes in soil *C, NEP*, and forest growth with time. These models require yield tables as input variables, where volume projections multiplied by a wood density factor compute stand biomass. Biomass estimates are then multiplied by a carbon factor to transform dry biomass into carbon density.

Growth models form a continuum from yield tables to single tree models. Volume growth and yield modeling methods are

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widely available in the scientific literature (Clutter *et al*. 1983; Vanclay, 1994, 1995; Peng, 2000). They include whole stand, stand class, and single tree models (Clutter *et al*., 1983; Vanclay, 1995; Peng, 2000). Whole stand models use parameters such as basal area, age, and stocking to predict stand growth or yield. They have been successfully tested in native coniferous forests of the Sierra Madre Occidental mountain range of

Table 1. Characteristics of trees planted in 23 plots in forests of the Western Sierra Madre Mountain Range of Durango, Mexico.

Species	*D*	*H*	*Rcopa*	Age	Stand Density (No	
	(cm)	(m)	(m)	(years)	ha^{-1})	
					T=1	*T=t*
LE1: *P.durangensis*	12,24	8,15	1,0,3	21	6667	4667
LE2: *P. arizonica*	10,60	5,78	1,04	21	6667	4217
LE3: *P. cooperi*	15,52	7,34	1,18	21	6667	1900
LE4: *P. arizonica*	9,55	4,61	-	21	6667	5500
LE5: *P. cooperi*	15,69	9,77	-	21	6667	2450
LE6: *P. cooperi*	15,93	8,63	1,27	21	6667	2882
LE7: *P. durangensis*	14,77	7,23	1,24	21	6667	3138
LE8: *P. durangensis*	14,84	8,91	1,22	21	6667	3090
LE9: *P. cooperi*	10,19	4,81	0,97	21	6667	3100
SA1: *P. durangensis*	16,27	6,06	1,25	17	2500	1867
SA2: *P. durangensis*	20,31	7,20	0,90	17	1111	689
SA3: *P. durangensis*	17,56	6,41	1,45	17	1600	1444
SA4: *P. durangensis*	14,43	6,14	1,94	17	4444	2633
PI1: *P. cooperi B*	14,00	3,63		18	2500	1633
AL1: *P. durangensis*	15,68	7,30	1,09	16	5000	2233
AL2: *P: cooperi*	11,03	5,83	1,65	16	5000	1817
SP1: *P. engelmannii*	11,16	2,87	1,06	10	2500	1617
SP2: *P. cooperi*	8,69	2,66	1,21	10	2500	1867
SP3: *P. durangensis*	8,41	2,81	1,38	10	2500	2133
LB1: *P. engelmannii*	5,61	2,80	0,59	11	10000	3575
LB2: *P. cooperi*	10,55	5,84	1,11	11	10000	4950
LC1: *P. durangensis*	6,32	2,26	1,29	7	2500	1767
LC2: *P. cooperi*	4,97	1,74	1,10	7	2500	1950

D= Diameter at 1,30 m, *H*= top height; *rCopa*= Average crown radius, *t*=time.

northern Mexico (Aguirre-Bravo, 1987; Návar *et al.*, 1996; Zepeda-Bautista and Dominguez-Pereda, 1998). Stand class models simulate growth and yield of tree classes within the stand and individual tree models contain a list of each tree in the stand (Botkin *et al.*, 1972; Moser, 1976; Shugart, 1984; Wykoff, 1986; Vanclay, 1994, 1995; Peng, 2000). None of these three types of growth models have been tested in reforested sites of the Sierra Madre Occidental mountain range of northern Mexico.

Methods. Carbon stock in aboveground biomass was estimated as the result of the multiplication of total stand dry biomass times a carbon factor. The 0,5 carbon factor was used since it has been widely accepted. Biomass equations were developed in seemingly unrelated regression, a regression methodology used estimate parameters of endogenous variables, following the methodology reported by Parresol (1999) and Návar *et al.* (2004a,b). The summation of all individual tree biomass estimates results in total stand biomass. The biomass equations used are reported as equation [1], [2], and [3], for *P. cooperii*, *P. durangensis*, and *P. engelmanii*, respectively. The first set of brackets estimates leaf, the second branch, and the third stem biomass.

The estimation of leaf, bark, and branch volume is also a difficult task. This data is rarely available and when it is included in most volume equations branch volume estimates comprise a large error (Contreras and Návar, 2002). Biomass components are usually strongly correlated (Cunnia and Briggs, 1984, 1985; Parresol, 1999; Návar *et al.*, 2004a,b). Therefore some components can be estimated by measuring other biomass components.

$$bt_{P.c} \quad [(\ 13.9108 \quad 0.0014db^2h \quad 19.6696Ldb \quad 4.9704Lh) \quad (25.42101 \quad 2.58648db$$
$$50.1084Ldb) \quad (\ 0.24462 \quad 0.009397db^2h)] \tag{1}$$

$$bt_{P.d} \quad [(3.3299 \quad 0.7384db \quad 3.6282Ldb^2h) \quad (0.2517 \quad 0.00298db^2h)$$
$$(\ 0.2452 \quad 0.009172db^2h)] \tag{2}$$

$$bt_{P.e} \quad [(10.0098 \quad 1.4498db \quad 9.1305Ldb^2h) \quad (\ 1.7333 \quad 0.007146db^2h)$$
$$(4.2778 \quad 0.6922db \quad 0.01424db^2h)] \tag{3}$$

where *db*=basal diameter (cm), *h*= top height (m), *L*= logarithm of base 10, *bt* = total tree biomass (stem+branch+leaf) (kg tree[-1]), *P.c*, *P.d*., and *P.e.*= *Pinus cooperii*, *Pinus durangensis*, and *Pinus engelmanii*, respectively.

In other studies, biomass is estimated based on equation [4] using a single wood density factor

$$B_w \quad V_w \quad _w \tag{4}$$

where: *Bw*= Total tree biomass, *Vw*= Tree volume, *pw*= tree density.

Measurements of biomass components (stem and crowns) and volume components (stem) were conducted in these plantations. Then, a stem density factor, pf, was empirically obtained by regressing stem biomass, *Bf*, against stem volume, *Vf*. Therefore, *pf* is the slope of this relationship and it is a weighted density estimate of stem bark and stem wood; a combination of cambium and duramen. Crown biomass, *Bc*, is usually not measured. Therefore total biomass projections require the relationship between stem volume, *Bf*, and crown biomass, *Bc*.

Methods to project carbon stocks in aboveground standing biomass

Model (1) is a stand class model because it describes the rate of carbon sequestration in aboveground standing biomass by modeling basal area and stand volume times a biomass and a carbon density factor. Volume growth and yield models are available. The theory behind the basal area and volume growth models is described in Clutter (1963) and Clutter *et al*. (1983).

$$C = (Bf + Bc)Cf; Bf = Vf * f; f = \frac{Bf}{Vf}; Bc = f(Vf) \tag{5}$$

$$\ln(Vf) = B_0 + B_1 SI + \frac{B_2}{t} + B_3 \ln(BA) \tag{6}$$

$$\frac{Vf}{t} = Vf \left(-\frac{B_2}{t^2} + B_3 \frac{\frac{BA}{t}}{BA} \right) \tag{7}$$

$$\ln(Vf_2) = B_0 + B_1 SI + \frac{B_2}{t_2} + B_3 \frac{t_1}{t_2} * \ln(BA_1) + c\left(1 - \frac{t_1}{t_2}\right) \tag{8}$$

$$\ln \frac{BA}{t} = \ln(BA_2) = \frac{t_1}{t_2} * \ln(BA_1) + c_1\left(1 - \frac{t_1}{t_2}\right) \tag{9}$$

$$SI = H_{\max}(1 - EXP(-B_0 t))^a \tag{10}$$

where: *C*= carbon stock in aboveground standing biomass (Mg C ha^{-1}), *Cf*= carbon factor to transform biomass to carbon (dimensionless), *t*= plantation age (years), *Bf*= stand stem biomass (Mg ha^{-1}), *Bc*= stand crown biomass (Mg ha^{-1}), *ρf*= a weighted stem density factor, *BA*= basal area (m^2 ha^{-1}), *Vf*= stand stem volume (m^3 ha^{-1}), *Vf$_2$*,*A$_2$*= projected stand stem volume and basal area at *t*=*t$_2$* (m^3 ha^{-1}; m^3 ha^{-1}), *SI*= Site Index, *H$_{max}$*= dominant top height, *C,a,B$_0$,B$_1$,B$_2$,B$_3$*= statistical parameters. The site index submodel is described as equation [10].

$$C = ((Vf * f) + Bc)Cf; Bc = f(Bf) \tag{11}$$

$$Vf = \sum_{i=1}^{n} Vfi \tag{12}$$

$$Vfi = (Db^{B_1} H^{B_2}) * N \tag{13}$$

$$Db = Dbm(1 - Exp(B_1 t))^{B_2} SI \tag{14}$$

$$H = Hm(1 - Exp(B_1 t))^{B_2} SI \tag{15}$$

$$N_2 = N_1 t^{-B0} e(-B_1 SI)t \tag{16}$$

where: *C*= carbon stock in aboveground standing biomass (Mg C ha^{-1}), *Cf*= carbon factor to transform stand biomass to stand carbon (dimensionless), *t*= plantation age (years), *Bf*= stand stem biomass (Mg ha^{-1}), *Bc*= crown biomass (Mg ha^{-1}), *ρf*= a weighted stem density factor, *Vf*= stand stem volume (m^3 ha^{-1}), *Vfi*= stem volume of tree *i* (m^3), *Db* = basal diameter of tree *i* (cm), *Dbm*= maximum basal diameter (cm), *H* = Top height of tree *i* (m), *Hm* = maximum top height (m), *N₁* = initial stand density at *t*=1 (no ha^{-1}), *N*= stand density at *t*=*t* years (no ha^{-1}), *SI* = site index (m at base age of 15 years), *t*= time, *α*, *B$_o$*, *B$_1$* and *B$_2$*= statistical parameters. Site index was estimated as in model (1), equation [10].

provided the weighted density parameter. In model (2), the basal diameter and top height projection equations required also observed data in the upper right hand side of the figure to increase reliability in estimates. Corral and Návar (2002) provided diameter at breast height, *DbH,* and top height, *H,* data for native forests of the study region (*t*=50 years, *Dbh*=26,5 cm; *H*=20 m).

RESULTS AND DISCUSSION
Model 1

Site index. Top height of dominant trees and age fitted well the Richards-Chapman function (Table 2; Figure 1). The base age considered for these forest plantations was 15 years and the mean curve estimates an average top height of 8 m. By using the

$$\ln(C) \quad B_1 \ln(BA) \quad B_2 SI \quad \frac{B_3}{t} \qquad [17]$$

$$BA \quad SI \quad (1 \quad e(\quad B_1 t))^{B_2} \qquad [18]$$

where: *C*= carbon stocks (Mg C ha^{-1}), *BA*= basal area (m^2 ha^{-1}), *SI*= site index (m), *t*= plantation age (m), *α*, *B$_1$*, *B$_2$*, *B$_3$* = statistical parameters. Site index was estimated as in model (1), equation [9].

The fourth model is also hybrid since it combines whole stand and individual tree variables. The weighted Chapman-Richards function projects individual tree attributes and tree biomass estimates are calculated by equation [1], [2], and [3], respectively.

$$C \quad f(Db, H, Db^2 H, \log(Db), Log(H), Log(Db^2 H) \quad Cf \qquad [19]$$

$$C \quad Bt \quad Cf; Bt \quad \sum_{i \ 1}^{n} Bti \qquad [20]$$

$$Db \quad Dbi \quad (1 \quad e(\quad B_1 t))^{B_2} \qquad [21]$$

$$H \quad Hi \quad (1 \quad e(\quad B_1 t))^{B_2} \qquad [22]$$

where: *Bti*= total tree biomass (stem, bark, branch and leaf) (kg tree^{-1}), *Db*= basal diameter (cm), *H*=top height (m), *log*= logarithm of base 10, *Bt*= total stand aboveground standing biomass (Mg ha^{-1}), *C* = carbon stock (Mg *C* ha^{-1}), *Cf* = carbon factor to transform biomass to carbon (dmless), *Dbi*, *Hi*= current basal diameter and top height of tree *i* (cm, m), *α*, *B$_1$*, *B$_2$*= statistical parameters.

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The second model projects stand volume by using individual tree attributes and models basal diameter and top height in time by using the Chapman-Richards function, weighted by site index. The choice of a diameter and top height growth function provides a final steady growth state. The diameter increment function as defined by Wykoff (1986), Hilt (1983), and Shifley (1987) are not suitable for these plantations since plants of these reforested sites are in the early stages of development and diameter growth and diameter increment are linear functions of current basal diameter or basal area. Even though the model estimates tree basal diameter, top height, and volume of trees in different site indexes, it uses stand attributes as explanatory variables as average volume of all trees, site index, and stand density. Therefore, model (2) is a hybrid class model that combines stand class and whole stand variables.

The third model is similar to the model of Clutter *et al.*, (1983) described in model (1). Model (3) projects carbon stocks in aboveground standing biomass at the whole stand scale, instead of projecting first stem volume as in model (1). The variables that contributed to explain the total carbon deviance were estimated in stepwise procedure in multiple regression and interestingly they were the same as those for the growth volume model of Clutter *et al.*, (1983). The rate of basal area change in time uses an additional variable, site index that requires its projections.

Measured and estimated carbon data in aboveground standing biomass allowed the computation of several goodness of fit statistics. The coefficient of determination (r^2) or total deviance accounted for by the model or equation, the standard error (*Sx*), and the coefficient of variation (*CV*) were estimated across models and equations. When contrasting model performance on carbon stocks, it was assumed that models are independent of each other. Although several models share some equations, a single model is finally required for the management of pines of these reforestation sites to maximize objectives where projections of carbon stocks are the basis for management. The strengths and weakness of each of the methods to project carbon stocks in aboveground biomass are discussed in this paper. Finally one model is recommended to account for baseline projections of carbon stocks in reforested sites of Durango, México.

A sensitivity analysis was conducted on total stand carbon stocks in aboveground standing biomass. The model that predicts carbon stocks with the highest precision was utilized for this purpose. The standard error was added to the model parameters and total carbon stock of all stands was estimated with this new set of parameters. This test indicated what parameters must be estimated with the highest precision to account for most variation in carbon stocks.

Procedure. In model (1), the basal area projection requires data in all range of reforestation age. Because maximum age recorded in these plantations was 21 years, the equation of Clutter *et al.*, (1983) underestimates basal area projections at 50 years (*c*=3,1336). Since this estimate is not likely, the Chapman-Richards function was fitted to the basal area versus time relationship. The Chapman-Richard equation estimated basal area at *t*=40 years. Measured basal area data and this estimate were used to fit the basal area projection model of Clutter *et al.*, (1983). The regression between stand stem volume and stand stem biomass

standard error of the Chapman-Richards equation to predict top height of dominant trees, and rounded to 2 m, a set of site index curves were fitted. Curves estimated site index of 4,0 m, 6,0 m, 8,0 m, 10,0 m, and 12,0 m at a base age of 15 years and they were classified as productivity 5, 4, 3, 2, and 1, respectively. The species *P. cooperii* B. *P. arizonica*, and *P. engelmanii* are observed below the 8,0 m site index curve. These species are not well adapted to several microsite conditions. *P. arizonica* and *P. engelmanii* are native to this forests but the former one distributes further north and west and the second one distributes further west of the reforestation sites. The species *P. durangensis* and *P. cooperii* are not growing well at several places within the ejidos La Ciudad, San Pablo, La Victoria, and La Campana (La Escondida) even though these species are native to these places. Forest plantations of Los Bancos and Alto de Latas are observed above the average curve of site index. These species appear to be well adapted to deep, well drained soils with gentle slopes (Graciano, 2001) and hence sites with steep slopes and shallow soils do not provide the optimum conditions for productivity.

Basal area. The basal area submodel had a c coefficient value of 3,4163, This estimate is smaller than the value of 4,45 estimated by Zepeda-Bautista and Acosta-Mireles (2000) for native forests of *P. montezumae* L. of Puebla, Mexico, by Zepeda-Bautista and Dominguez (1998) for native coniferous forests of northern Mexico, and by Alder (1979) for forest plantations of east Africa. The *c* coefficient value estimated for our reforestation sites attain a maximum basal area of 26 m^2 ha^{-1} at 40 years of age.

Projecting standing volume. The equation that predicts standing stand volume fitted well

observed data (Table 2). The total deviance explained by the equation was 93 % (Sx= 21,3 m^3 ha^{-1} and CV= 20,4 %). Estimated volume increments are three to four times of magnitude the average volume increment reported by Hernandez-Diaz *et al.*, (1992) as well as by a model described by Aguirre-Bravo (1987) for understocked stands with native coniferous forests.

Estimating crown biomass. Stem and crown biomass fit well a linear relationship with a total deviance explained by equation of 0,85 (Sx= 3,3 Mg ha^{-1} and CV= 19 %) (Table 2). The weakness of this equation is that it has an intercept value of 6,29 Mg ha^{-1}. However, other equation did not fit the data well. Crown biomass is on the average 35 % of the total stem biomass. Leaf makes 16 %, branches 30 %, and stems 54 % of the total aboveground standing biomass. In terms of volume, Contreras and Návar (2002) estimated that of the total tree volume 18 % is composed of branches for pine species of native coniferous forests of the study region.

Predicting carbon sequestration in aboveground standing biomass. Model (1) recorded one of the best goodness of fit statistics, with a total deviance explained by the model of 84 % (Table 3). However, model 2 does not completely envelop the observed carbon stock variation. By using this model to project carbon sequestration in stands with average site index, the maximum periodic and maximum mean annual increments would be 2,04 Mg ha^{-1} y^{-1} and 1,50 Mg ha^{-1} y^{-1}, respectively. These figures are attained at plantation ages of 8 and 16 years.

The growth and yield part of Model (1) was developed with a strong theoretical basis (Clutter, 1963; Clutter *et al.*, 1983) and provides robust volume estimates. When

adapted to forecast carbon stocks it also increases precision in contrast to several other methods used. It requires the estimation of only nine parameters and it is somehow independent of stand density. Some disadvantages of this model are that basal area predictions require a full set of data or other forecasting methods when information does not meet the full range of projections.

Model 2

The stem volume equation. Stem volume fitted well the Schumacher and Hall function since the total deviance explained by this equation was 95 % (Sx=0,006 m^3 and CV=20 %) (Table 2). Even though the equation provides reliable volume estimates projections beyond the range of observed tree data appear to be positively biased. Volume equations developed for pine species of the region of study by Contreras (1997) and Corral (1999) are appropriate for trees with higher *Dbh* and *H* dimensions and they are also biased for small trees. The equation is recommended for *Db*h values up to 20 cm and top heights up to 15 m.

The diameter and top height growth function. The basal diameter and top height versus age fit well the Chapman-Richards growth function (Table 2) and envelope all observed basal diameter and top height when weighted by site index. The total deviance explained by the equations were 0,49 and 0,72 (*Sx1*= 2,6 cm, *Sx2*= 1,3 m, *CV1*=33 %, *CV2*=30 %, respectively. basal diameter attains soon a maximum periodic annual increment, in less than 5 years, unlike top height, which takes longer to approach this state. The Chapman-Richards equation predicts a basal diameter of 21 cm and 18,6 m at an age of 50 years for average site index of 8 m. These figures are close to estimates for

native pine species of coniferous forests of Durango, Mexico (Corral, 1999).

The stand stocking function. Stand stocking versus age and site index fit well a nonlinear function (Table 2). The total deviance explained by the model was 71 %, (Sx=702 trees ha^{-1} and CV= 26 %). The model predicts a decaying stand density function with increasing age. The stand stocking by competition-induced regular mortality model proposed by Reineke (1933), Yoda *et al*. (1963), and Lonsdale (1990) did not fit well the number of trees present in stands, since mortality by competition is present at crown closure. Because crown closure happens between 10 to 16 years of reforestation age, before canopy closure tree mortality is a stochastic process. Site index was negatively related to stand mortality and it is likely in high productivity stands, competitive exclusion happens at the earlier stages of growth.

Predicting carbon sequestration in aboveground standing biomass. The cumulative carbon sequestration in time projected by model 2 (Figure 2) recorded one of the worst goodness of fit statistics (Table 3). Although model (2) envelops well the carbon stock variation, it appears to overestimate the rate of carbon sequestration. By using this model to project carbon sequestration in stands with average site index, the maximum periodic and maximum mean annual increments would be 1.82 Mg ha^{-1} y^{-1} and 2,62 Mg C ha^{-1} y^{-1}, respectively. These figures are attained at plantation ages of 24 and 40 years, respectively.

Model 3

Carbon stocks. Carbon stocks were predicted well by basal area, site index and age of reforestation since the model explained 92 % of the total deviance (Sx=4,5 Mg *C* ha^{-1}

and *CV*= 19 %) (Table 2). This equation is quite similar to the growth and yield model of Clutter *et al*., (1983) since it has the same explanatory variables with the same transformations. The goodness of fit statistics of both models are also quite similar. The Chapman-Richards equation weighted by site index to project basal area provided better goodness of fit than the equation of Clutter et el., (1983). The total deviance explained by this new basal area equation was 67 % (*Sx*=6,57 m^2 ha^{-1} and *CV*=39 %) (Table 2).

Projecting carbon sequestration in aboveground standing biomass. The cumulative carbon sequestration in time projected by model 3 (Figure 2c) recorded the best goodness of fit statistics (Table 3). The model 3 envelops well the bottom part of the carbon stock variation and it appears to underestimate the rate of carbon sequestration of three stands. By using this model to project carbon sequestration in stands with average site index, the maximum periodic and maximum mean annual increments would be 2,12 Mg ha^{-1} y^{-1} and 1,67 Mg *C* ha^{-1} y^{-1}, respectively. These figures are attained at plantation ages of 14 and 29 years, respectively. Model (3) predicts carbon stocks with the highest precision as seen by the goodness of fit statistics. It requires only seven parameters and two variables (basal area and site index) to project carbon stocks at the stand scale.

Model 4

The equations to estimate basal diameter and top height increments (Table 2) fit well a linear function, with a total deviance explained by the models of 98 %. The Chapman-Richards equations to estimate basal diameter and top height growth provided reasonable goodness of fit statistics. The total deviance explained

by the basal diameter and top height models are 87 and 93 %, respectively (Table 2).

Projecting carbon sequestration in aboveground standing biomass. The cumulative carbon sequestration projected by model 4 (Figure 2d) appears to be biased and recorded the worst goodness of fit statistics (Table 3). Model (4) envelops well the carbon stock variation and underestimates the rate of carbon sequestration of the young stands planted in high productivity sites. By using this model to project carbon sequestration in stands, the maximum periodic and maximum mean annual increments would be 3,0 Mg ha^{-1} y^{-1} and 2,10 Mg *C* ha^{-1} y^{-1}, respectively. These figures are attained at plantation ages of 25 and 40 years, respectively.

Model (4) is biased and requires the highest number of parameters to be estimated (22), and results in the worst goodness of fit statistics. Biased stand stocking estimates, coupled with biased biomass forecasts in the smallest trees resulted in large carbon stock errors. Small errors in stand stocking projections (*Sx*=702 trees ha^{-1}) result in large carbon stock deviances, as pointed out by Alder and Synnott (1992).

The conventional procedure of estimating carbon stocks

Mean, standard deviation, and confidence intervals of wood density estimates for all pine species were 0,3743 g cm^{-3}, 0,03688 g cm^{-3}, and 0,0024 g cm^{-3}, respectively (n=882 samples). Wood density estimates appear to be slightly underestimated when comparing reported figures. Davalos *et al*. (1977) reported values of 0,39 and 0,46 g cm^{-3} for *P. cooperii* and for *P. durangensis*, respectively. Compean-Guzman (1996) reported wood density figures of 0,43 for *Pinus cooperi*. Estimates of wood

Table 2. Equation parameters to project carbon stocks
in reforested sites of Durango, Mexico.

(Model)/Equation	Goodness of Fit Parameters		
	R^2	Sx	CV(%)
(1)(2) $Bc=6,29+0,35Bf$	0,85	3,30 (Mg ha^{-1})	19
(1)$Ln(Vf)=2,73+0,145SI-16,22/t+0,61\ln(BA)$	0,93	21,3 (m^3 ha^{-1})	20
(1)$Ln(BA2)=65,36(1-e(-0,0398t))^{1,7805}$	0,43	8,67 (m^2 ha^{-1})	52
(1)(2)(3)$SI=11,92(1-e(-0,1065t))^{1,7658}$	0,80	1,80 (m)	20
(2)$\ln(Vfi)=-7,7369+1,2883\ln(D)+0,7134\ln(H)$	0,95	0,006 (m^3)	20
(2)$Db=29,27(1-e(-0,021t))^{0,7597}$	0,49	2,6 (cm)	30
(2)$H=31,07(1-e(-0,0233t))^{1,353}$	0,72	1,33 (m)	33
(2)(4)$N_2=N_1 t^{-1,1484}e(0,676-0,1067SI)t$	0,71	733 (trees ha^{-1})	26
(3)$\ln(C)=1,1517+0,7499\ln(BA)+0,04893SI-7,5304/t$	0,92	4,47 (Mg C ha^{-1})	19
(3)$BA=8,5745SI(1-e(-0,0354t))^{1,7214}$	0,67	6,57 (m^2 ha^{-1})	39
(4)$Dbi+1=0,7237+0,9679Dbi$	0,98	0,32 (cm)	9
(4)$Hi+1=0,7217+0,9686Dbi$	0,98	0,38 (m)	9
(4)$Db=2,1293Db_{20}(1-e(-0,0253t))^{0,8368}$	0,87	1,39 (cm)	16
(4)$H=1,5393H_{20}(1-e(-0,0811t))^{2,0696}$	0,93	0,71 (m)	17

density are higher than the weighted wood density parameter of 0,2691 g cm^{-3}, which resulted from the slope of the regression between stem volume and stem biomass of equation [1]. Therefore, when using the conventional approach, stem biomass or stem carbon estimates will probably be overestimated.

Carbon stock estimates. Using stem volume with bark and wood density measurements as in the CO_2 fix model (Mohren and Klein Goldewijk, 1990), stem carbon stocks would probably be underestimated by 34 %. The wood density parameter, when multiplied to stem volume, overestimates stem tree or stand stem biomass by a factor of 0,3 to 2,0 (Houghton, 1991; Fang et al., 1998). A single wood density parameter does not integrate the internal wood density variation since it does not account for bark or leave density neithr for transient wood density changes with stem height or stem diameter. However, the conventional approach underestimated carbon stocks by 33 %. The explanation must be in the leakage or C losses accounted for by conducting the project. Preliminary volume and biomass measurements of stems indicate that the weighted density factor must be reduced by 28 % in contrast to the conventional wood density factor used by the CO_2 fix model. It is likely that this factor remains more less constant for branches and therefore biomass estimates at the stand scale would be more biased. This is a matter of further study.

Sensitivity analysis. Model (3) was most sensitive to the intercept, the basal area and site index parameters because total carbon stocks deviated by 34, 42, and 33 % when adding the standard error of each parameter

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

Statistic of Goodness of Fit		Models				Conventional CO₂ 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
Bias (Mg C ha^{-1})	Total	38	-8	-2	125	-130
	Mean	1,6	-0,3	-0,1	5,4	-5,6
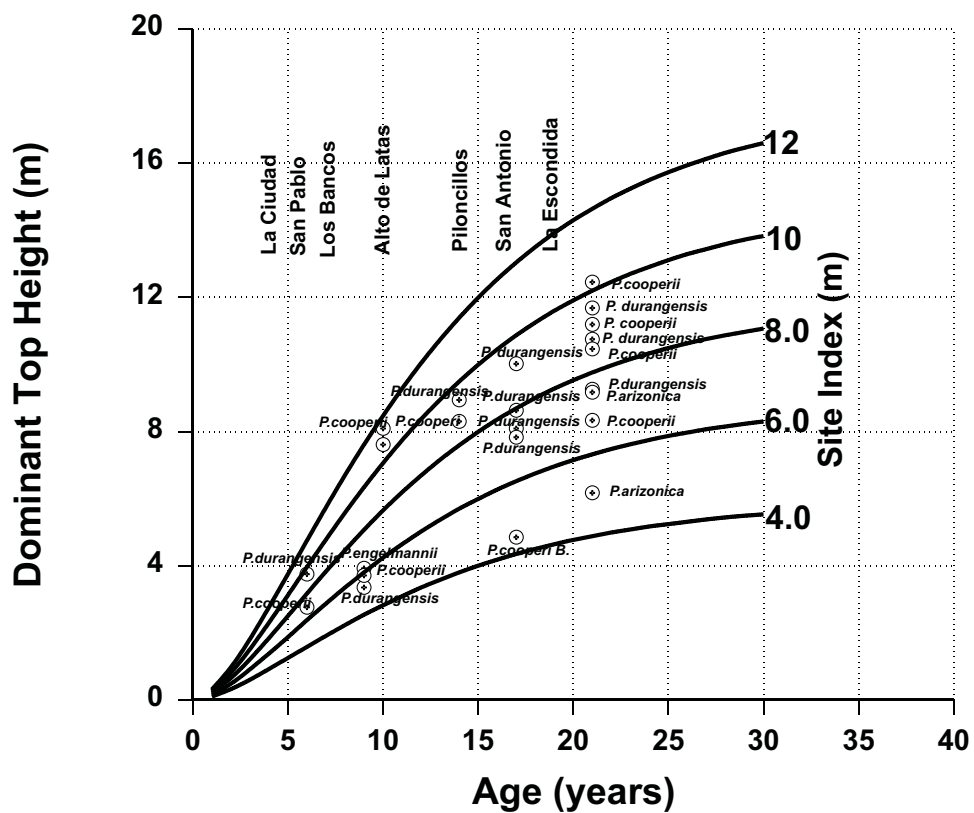
Figure 1. Estimates of site index for 23 reforested sites on seven places located on the uplands of the Sierra Madre Occidental mountain range of Durango, Mexico.

within equation [17]. The standard error of the age parameter reduced total carbon stocks by 11 %. When adding the standard errors to each parameter, total carbon stocks increased 123 % of the observed *C* stocks in all stands. Therefore, the basal area parameter has to be most precisely estimated

since it accounts for most variation in carbon stocks.

DISCUSSION

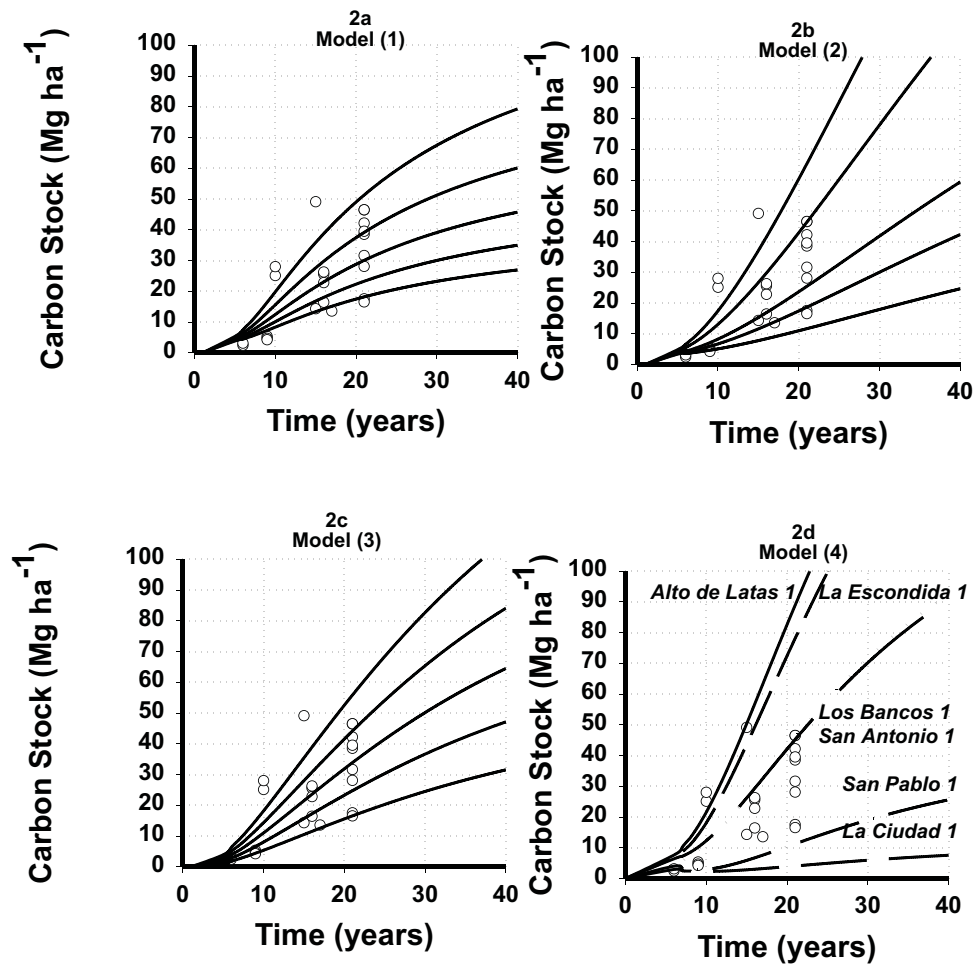Reforested sites provide additional carbon sequestration benefits when

Figure 2. Carbon stock projections by models 1, 2, 3, and 4 for 23 reforested sites on seven places located on the uplands of the Sierra Madre Occidental mountain range of Durango, Mexico.

contrasted to carbon sequestration by native coniferous forests (Table 4). The average current rate of carbon sequestration by native coniferous forests approximated to 0,85 and 0,98 Mg *C* ha^{-1} y^{-1} at *t*=20 and *t*=40 years, respectively. The mean carbon sequestration rate by the reforested sites for average site index of 8 m at 15 years were 1,60 and 1,62 Mg *C* ha^{-1} y^{-1} at *t*=20 and *t*=40 years, respectively. High stand stocking and slightly higher growth rates in reforested sites appear to be the single most important factors to increase the rate of stand volume growth and therefore carbon sequestration in aboveground standing biomass. Average stand stocking at *t*=40 years continue to be high in these reforested sites (1300 trees ha^{-1}), when for native coniferous forests at *t*=40, Návar (Unpublished data) observed 800 trees ha^{-1}. In addition, Návar *et al*., (2001) reported that several forest stands of the western Sierra Madre mountain range are loosing potential productivity since natural regeneration is not being promptly established. Several sources of disturbance are limiting the establishment of quick natural regeneration in forest stands. Currently, most mature forests are also understocked. Návar *et al*., (2002a) reported an average of 694 trees ha^{-1}, with average *db*h of 26 cm for 1500 stands distributed in south central Durango, México. Aguirre-Bravo (1987) reported mean quadratic *db*h estimates of 27 cm for stands of *Pinus cooperii* with age of 40 years.

Several factors explain the sources of variation between observed growth and stocking densities in different communities. Density of plantation is highly variable in different reforested sites, it goes from 625 (4 x 4) to 10 000 (1 x 1) seedlings per ha. In three reforested sites, there was a first thinning during the year 2000, Landscape variations expressed in slope, aspect, topoform (ridge, slope, valley), as well as other factor appeared to play a role in determining seedling mortality and growth and yield.

The Clean Development Mechanism, CDM, of the Kyoto Protocol as well as any carbon fund require that projects should be, by its definition, both financially and environmentally additional. Reforested sites meet the environmental requirements since: (a) native pine species are the choice and the rule for afforestation and reforestation practices, (b) regeneration is quickly ensured in disturbed forests stands, since Návar *et al*., (2001) observed that 5 years are lost before pines fully restore plant cover by natural regeneration, (c) site productivity is regenerated in degraded forest stands. Therefore, reforestation practices promote a real and long-term carbon sequestration benefit in contrast to a potential baseline scenario, which would have not been taken place in the absence of this project. Since most native coniferous forests are mixed, planting diverse native pine species would likely enhance the rate of carbon sequestration and provide additional carbon sequestration benefits as well as other environmental services.

CONCLUSIONS

In this research we tested four models to project carbon stocks in aboveground standing biomass of forest plantations of the Sierra Madre Occidental mountain range of Durango, Mexico. Results were contrasted with projected carbon sequestration by the conventional CO2-fix model as well as to carbon sequestration by native coniferous forests to test the additionallity of reforestation sites in Durango, Mexico. A stand class model provided the highest precision in projecting

Table 4. Comparisons of carbon stock estimates in forest
plantations and native coniferous forests of Durango, Mexico.

Time (years)	Volume Estimates ($m^3 ha^{-1}$)		Carbon Stocks (Mg C ha^{-1})	
	T=20 years	*T*=40 years	*T*=20 years	*T*=40 years
Model (3)			32,0	64,5
Hernandez-Diaz (1992)	50	100	12,2	21,3
Corral (1999)	39	103	10,4	27,7
Aguirre-Bravo (1987)1	72	181	16,2	36,1
Aguirre-Bravo (1987)2	144	379	29,3	71,9

Note: Model (3) is the recommended model for reforestation sites in Durango, Mexico. Hernandez-Diaz (1992) reported mean annual increments of 2,5 $m^3 ha^{-1} y^{-1}$ for native coniferous forests of the UCODEFO No 6, Corral (1999) reported average stem volume for five pine species of the UCODEFO No 6, Stand volume was computed by multiplying average volume growth times density estimates of natural regeneration (Návar, Unpublished Data *Den*=304500$T^{-1,6124}$). Aguirre-Bravo (1987) reported volume estimates for stands before crown canopy closure (1) and full site occupancy (2). Note that the full site occupancy model of Aguirre-Bravo (1987) and model (3) provide consistent estimates of carbon stocks, indicating the importance of stocking on growth and yield as well as on carbon sequestration rates.

Table 5. The carbon balance in aboveground trees of reforested sites of Durango, Mexico.

Time (Years)	Standing Live Trees				Dead Trees		
	Basal Area ($m^2 ha^{-1}$)	*Dbh* (cm)	Stocking (no ha^{-1})	Carbon Stocks (Mg C ha^{-1})	Mortality (no ha^{-1})	Carbon Stocks (Mg C ha^{-1})	Fate of Mortality: Forest Products
0	0,00	0,0	5000	0,00	0	0,00	Soils
5	3,00	3,3	3480	2,36	1520	0,72	Soils
10	8,54	5,8	3213	11,01	1787	3,93	Poles P&P
15	14,91	7,9	3067	21,48	1933	8,30	Poles P&P
20	21,33	9,6	2967	31,86	2033	12,95	Poles P&P
25	27,44	11,0	2892	41,49	2108	17,49	Boxes P&P
30	33,04	12,2	2832	50,15	2168	21,74	Boxes P&P
35	38,07	13,2	2783	57,81	2217	25,64	Boxes P&P
40	42,51	14,1	2740	64,50	2260	29,15	Boxes P&P

carbon stocks and fluxes in aboveground biomass. Reforested sites provide higher carbon sequestration rates than native forests providing society with additional environmental benefits.

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