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Article

Crecimiento de procedencias de *Pinus greggii* Engelm. ex Parl. en suelos degradados de la Mixteca Alta, Oaxaca

Growth of *Pinus greggii* Engelm. ex Parl. provenances on degraded soils of the *Mixteca Alta, Oaxaca* State

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Resumen

El crecimiento de los pinos en suelos erosionados es limitado, por la existencia de poca materia orgánica. Conocer el crecimiento de diferentes procedencias de una especie en suelos degradados permite entender su adaptabilidad, lo que favorece la toma de decisiones en reforestaciones posteriores. El objetivo del presente trabajo fue conocer el crecimiento de 13 procedencias de *Pinus greggii* var. *greggii* y *Pinus greggii* var*. australis* establecidas en suelos erosionados de dos localidades de la Mixteca Alta de Oaxaca. Se midió la altura, diámetro normal, diámetro basal y diámetro de copa en tres árboles centrales por cada unidad experimental de 3 × 3; se utilizó un diseño de 12 boques completos al azar. Se realizó un ANOVA y prueba de *Tukey* con un nivel de confianza de 95 % para la comparación de medias. Después de 17 años de la plantación, la supervivencia fue de 89 %. El mayor crecimiento promedio se registró en *P. greggii* var. *australis*, con una altura de 10.99 m en la procedencia El Madroño, Qro.; y en la de El Piñón, Hgo., con mayor crecimiento promedio de diámetro basal (20.33 cm), diámetro normal de 15.88 cm, diámetro de copa con 4.52 m y área de copa con 17.81 m^2 árbol^{-1}. Los resultados indican la existencia de un efecto de interacción del crecimiento de procedencias en cada localidad. Las procedencias de la variedad *australis* son las más apropiadas para las reforestaciones de suelos erosionados de Oaxaca.

Palabras clave*:* Erosión, Mixteca alta, *Pinus gregii var australis* Donahue & López*, Pinus greggii* var. *greggii* Engelm.*,* plantación, reforestación.

Abstract

The growth of pines in eroded soils is limited by low organic matter. Knowing the growth of different origins of a species in degraded soils allows understanding its adaptability, and thus, favoring decision-making in subsequent reforestation. The aim of this work was to know the growth of 13 provenances of *Pinus greggii* var. *greggii* and *Pinus greggii* var. *australis* established on eroded soils of two localities of *Mixteca Alta* of *Oaxaca*. Height, normal diameter, basimetric diameter, and crown diameter were measured in 3 central trees for each experimental unit of 3 × 3 and 12 complete blocks at random. An ANOVA and Tukey's test were performed with a confidence level of 95 % for the comparison of means. After 17 years of plantation, survival was 89 %. The greater average growth was in var. *australis* with a height of 10.99 m in the provenance *El Madroño, Qro*. and in *El Piñón, Hgo*., with a greater average growth of basimetric diameter with 20.33 cm, normal diameter with 15.88 cm, crown diameter with 4.52 m and crown area with 17.81 m^2 tree^{-1}. Results indicate the existence of an interaction effect of provenance growth in each locality. The provenances of var. *australis* indicate to be the most appropriate in reforestation of eroded soils in *Oaxaca*.

Key words: Erosion, *Mixteca Alta*, *Pinus gregii var australis* Donahue & López*, Pinus greggii* var. *greggii* Engelm.*,* plantation, reforestation.

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Introduction

Conifers are dominant vegetation components in Mexico, but their distribution is affected by soil erosion (Cardoza *et al.,* 2007; Gernandt and Pérez, 2014). The loss of large amounts of soils due to water, wind and anthropogenic erosion accelerates the process by reducing the soil's potential for plant development (Contreras-Hinojosa *et al.,* 2003; Guerrero *et al*., 2010).

In order to reduce erosion, provenance trials are conducted to identify species that adapt to the conditions of eroded soils. The tests evaluate growth and adaptation of the plants according to the geographic regions and the variation in growth between stands and between individuals (Zitácuaro and Aparicio, 2004; White *et al.,* 2007). In the same way, they are used to preserve biologically and economically sustainable genes (Chhin *et al*., 2018).

In the tree growth process during the test, the interaction between the environmental conditions in which the essay is established and the genotype define the phenotype with characteristics of the heritable component and the environment where the tree grows (Climent *et al*., 2002; White *et al*., 2007). Environmental conditions have an influence on the increase in tissues due to cell division, elongation and thickening of meristems, as well as on the genotypic characteristics of the tree (Klepac, 1983; Gadow *et al*., 2007; Imaña and Encinas, 2008).

In eroded soils, tests are carried out with *Pinus* sp. due to their structural and functional adaptation, and because where they are established, the economy of water and its potential to improve the soil are optimized, in addition to being affordable and easy to manage in the nursery (Alía *et al.,* 1999; López *et al*., 2004). One of the species with these attributes is *Pinus greggii* Engelm ex Parl. (Gómez *et al.,* 2012), and knowing the growth of the provenances of older specimens allows evaluating their variation as a function of time (López *et al*., 2004). In addition, compared to *P. oaxacana* Mirov, a native species from the same region where this work was carried out (López *et al*., 2017), it contributes a greater amount of litter to the soil, which suggests its potential to develop plantations in degraded soils.

In the *Mixteca Alta* region of the state of *Oaxaca, Pinus greggii* is used for reforestation in eroded areas. However, the species is naturally distributed in the *Sierra Madre Oriental*, in the states of *Coahuila, Nuevo León, San Luis Potosí, Hidalgo, Veracruz* and *Puebla* (Perry, 1991). The objective of the present work was to analyze the growth of 13 provenances of *P. greggii* established in two places of the *Mixteca Alta* of *Oaxaca* to know their response according to the growth in height, basal diameter, normal diameter, crown diameter and crown area.

Materials and Methods

Study area

The work was carried out in two plots located in the aforementioned *Mixteca Alta* region: in *Magdalena Zahuatlán locality* and in *Tlacotepec Plumas.*

The *Tlacotepec Plumas* lot is located between 17°52'11.02'' N and 97°26'16.97'' W at 2 143 masl. There, the climate is temperate semi-dry, with an average annual temperature of 16 °C, average rainfall of 420.8 to 650 mm; soils have 7.66 pH, 2.80 % organic matter content, 16.50 mg kg^{-1} phosphorus and 0.16 % nitrogen (Sedesol-CIBCEC, 2003).

The *Magdalena Zahuatlán* lot is located at 17°24'14.97'' N and 97°12'32.22'' W, with 2 166 meters above sea level. The climate in the place is temperate semi-dry, with an annual average temperature of 15 °C, average rainfall of 650; soils have 8.12 pH, 2.68 % organic matter content, 13.1 mg kg^{-1}-phosphorus and 0.08 % nitrogen (Valencia *et al.,* 2006; INEGI, 2010, Velasco *et al*., 2012).

Experimental material

With the plan of the plantation provided by the INIFAP-*Valles Centrales de Oaxaca* Experimental Field, the distribution of the provenances within the plot was specified. The plantations were established in 1997 with 13 provenances of *P. greggii*, of which six grow naturally in northern Mexico (*P. greggii* var. *greggii* Engelm.) and seven in central Mexico (*P. greggii* var. *australis* Donahue & López) (Table 1).

Table 1. Environmental characteristics of the *Pinus greggii* Engelm.assessed provenances.

Provenance	North Latitude	West Longitude	Altitude (masl)	T (°C)	Pp (mm)	Soil pH
1. *Puerto Los conejos, Coahuila*[g]	25°28′	100°34′	2 450	16	600	6.0
2. *Santa Anita, Coahuila*[g]	25°27′	100°34′	2 500	16	600	6.8
3. *Puerto San Juan, Coahuila*[g]	25°25′	100°33′	2 650	16	600	6.1
4. *Los Lirios, Coahuila*[g]	25°23′	100°34′	2 400	16	600	7.4
5. *Jamé, Coahuila*[g]	25°21′	100°36′	2 450	16	600	7.2
6. *Galeana, Nuevo León*[g]	24°56′	100°10′	2 100	15	650	7.1
7. *El Madroño, Querétaro*[a]	21°16′	99°10′	1 650	17	737	4.5
8. *Tres Lagunas, Querétaro*[a]	21°20′	90°08′	-	17	722.8	-
9. *El Piñón, Hidalgo*[a]	20°56′	99°12′	1 830	17	700	6.2
Con una antigüedad de 10. Laguna Atezca, Hidalgo[a]	20°49′	98°46′	1 330	20	1 438	4.5
11. *Molango, Hidalgo*[a]	20°48′	98°46′	1 200	17	1 750	4.4
12. *Xichicoatlán, Hidalgo*[a]	20°47′	98°40′	1 700	17	1 625	4.5
13. *Zimapan, Hidalgo*[a]	20°46′	99°23′	1 850	17	1 100	6.0

masl = Meters above sea level; T = Temperature; °C = Degrees centigrade; Pp = Mean annual rainfall; mm = Milimeters; [g] = *Pinus greggii* var. *greggii*; [a] = *Pinus greggii* var. *australis*.

The plantation was carried out in a common strain system of 40 × 40 × 40 cm in a staggered arrangement at a distance of 3 m, with an experimental design of complete random blocks with 12 blocks (replications) and nine plants per experimental unit (3 × 3), which gave a total of 1 404 trees per location.

Measurement of growth parameters

The study plantations are 17 years old. The three central trees of the experimental unit were selected, considering that they showed lower competition effects with trees from other sources. The height of each one was measured with a Haga altimeter, the normal diameter at 1.30 m from the ground and the basal diameter at 10 cm from the ground with a Forestry Suppliers Model 283D/5M diameter tape, and the crown diameter with two measurements, one in the north-south direction and another in an east-west direction with a Spencer Logger's Model 975DC tape. A total number of 36 trees were measured by provenance in each location, with a total of 468 trees per location. A dead tree or a stump without a tree was recorded, with which survival was calculated. From the crown diameter, the crown area was calculated for each individual.

Data analysis

An analysis of variance was performed by using a randomized complete block model to compare the means of height, normal diameter, basal diameter, crown diameter and crown area between provenances and localities. When significant differences were defined, the Tukey test was applied with a confidence level of 95 % for the comparison of means. The R program was used with the *agricolae* library version 1.2-3 (Mendiburu, 2015). The survival data were transformed with the arcsen function ($p' = arcsin\sqrt{p}$) for homoscedasticity and normality in which p are the proportions from 0 to 1 (Zar, 1999).

$$y_{ijk} = \mu + L_i + P_j + B_k + LP_{ij} + LB_{ij} + E_{ijk}$$

Where:

y_{ijk} = Value of the observation in the i^{th} locality, in the j^{th} provenance of the k^{th} block

μ = General mean effect

L_i = Effect of the i^{th} locality

P_j = Effect of the j^{th} provenance

B_k = Effect of the k^{th} block

LP_{ij} = Effect of the interaction between the i^{th} locality and the j^{th} provenances

LB_{ij} = Effect of the interaction between the i^{th} locality and the j^{th} block

E_{ijk} = Effect of the interaction between the i^{th} locality of the j^{th} provenance and of the k^{th} block (experimental error)

Results and Discussion

At 17 years of establishment of the plantation, survival was 95.9 % in *Tlacotepec Plumas* and 82.4 % in *Magdalena Zahuatlán*, with 89 % average between both locations. The slope of the plots probably influenced the growth between localities, as confirmed by Gómez *et al*. (2012) when recognizing survival variation on different slopes.

The longest survival occurred in *P. greggii* var. *australis* in the provenance of *Zimapán, Hgo*. (97.7 %) while in *P. greggii* var. *greggii* it was *Puerto San Juan, Coah*. (94.07 %). These data are similar to those obtained by Rodríguez *et al*. (2008) in *Galeana, Nuevo León* and by Gómez *et al*. (2012) who identified that in degraded areas, *P. greggii* reached 70 % survival after *P. cembroides* Zucc. and *P. devoniana* Lindl. with 80 and 90 %, respectively.

Differences between localities

The statistical analysis showed the existence of significant differences between localities (p <0.001) in all the assessed variables (Table 2). In *Magdalena Zahuatlán*, the provenances recorded an average height of 7.18±2.85 m, 14.07±6.03 cm in basal diameter, 10.55±5.54 cm in normal diameter, 3.48±1.24 m in crown diameter and 10.74±7.55 m^2 $tree^{-1}$ in the crown area. In *Tlacotepec Plumas*, the average growth was higher, with an average height of 10.50±2.20 m, 18.28±5.48 cm in basal diameter, 14.33±4.64 cm in normal diameter, 4.22±1.13 m in crown diameter and 15.03±8.03 m^2 $tree^{-1}$ in the crown area.

Table 2. Observed *F* values and size of the effects obtained from the mean comparison between localities and provenances.

Assessed variables	Between localities (*df*=1/468)		Between provenances (*df*=12/78)	
	F	**Effect**	***F***	**Effect**
Height	538.52	0.41	24.16	0.27
Basal diameter	143.61	0.16	16.31	0.20
Normal diameter	144.76	0.16	12.74	0.16
Crown diameter	94.66	0.11	9.98	0.13
Crown area	73.17	0.09	10.57	0.14

The higher growths of *Tlacotepec Plumas* suggest better quality of the site for the growth of provenances (Table 3), which coincides with López *et al.* (2017) as there is a greater accumulation of litter in soils of *Tlacotepec Plumas* than in *Magdalena Zahuatlán*. Growth was favored by 50 % more nitrogen and 42 % more potassium concentration in soils of *Tlacotepec Plumas* (Velasco *et al*., 2012), which favor growth in height and diameter (Vázquez *et al*., 2018).

Table 3. Range of growth values in the studied localities.

Assessed variables	*Magdalena Zahuatlán*	*Tlacotepec Plumas*
Height	1.00-13.50	3.00-16.00
Basal diameter	2.55-31.51	8.28-32.79
Normal diameter	0.64-28.01	1.91-26.74
Crown diameter	0.85-8.15	1.19-8.30
Crown area	0.57-52.17	1.11-54.11

Differences between provenances

Growth between provenances showed significant differences (P <0.001) in all the variables evaluated (Table 2). The analysis of the localities as a whole indicated greater growth of the provenances of *P. greggii* var. *australis*. The provenance with the highest average growth in height was *El Madroño, Qro*. (10.99±3.07 m) and in basal diameter, normal diameter, crown diameter, and crown area, *El Piñón Hgo.*, with values of 20.33±7.27 cm, 15.88±6.32 cm, 4.52±1.50 m and 17.81±10.75 m^2 $tree^{-1}$, respectively. The provenances of *P. greggii* var. *greggii* recorded lower average height; the highest growth was reached by the specimens from *Puerto San Juan, Coah.* with 8.86±3.15 m in height, 16.21±7.47 cm in basimetric diameter, 12.63±6.57 cm in normal diameter, 3.79±1.44 m in crown diameter and 12.89±10.06 m^2 $tree^{-1}$ in crown area (tables 4 and 5).

Table 4. Height and basimetricdiameter growth of 13 *Pinus greggii* Engelm. provenances in the *Mixteca Alta, Oaxaca*.

Provenance	Height (m)				Basimetric diameter (cm)			
	MZ	TP	Prom.	G	MZ	TP	Prom.	G
El Madroño, Qro.	8.82	12.97	10.99±3.07	a	15.78	22.04	19.03±5.77	abc
El Piñón, Hgo.	8.35	12.23	10.35±3.30	ab	17.78	22.74	20.33±7.27	a
Zimapan, Hgo.	8.10	11.85	10.15±2.83	abc	16.21	21.91	19.32±6.18	ab
Molango, Hgo.	8.08	11.20	9.79±2.71	abcd	16.41	20.55	18.68±6.34	abc
Santa Anita, Coah.	7.82	9.07	8.50±1.97	efg	12.74	14.50	13.69±3.64	fgh
Tres Lagunas, Qro.	7.52	11.60	9.78±3.19	bcd	13.58	19.83	17.04±6.38	bcd
Puerto San Juan, Coah.	7.07	10.25	8.86±3.15	def	13.40	18.40	16.21±7.47	cdefg
Xichicotlán, Hgo.	6.98	10.96	9.14±2.90	cde	13.62	19.44	16.77±5.33	bcde
Laguna Atezca, Hgo.	6.82	11.20	9.29±2.81	bcde	12.94	19.39	16.58±5.66	bcdef
Jamé, Coah.	6.48	8.93	7.76±2.31	fg	14.21	14.60	14.41±4.42	defgh
Puerto Los Conejos, Coah.	5.95	8.68	7.45±2.07	gh	12.38	14.24	13.40±3.64	gh
Los Lirios, Coah.	5.50	8.64	7.28±2.65	gh	11.16	13.90	12.71±4.25	h
Galeana, N. L.	5.48	8.78	7.21±2.75	h	11.84	15.77	13.90±5.07	efgh

MZ = Magdalena Zahuatlán; TP = Tlacotepec Plumas; Prom = Average of the two localities; *Qro = Querétaro*; *Hgo = Hidalgo*; *Coah = Coahuila*; *N. L. = Nuevo León*; G = Growth groups. Letters indicate formed groups, same letters indicate that the means are not statistically different (Tukey $P<0.05$).

Table 5. Growth of normal diameter, crown diameter and crown area of 13 provenances of *Pinus greggii* Engelm. in the *Mixteca Alta, Oaxaca.*

Provenance	Normal diameter (cm)				Crown diameter (m)				Crown area (m^2 árbol^{-1})			
	MZ	**TP**	**Prom.**	**G**	**MZ**	**TP**	**Prom.**	**G**	**MZ**	**TP**	**Prom.**	**G**
EPH	13.88	17.76	15.88±6.32	a	4.14	4.87	4.52±1.50	a	15.84	19.67	17.81±10.75	a
MH	12.56	16.00	14.44±5.70	ab	4.12	4.59	4.38±1.16	ab	14.85	17.22	16.15±7.37	ab
ZH	12.44	16.48	14.68±5.37	ab	3.84	4.79	4.36±1.28	ab	12.70	19.10	16.26±9.03	ab
EMQ	11.95	17.81	15.02±4.99	ab	3.73	4.94	4.36±1.12	ab	11.72	19.79	15.94±7.42	ab
PSJC	10.10	14.60	12.63±6.57	bcd	3.42	4.07	3.79±1.44	bcd	10.88	14.46	12.89±10.06	bcd
JC	10.99	11.62	11.32±4.30	cde	3.51	3.61	3.56±0.86	cd	10.55	10.59	10.57±4.89	cd
SAC	9.93	11.38	10.71±3.46	cde	3.32	3.72	3.54±0.93	cd	9.55	11.33	10.51±5.25	cd
LAH.	9.46	15.20	12.70±5.17	bcd	3.30	4.32	3.88±1.08	abcd	9.39	15.34	12.75±6.62	bcd
TLQ	9.78	15.33	12.85±5.66	bc	3.20	4.63	3.99±1.53	abc	9.18	18.53	14.36±10.43	abc
LLC	8.31	10.82	9.73±4.17	e	3.22	3.57	3.42±1.03	cd	9.14	10.71	10.31±5.63	d
GNL	8.44	12.63	10.63±4.83	cde	3.12	3.60	3.37±1.11	cd	8.99	10.73	9.90±5.83	d
XH	9.57	15.36	12.65±4.94	bcd	3.24	4.56	3.94±1.12	abc	8.66	17.23	13.22±10.43	bcd
PLCC	9.02	11.07	10.14±3.39	de	2.94	3.55	3.28±0.85	d	7.50	10.27	9.02±4.36	d

MZ = Magdalena Zahuatlán; TP= Tlacotepec Plumas; EPH= El Piñón, Hgo.; MH= Molango, Hgo.; ZH= Zimapan, Hgo.; EMQ= El Madroño, Qro.; PSJC= Puerto San Juan, Coah.; JC= Jamé, Coah.; SAC= Santa Anita, Coah.;LAH= Laguna Atezca, Hgo.; TLQ= Tres Lagunas, Qro.; LLC= Los Lirios Coah.; GNL= Galenana N.L.; XH= Xichicotlán, Hgo.; PLCC= Puerto Los Conejos, Coah.; Prom. = Average of the two lots; G = Growth groups. Letters indicate formed groups, same letters indicte that the means are not statistically different (Tukey $P<0.05$).

In the provenances of *P. greggii* var. *greggii* at higher altitudes, a lower growth was observed, while those of *P. greggii* var. *australis* present at longitudes, latitudes, altitudes and lower soil pH, the data were higher. Being distributed near the area of the establishment of the plantations, the provenances of *P. greggii* var. *australis* showed better adaptation in the eroded areas of the *Mixteca Alta de Oaxaca* with a larger crown area, which protects the ground and provides woody residues and mulch, reduces the dragging of soil particles and decreases erosion, suitable conditions for reforestations in arid zones.

Pinus greggii shows a good response to erosion in the *Mixteca Alta de Oaxaca,* which coincides with the results of Gómez *et al*. (2012) who concluded that in degraded areas, *P. greggii* increases growth in height and basal diameter as the years have passed since its planting. This has a positive effect by providing more needles and carbon to the soil than *P. oaxacana*, a native species of the region where the present work was carried out (López *et al.,* 2017). However, the provenances of *Pinus greggii* var*. australis* grew faster than *P. greggii* var. *greggii*, as described by Donahue and López (1996) and Velasco *et al.* (2012).

The difference in growth between provenances and localities in the study area began to be verified 2.5 years after the plantations were established, according to the work carried out by Velasco *et al*. (2012), who recorded the highest growth in *Magdalena Zahuatlán*, in particular with the same outstanding provenances in this work. The variation in growth between varieties may be due to the absence of nutrients in the soil (Velasco *et al.,* 2012), which had repercussions in both provenances as reported by Sánchez *et al.* (2017) in *P. greggii* var. *australis* and Vázquez *et al*. (2018) in *P. greggii* var. *greggii*, a variation that recommends the application of nitrogen and phosphate fertilizers in plantations.

Outstanding growth results are shown by provenances of *P. greggii* var. *greggii* in this study are opposite to those of Rodríguez *et al.* (2013) obtained in *Galeana, Nuevo León*; the provenances of *P. greggii* var. *greggii* with a distribution closer to the poles showed a slow growth, which can be explained by the influence of temperature and the precipitation regime (Chhin *et al*., 2018; Taïbi *et al*., 2018). The highest growth of the of *P. greggii* var. *australis* provenances is related to its distribution at lower latitudes, where conditions are less restrictive for its development, compared to the of *P. greggii* var. *greggii* provenances (Valencia *et al*., 2017); therefore, they are better adapted to warmer, more humid environments and with higher rainfall (Donahue and López, 1996).

The *P. greggii* var. *australis* provenances have genotypes with sufficiently vigorous roots to reach the available moisture in the deep layers, as well as a greater accumulation of biomass, characteristics that influence a greater protection of the soil from erosion (Asbjornsen *et al*., 2004; Villegas *et al.,* 2013); consequently, the nearness of the distribution environment of the provenances of *P greggii* var. *australis* with the study area favored its adaptation and growth by resisting temperature and drought Some essays established in Brazil, Colombia and South Africa with the same species and the same provenances (White *et al*., 2007; Aitken and Bemmels, 2016). Dvorak *et al*., (1996) produced similar results in terms of higher growth of this species.

The results of the present work suggest the existence of a strong relationship between growth and the descriptive variables of the places of natural distribution of each provenance, which agrees with the findings of Salazar *et al*. (1999) in *Puebla*, that at a younger age there is a positive correlation between height and altitude and, at an older age, the correlation becomes negative. In addition, with time, provenances of lower altitude adapt better by showing more noticeable growth in height, basal diameter and crown diameter.

Conclusions

17 years after the *Pinus greggii* plantations were established, the species had greater survival in *Tlacotepec Plumas*, which implies greater potential and better condition of the site for growth in height, basal diameter, normal diameter, crown diameter and crown area; these provenance data were grouped according to the variety of the species with more prominent values for *P. greggii* var. *australis*. The most outstanding of them were *El Madroño, Qro*. and *El Piñón, Hgo*., by showing better growths in eroded areas, as they provide protection to the soil from erosion which is proper to the *Mixteca Alta* region of *Oaxaca.*

These results provide important information on the growth variation between the two varieties of *P. greggii* in eroded soils after almost two decades of establishment. It is convenient to convert the essays into seed orchards and apply thinning by genotypic and phenotypic selection.

Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Ruben Ortiz Mendoza: field work, data analysis and writing of the manuscript; Oscar Alberto Aguirre Calderón: review of the manuscript and its correction; Martín Gómez Cárdenas: design of the study and field work; Eduardo Javier Treviño Garza: review of the manuscript; Marco Aurelio González Tagle: review of the manuscript.

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