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Research article

Modelo 3PG para estimar la productividad, almacenamiento de Carbono e Índice de Aridez en plantaciones forestales de *Eucalyptus* L'Hér. en México

3PG model to estimate the productivity, Carbon storage and Aridity Index of *Eucalyptus* L'Hér. forest plantations in Mexico

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Abstract

One of the most efficient ways to mitigate climate change is through the sequestration and storage of carbon through forest plantations, which, in addition to storing it, can generate a change in the soil water balance; therefore, the two parameters, evaluated together, generate valuable information. The objective of this work was to estimate carbon storage and the Aridity Index (evapotranspiration/precipitation) utilizing ecophysiological modeling (3PG model) for eucalyptus plantations in Mexico, and the main factors influencing evapotranspiration and Carbon storage were identified. From a practical point of view, maps were drawn showing the suitability of the land for eucalyptus plantations. The estimated average achievable productivity was 55 m^3 ha^{-1} yr^{-1}, with a variation of 18 to 117 m^3 ha^{-1} yr^{-1}; while, the above-ground Carbon storage was 26 to 288 t ha^{-1} at six years, with an average of 80 t ha^{-1}. Evapotranspiration ranged from 426 to 1 713 mm yr^{-1} (average 1 053 mm yr^{-1}), which resulted in an Aridity Index of 0.61 to 8.87. The main variables controlling productivity, Carbon stock, and the Aridity Index in Mexico are precipitation and latitude. The suitability maps for eucalyptus plantations in Mexico showed areas of high and very high suitability totaling 1.4 million hectares, confirming the country's enormous potential for developing eucalyptus plantations.

Key words: Suitability for plantations, water balance, Mean Annual Increment, process-based modeling, ecophysiological model, productivity.

Resumen

Una de las maneras más eficientes de mitigar el cambio climático es a través del secuestro y almacenamiento de Carbono por medio de plantaciones forestales; las cuales además de almacenarlo, pueden generar un cambio en el balance hídrico del suelo; por lo tanto, los dos parámetros, evaluados de manera conjunta, generan información valiosa. El objetivo del trabajo fue estimar el almacenamiento de Carbono y el Índice de Aridez (evapotranspiración/precipitación) mediante modelaje ecofisiológico (modelo 3PG) para plantaciones de eucalipto en México; se identificaron los principales factores influyentes en la evapotranspiración y en el almacenamiento de Carbono. Desde el punto de vista práctico, se elaboraron mapas con la aptitud de las tierras para plantaciones forestales de eucalipto. La productividad alcanzable promedio estimada fue de 55 m^3 ha^{-1} año^{-1}, con una variación de 18 a 117 m^3 ha^{-1} año^{-1}; mientras que el almacenamiento de Carbono arriba del suelo fue de 26 a 288 t ha^{-1} a los seis años, con un promedio de 80 t ha^{-1}. La evapotranspiración varió entre 426 y 1 713 mm año^{-1} (promedio de 1 053 mm año^{-1}), que resultó en un Índice de Aridez de 0.61 a 8.87. Las principales variables que controlan la productividad, reserva de Carbono y el Índice de Aridez en México son la precipitación y la latitud. Los mapas de aptitud para plantaciones de eucalipto en México mostraron áreas de aptitud alta y muy alta que sumaron 1.4 millones de hectáreas, confirmando el enorme potencial del país para desarrollar plantaciones forestales con eucalipto.

Palabras claves: Aptitud para plantaciones, balance hídrico, Incremento Medio Anual, modelaje basado en procesos, modelo ecofisiológico, productividad.

Introduction

Forests cover 30 % of the earth's land surface, and more than 1.6 billion people depend directly on them for energy generation, food, and production of timber and non-timber forest products (Food and Agriculture Organization of the United Nations [FAO], 2018). In Mexico, the forest area occupies about 66 million hectares and 34 % of the country's area, with about 57 % covered by subtropical forests, and 43 %, by tropical forests (FAO, 2020). Of the 4 billion hectares covered by forests worldwide, about 280 million belong to the so-called forest plantations, whose main objective is to generate forest products, as well as ecosystem services such as carbon sequestration (FAO, 2022).

One of the most current issues related to forestry is climate change, and one of the most efficient ways to mitigate it is through the sequestration and storage of Carbon through sustainable land use (Pörtner et al., 2022). Compared to other crops, forest plantations have the advantage of exhibiting longer cycles, and their products can remain longer on the earth's surface before returning to the atmosphere as Carbon. Campoe et al. (2020) evidenced that the average carbon storage in *Eucalyptus* is 100 t h^{-1} at seven years, signaling an enormous potential independent of the production of timber products.

In Mexico, a study by Guevara-Escobar et al. (2020) recorded a biomass of *Eucalyptus globulus* Labill. of 83 t ha^{-1} after eight years and estimated that 28 % of this biomass would be stored in the roots, which betokens a larger permanence of Carbon stock in the soil.

Many studies have shown the effect of plantations on the change of soil water balance (Hakamada et al., 2020; Whitehead & Beadle, 2004) and the importance of an adequate selection of sites for their establishment based on soil and climate characteristics (Gonçalves et al., 2013; van Dijk & Keenan, 2007). One of the ways to estimate Carbon storage and evapotranspiration in forest plantations is through ecophysiological modeling or process-based modeling, which uses knowledge of various biological processes such as transpiration, photosynthesis, nutrition, Carbon partitioning among plant components to estimate biomass production, and evapotranspiration (Marques et al., 2020; Hakamada et al., 2020).

The 3PG model (Physiological Principles in Predicting Growth) is the most widely used in plantation forestry (Landsberg & Waring, 1997). One of its main uses has been the zoning of areas for cultivated forest species worldwide (Coops & Waring, 2011), such as *Larix* spp. (Xie et al., 2020), *Eucalyptus* spp. (Marques et al., 2020; Palma et al., 2021), and *Pinus* spp. (Coops & Waring, 2011).

In Mexico, the area of forest plantations is 56 thousand hectares and occupies 0.08 % of the territory (FAO, 2020). However, to date, no study has been documented in which the 3PG model is utilized; therefore, in this research, this model was applied to *Eucalyptus* L'Hér. plantations established throughout Mexico, since they are of great commercial interest and are increasing in several regions of the country. The objective was to identify the main factors influencing evapotranspiration and Carbon storage, for the purpose of drawing suitability maps for these plantations according to the productive potential without compromising the water flows of the country's basins.

Materials and Methods

Study area

The study was carried out considering the entire area occupied by Mexico, which corresponds to 1 964 million km^2 and is located between latitudes 14° and 33° N and longitudes -87° and -117° W. The rainfall and temperature data were obtained from the National Aeronautics and Space Administration (NASA), the Langley Research Center (LaRC), and the Prediction of Worldwide Energy Resource (POWER). The study area was divided into grids every 0.5 degrees of longitude and latitude, for 699 grids total; each grid was associated with the center of the polygon, connected to UTM coordinates and 3PG input and output data.

Input data for model 3PG

The 3PG model requires the input of location parameters, climate and soil data, and data of the plantation under study (crown, stem, roots, leaf litter, allometric equations, and age) which in this case is *Eucalyptus* (Marques et al., 2020).

Climate data. Climatological data were obtained from NASA's Project Power (National Aeronautics and Space Administratio [NASA], 2021). The resolution was 0.5°×0.5° for the period 2001 to 2021. The 3PG model uses a monthly period for its estimates. The number of monthly frosts (*Nh*) was estimated according to the methodology applied by Alvares (2011) with Equation 1, where *Tmin* represents the mean monthly minimum temperature (°C).

$$Nh = 21.16 - 1.74 \times Tmin \quad (1)$$

The mean temperature was calculated with the minimum and maximum temperature data and the vapor pressure deficit was calculated according to Allen et al. (1998).

Soil data. The soil database of the National Commission for the Knowledge and Use of Biodiversity (*Comisión Nacional para el Conocimiento y Uso de la Biodiversidad*, *Conabio*), and the *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias* (*INIFAP*), was used (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [Conabio], 2021). Four parameters need to be inserted according to the soil type: the soil moisture ratio deficit ($c\theta$) and the soil moisture ratio deficit power ($n\theta$), obtained from the *INIFAP* database, are fixed parameters (Landsberg & Waring, 1997) and vary with soil texture; the water retention capacity (*WRC*) was determined according to the model proposed by Stape et al. (2004), with Equation 2.

$$WRC\ (mm) = \left(0.1503 - 0.137 \times sand(\%) - 0.0057 \times clay(\%)\right) \times density\left(\frac{kg}{dm^3}\right) \times depth\ (m) \quad (2)$$

The sand and clay contents and depth were drawn from the *INIFAP* database; the densities were estimated based on soil type according to the U. S. Department of Agriculture classification (Baillie, 2001). The soil fertility factor, which varies between 0 and 1, was set at a value equal to 1 (Gonçalves et al., 2017; Nyland et al., 2016).

Plantation data and parameters. A rotation of *Eucalyptus* was evaluated from the first to the sixth year, based on the initial data of trunk, root, and leaf biomass estimated in a previous study by Marques et al. (2020), and a density of 1 212 trees ha^{-1} was used (Roldán, 2013). That study selected the age 6 as the standard for estimating productivity. With climate change, the optimal rotation is likely to change, as it is related to environmental conditions and the productive potential of the sites. Future work can evaluate, through a sensitivity analysis, how age would be affected by changes in temperature and precipitation (Dumollard, 2018; O'Donoghue et al., 2024). Table 1 shows the parameters of the *Eucalyptus* plantation with the source from which they were drawn, as well as the fine-tuned parameters for the present research.

Table 1. Parameters common to all points used in the 3PG model according to Marques's parameterization (2020).

Parameter	Symbol	Value	Unit	Source
Net/gross primary productivity ratio	PN/PG	0.50	-	Landsberg & Waring (1997)
Basic wood density	W_D	440	Kg m^{-3}	Marques et al. (2020)
Maximum stem biomass for 1 000 stems ha	B_{LX} 1 000	300	Kg árv^{-1}	Landsberg & Waring (1997)
Quantum canopy efficiency		0.05	mol C mol PAR^{-1}	Ajustado
Maximum canopy conductance	g_{Cx}	0.0072	ms^{-1}	Marques et al. (2020)
Maximum stomatal conductance	g_{Sx}	0.0182	ms^{-1}	
Response coefficient of stoma to *DPV*	k_g	0.5	1 kPa^{-1}	Sands &

				Landsberg (2002)
Canopy conductance boundary layer	g_B	0.2	ms^{-1}	Marques et al. (2020) L3
Husk fraction: branch for initial age	F_{bb0}	0.35	-	
Husk fraction: branch for mature age	F_{bbm}	0.15	-	
Age at which the husk: branch fraction has a medium value	fbb_{med_age}	2	Year	
Specific leaf area at initial age	AFE_0	9.4	$m^2\ kg^{-1}$	
Specific leaf area at maturity	AFE_m	8.4	$m^2\ kg^{-1}$	
Age at which the specific leaf area has a medium value	*tAFE*	2	Year	
Light extinction coefficient	*K*	0.5	Year	Sands & Landsberg (2002)
Age of the canopy closure	*Tfullcan*	2	Year	Sands & Landsberg (2002)
Intercepted/evaporated rainfall ratio	*Cpir*	0.26	-	Hakamada et al. (2020)
Canopy albedo	*A*	0.2	-	Stape, (2002)
Maximum litter rate	Υ_{Fx}	0.13	1 $month^{-1}$	Marques et al. (2020)
Litter rate at the initial rate	Υ_{F0}	0.06	1 $month^{-1}$	
Litter rate at the medium age	$t_{\Upsilon F}$	4	Month	
Monthly root renewal rate	Υ_R	0.015	1 $month^{-1}$	Sands & Landsberg (2002)
Maximum *PPL* fraction for roots	n_{Rx}	0.23	-	Marques et al. (2020)
Minimum *PPL* fraction for roots	n_{Rn}	0.06	-	
Partitioning of leaves and stems *DBH*=2	pFS_2	0.5	-	
Partitioning of leaves and stems *DBH*=20	pFS_{20}	0.15	-	
Ligneous mass ratio	a_S	0.025	-	
Ligneous mass power	n_S	3.02	-	
Available water capacity	*Sxaw*	31-145	mm	Calculado para cada sitio
Texture coefficient for the soil water modifier	*sk1w*	0.5	mm	Sands & Landsberg (2002)
Power coefficient for the soil water modifier	*sk2w*	5.5	mm	
Value of m when *RF*=0		0	-	

Value of f_N when RF=0		0.4	-	
Maximum temperature for growth	*Tmax*	37.38	ºC	Queiroz et al. (2020)
Optimum temperature for growth	*Tmin*	23.95	ºC	
Minimum temperature for growth	*Topt*	7.25	ºC	

Inventory data to calibrate the model

Three 250 m^2 inventory plots were measured in a 10 ha field cultivated at 3×3 m spacing. The area was prepared with subsoil plow (Rigel®, 7 teeth series), plants aged approximately 60 days were planted, and weeds were controlled for almost 2.5 years. For fertilization, triple superphosphate (Agrocolmex®, Mexico) was applied at a rate of 1.1 t ha^{-1} plus 0.2 t ha^{-1} at six months. The diameter at breast height (1.3 m) was measured with a model D1 Meter Group® dendrometer tape, and the height with a model Forestry Pro II Nikon® hypsometer. The volume equation utilized was the one generated for *Eucalyptus* spp. by Scolforo et al. (2019).

Data processing, output variables, and map production

The r3PG was used to process the data (Trotsiuk et al., 2020), and certain statements were included in the script to carry out the automatic processing of all the points. The r3PG generates 149 output variables; in this study, only evapotranspiration, total volume, and total aboveground biomass were used. As a risk measure for the excessive use of water in the basin due to the implementation of forestry plantations (Ferraz et al., 2019), the Aridity Index, Carbon storage (t ha^{-1}), and the Mean Annual Increment (m^3 ha^{-1} year^{-1}) were estimated.

Maps of Mean Annual Increment (*MAI*), Carbon storage, evapotranspiration, Aridity Index, and, finally, the suitability for *Eucalyptus* plantations were elaborated. In order to determine the suitability, divided into four categories (Low, Medium, High, Very High), four classes of Carbon storage (<90, 90-100, 100-110, >110 t C ha^{-1}), and four classes of Aridity Index (<0.76, 0.76-1.00, 1.00-1.25, >1.25) were utilized to represent the productive potential of the site. The Carbon storage classes were determined with parsimony, considering 37 m^3 ha^{-1} year^{-1} as the maximum value for *MAI*, and 30 m^3 ha^{-1} year^{-1} as the minimum value, with two intermediate values. Once the grid of points for each variable was plotted, interpolation was applied to obtain rasters estimating each variable for the entire study area. The tool used was the TIN Interpolation (Hakamada et al., 2020), with a linear method and a pixel size of 0.01.

Relationship between Carbon storage and the Aridity Index and edaphoclimatic variables

Carbon storage and Aridity Index results were correlated through Pearson's correlation with all 3PG soil and climate input variables, as well as evapotranspiration. The most significant variables were utilized to generate equations that have Carbon storage and Aridity Index as response variables. The best-fit equations were chosen based on the lowest Akaike Information Criterion (*AIC*) corrected for small sample sizes using CurveExpert 2.6 (Hyams, 2010). Figures were generated in R software version 3.6.3 (R Core Team, 2021).

Results and Discussion

Productivity and Carbon storage

The estimate of achievable productivity was 55 m^3 ha^{-1} yr^{-1}, with a variation of 18 to 117 m^3 ha^{-1} yr^{-1} (Figure 1), which is higher than the productivity recorded for other countries with larger areas of tropical *Eucalyptus* species plantations, such as Brazil (38 m^3 ha^{-1} yr^{-1}), Indonesia (28 m^3 ha^{-1} yr^{-1}) or Vietnam (25 m^3 ha^{-1} yr^{-1}) (Indústria Brasileira de Ávores [IBÁ], 2020).

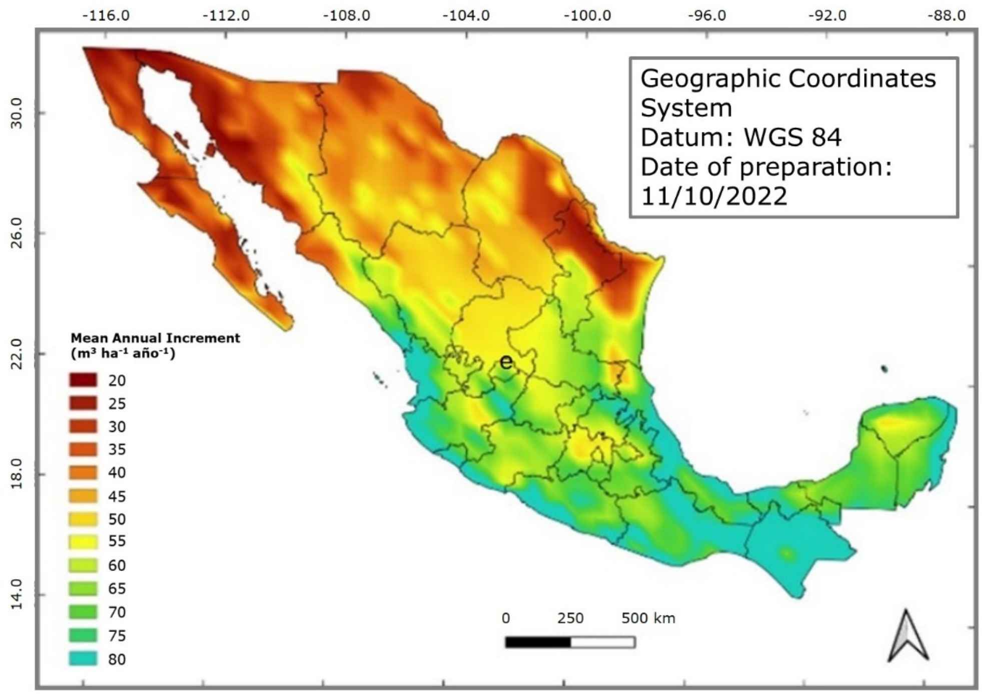


Figure 1. Theme map calculated using the 3PG ecophysiological model on achievable productivity in Mean Annual Increment (m^3 ha^{-1} yr^{-1}).

A shortcoming of the 3PG model is that trees do not die when there is a water deficit and it still continues to estimate productivity based on incoming radiation (Sands & Landsberg, 2002). Mexico has a large area of desert and semi-arid climate according to Köppen's climate types (BWh, BWk, BSk, and BSh) covering all or part of the states of *Baja California*, *Baja California Sur*, *Sonora*, *Chihuahua*, *Coahuila*, *Nuevo León*, *Durango*, *Zacatecas*, *Tamaulipas* and *San Luis Potosí*. In these states, the 3PG still estimates an achievable productivity of 20 to 40 m^3 ha^{-1} yr^{-1}, which can be considered an error for the climate conditions (rainfall<500 mm yr^{-1}). However, the study by Binkley (2021) indicated that the productivity of genetic materials rated as "elite" tends to zero when the rainfall is less than 800 mm yr^{-1}. In China, it has been reported that the ideal rainfall for commercial *Eucalyptus* plantations is between 1 400 and 1 600 mm yr^{-1} with a temperature of 19 to 21 °C, and they do not tolerate annual rainfall below 600 mm yr^{-1} (Zhang & Wang, 2021).

As for Carbon storage (Figure 2), it varies from 26 to 289 t ha^{-1} at 6 years, with an average of 80 t C ha^{-1}. In the storage, not only the biomass of the stem is considered, but also the whole aerial part and the roots. The huge 11-fold interval between the minimum and maximum values evidences the climatic diversity of Mexico, as well as the significant influence of climate on the use of plantations for Carbon storage. No differences were obtained between the inventory measurements and the 3PG model estimates for the Mean Annual Increment; the former had a Mean Annual Increment of 33.3 m^3 ha^{-1} yr^{-1} at the age of 30 months, while the estimate using the 3PG model was 30.2 m^3 ha^{-1} yr^{-1}; that is a difference of 9 %. This result shows that the calibration was reasonable and can represent tropical *Eucalyptus* plantations (Lemos et al., 2018; Marques et al., 2020).

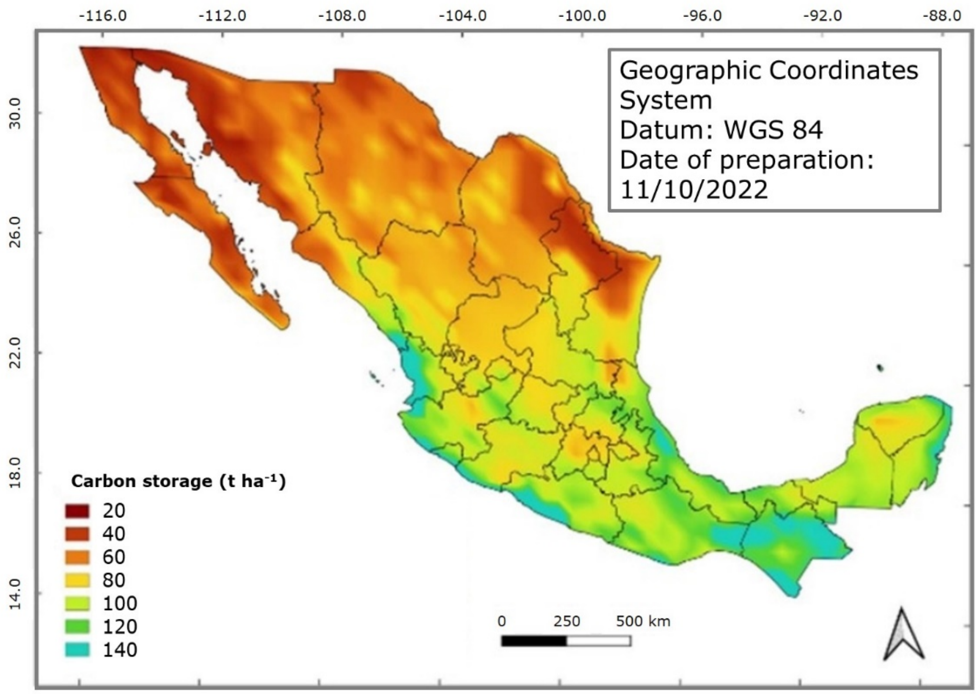
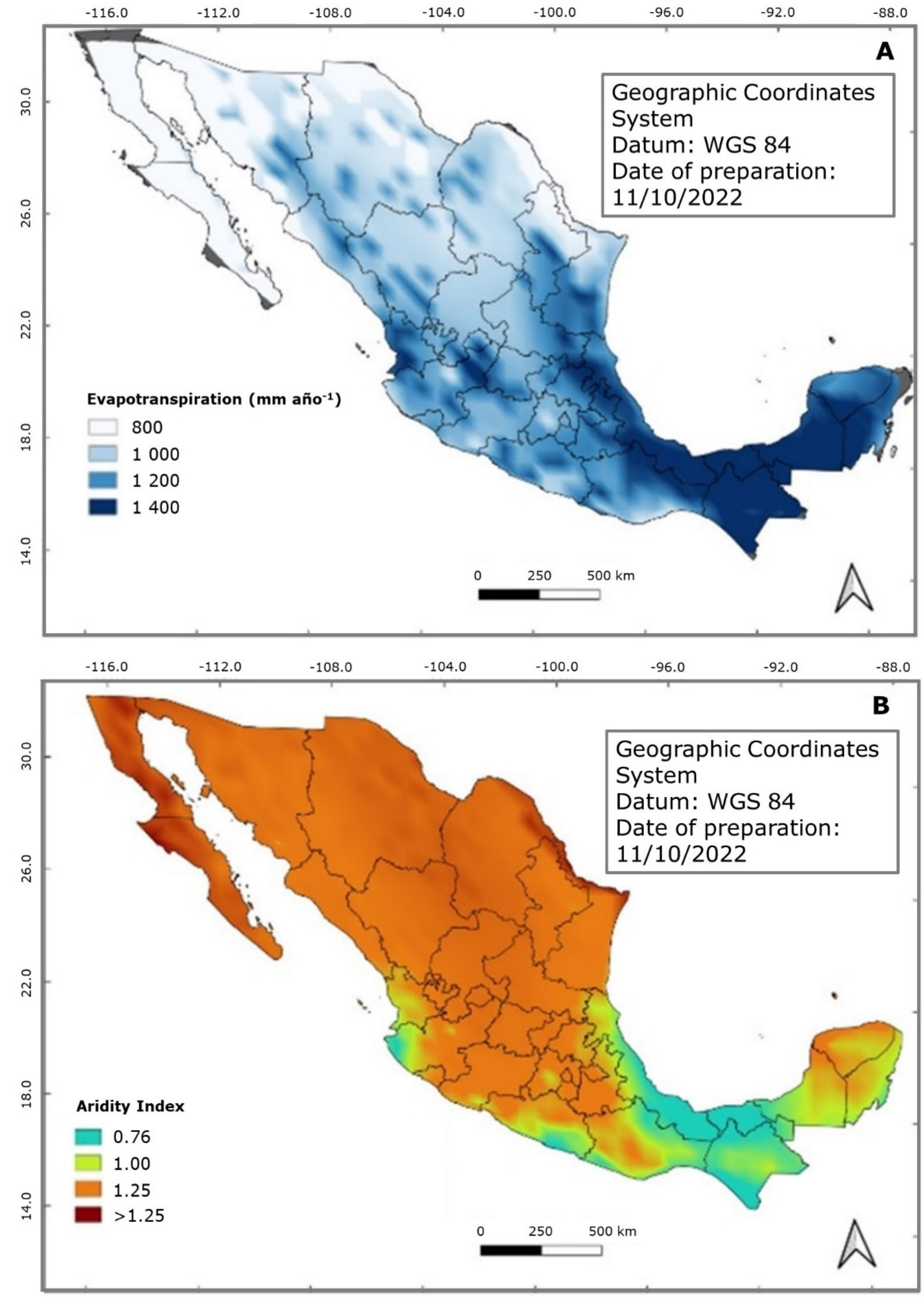


Figure 2. Theme map calculated using the 3PG ecophysiological model for *Eucalyptus* L'Hér. Carbon storage in Mexico.

Evapotranspiration and Aridity Index

The evapotranspiration was estimated based on the precipitation data for Mexico during the period 2000-2021 period (77 to 2 423 mm yr^{-1}); these results exhibit a variation of 425 to 1 713 mm yr^{-1} (Figure 3A), generating an Aridity Index between 0.61, in the state of *Oaxaca*, and 8.87, in *Baja California Sur* (Figure 3B).



A = Evapotranspiration; B = Aridity Index.

Figure 3. Estimates with the 3PG ecophysiological model for *Eucalyptus* spp. in a 6-year rotation.

Aridity Index (*AI*) values equal to or less than 0.76 represent areas where there is no risk of water availability for other users in the basins (Figure 3B). In areas with values above 0.76, the water yield in the basin may amount to less than 10 % of the precipitation (Ferraz et al., 2019). Only 3 % of the country in this analysis has an *AI* equal to or lower than 0.76, concentrated mainly in the states of *Oaxaca*, *Chiapas*, *Veracruz* and *Tabasco*, as well as on the coast (Pacific Ocean) of the state of *Jalisco*, the border of the state of *Campeche* with the state of *Tabasco*, and the South of the state of *Quintana Roo*.

Relationship between response variables and environmental variables

As shown in Figure 4, the three main factors influencing productivity are precipitation, latitude, and the Aridity Index; these indirectly represent the potential for water stress. Figure 5 shows the Pearson correlation between the environmental variables with focus on Carbon and the Aridity Index.

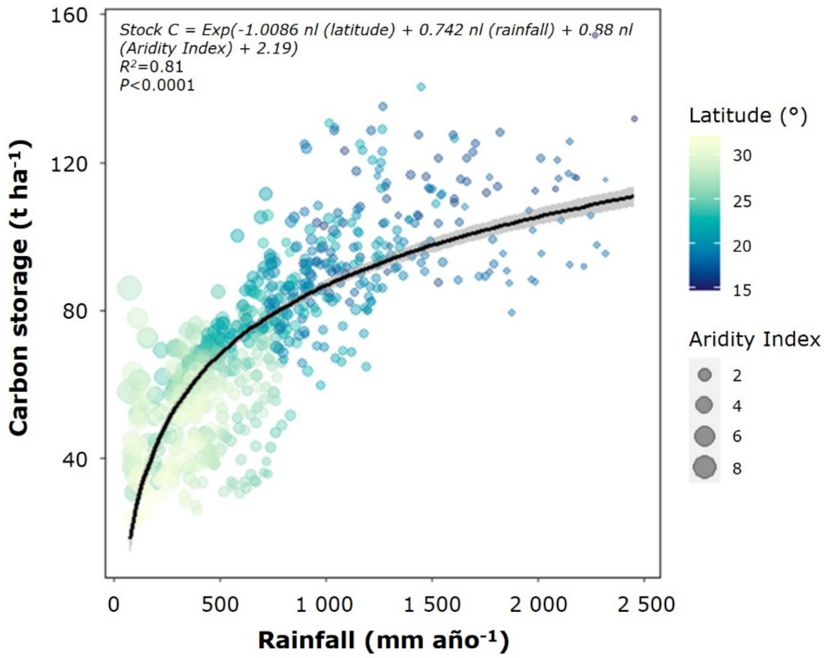
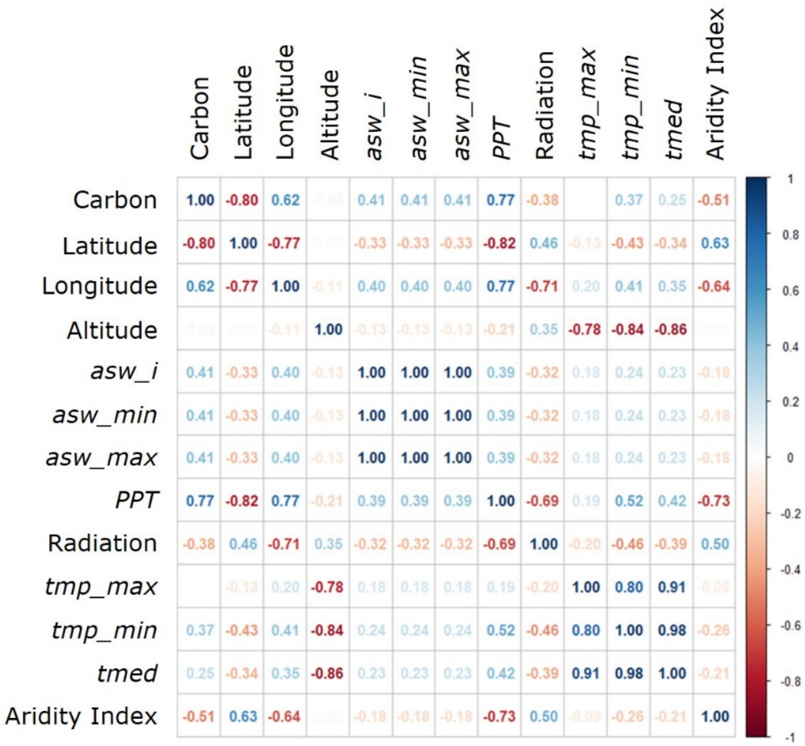


Figure 4. Relationship between the Mean Annual Increment (m^3 ha^{-1} yr^{-1}) and the precipitation with a stabilization at approximately 1 600 mm of annual rainfall.



Deep blue: Represents a high positive correlation (values close to +1); Deep red: Represents a high negative correlation (values close to -1); White or soft colors: Represent low correlations or close to 0; *asw_i* = Water available in the initial soil; *asw_min* = Minimum soil water available; *asw_max* = Maximum soil water available; *PPT* = Precipitation; *tpm*_mx = Maximum monthly average temperature; *tpm_mim* = Minimum monthly average temperature; *tmed* = Average temperatura.

Figure 5. Pearson correlation between environmental variables with a focus on Carbon and Aridity Index.

In several studies, precipitation has been the main variable influencing the productivity of *Eucalyptus*, in which, for every 100 mm of rainfall, there is a Mean Annual Increment increase of 3.0-4.6 m^3 ha^{-1} $year^{-1}$ (Binkley, 2021; Stape et al., 2004).

The Aridity Index was closely related to precipitation and latitude (Figure 6). In Mexico, the precipitation increases with the latitude, a fact that can be interpreted as a collinearity. However, there are areas with a higher latitude, *i. e.*, more distant from the equator, but with more rainfall than in areas with lower latitude, as was the case in certain parts of the states of *Jalisco*, *Nayarit*, *Veracruz*, *Hidalgo*, *San Luis Potosí* and *Tamaulipas* (NASA, 2021).

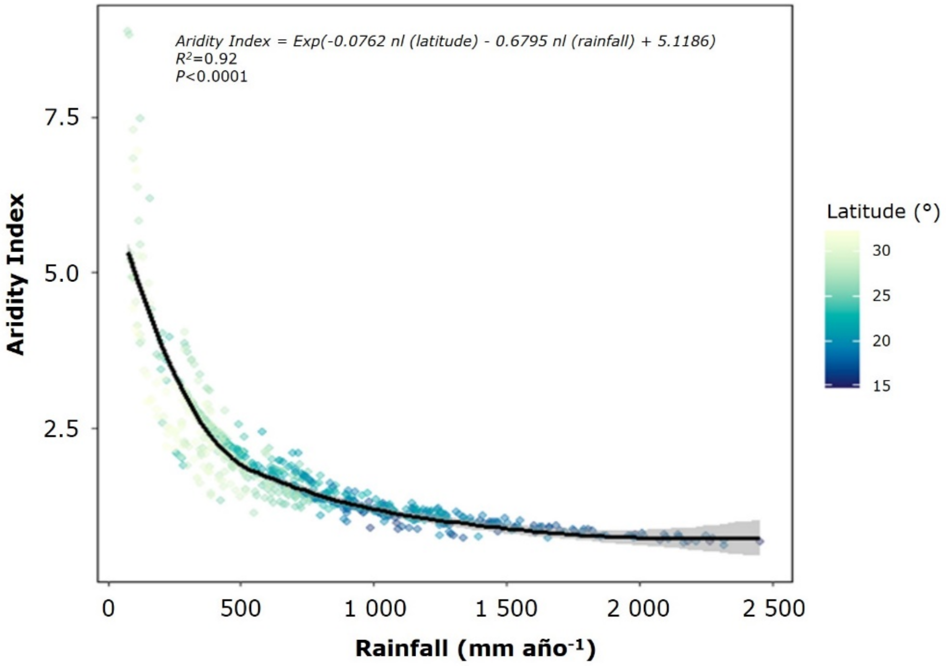


Figure 6. The Aridity Index in Mexico is closely related to the precipitation and latitude according to 3PG evapotranspiration estimates.

The map of areas suitable for *Eucalyptus* plantations based on their productivity and Aridity Index (Figure 7) differed slightly from the map published by the National Forest Commission (Comisión Nacional Forestal [Conafor], 2022), in which most of the state of *Veracruz* is shown to be suitable for plantations. When the water factor is included, there is a limitation towards the West of the state, as the Aridity Index is higher than 1, which implies risks from the water point of view. Coincidentally, in this study, the states with the largest area of forest plantations were those with high and very high suitability. Currently, the states with the largest planted area are *Tabasco*, *Veracruz* and *Campeche*, which represent 49 % of the total planted area (Monreal, 2022).

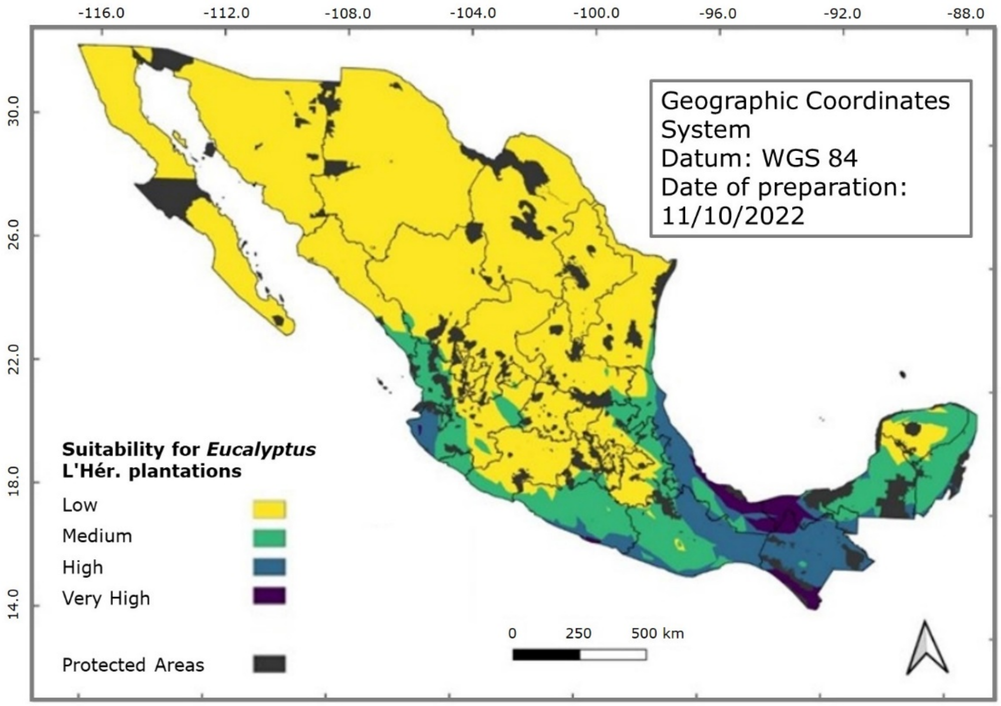


Figure 7. Suitability for *Eucalyptus* L'Hér. plantations for Mexico based on their productive potential plus their Aridity Index, which reflects a sustainable water use.

As Figure 7 shows, the total area rated as of very high suitability outside protected areas was 400 thousand hectares, and that of high suitability areas was 1 million hectares, evidencing the enormous potential of the country for the growth of eucalyptus plantations. It should be noted that the country imports approximately 70 % of its forest-based products (Conafor, 2023), and only 15 % of forest products come from plantations.

Conclusions

The main variables controlling the productivity, Carbon storage, and Aridity Index (evapotranspiration/precipitation) in Mexico are precipitation and latitude. Areas with high and very high suitability for *Eucalyptus* plantations, considering the productive potential, as well as a low risk related to the modification of the water balance (Aridity Index<0.76), add up to 1.4 million hectares, which confirms the enormous potential of the country to develop *Eucalyptus* plantations.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Rodrigo Hakamada, Jesús Prados Coronado and Omar Carrero: study design, data registry, interpretation of the results, and drafting of the manuscript; Cassiano José Lages Marinho Falcão and Belkis Sulbarán-Rangel: data review and analysis, research consultancy, and drafting of the manuscript.

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