Landform heterogeneity drives multi-stemmed *Neltuma flexuosa* growth dynamics. Implication for the Central Monte Desert forest management

La heterogeneidad de paisaje modula la dinámica en el crecimiento de *Neltuma flexuosa*. Implicancias para el manejo forestal de los bosques del Desierto del Monte Central

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Abstract

Drylands represent the main earth biome, providing ecosytemic services to a large number of people. Along these environments, woodlands are often dominated by multi-stemmed trees, which are exploited by local inhabitants to obtain forest products for their livelihood. In central-west Argentina, *Neltuma flexuosa* (algarrobo) woodlands are distributed across different landform units, varying in topographical and soil characteristics. This research aimed to reconstruct stem-growth time until harvestable diameter was achieved, and biological rotation age according to topo-edaphic variability in three algarrobo forests using dendrochronological methods. Results indicated that landform heterogeneity modulated species radial growth, influencing stem increments and cutting cycle period. In this sense, a decreasing trend in tree productivity emerged along a loamy-to-sandy textured soil gradient. These findings provide useful novel information for *N. flexuosa* forest management, suggesting the need to account for spatial landform/soil heterogeneity when examining desert forest dynamics.

Keywords

arid woodlands • forest management • growth form • tree-rings

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Resumen

Las tierras secas representan el principal bioma terrestre, proveyendo numerosos servicios ecosistémicos a un ingente número de personas. En estos ambientes, los bosques son a menudo dominados por árboles de porte multi-fustal, explotados por los habitantes locales para obtener productos forestales útiles para su sustento. En los territorios del centro-oeste de Argentina, los bosques de *Neltuma flexuosa* (algarrobo) están distribuidos en diferentes unidades de paisaje, los que presentan variaciones en las características topográficas y edáficas. En este estudio reconstruimos, a través de métodos dendrocronológicos, el crecimiento, el intervalo para obtener productos maderables, y el turno biológico de corta en función de la variabilidad topo-edáfica en tres bosques diferentes de algarrobo. Los resultados indican que la heterogeneidad del paisaje modula el crecimiento radial de la especie, influenciando el incremento diamétrico y el turno de corta. En este sentido, se evidencia una tendencia decreciente en valores de productividad según un gradiente edáfico desde textura limosa a arenosa. Estos hallazgos proveen información novedosa y de utilidad para los planes de manejo forestal de los bosques de *N. flexuosa*, indicando la necesidad por considerar la heterogeneidad espacial establecidas por las unidades de paisaje/suelos en estudios relativos a la dinámica forestal de los bosques de tierras secas.

Palabras claves

bosques de tierras secas • manejo forestal • forma de crecimiento • ancho de anillo

Introduction

Worldwide, drylands represent the largest biome on Earth, covering more than 40% of land surface (7, 29). These environments, characterized by precipitation/evapotranspiration ratio below 0.2, include 20% of plant diversity hotspots, play a fundamental role in various biogeochemical cycles, and contribute to approximately 40% of global net primary productivity (11, 16, 29).

Drylands host more than two billion people (29). Along these biomes, forests cover approximately 1.400 Mha, providing several ecosystemic services like water and soil regulation, food, biochemical, and raw material provision, as well as cultural services (7, 24). Physiognomically, many desert forests are dominated by tree species capable of regeneration through development of new tissue following disturbance, a physiological trait known as resprouting (8, 30). This results in vegetation with coexisting one- and multi-stemmed trees, which differ in growth, productivity, reproduction, and survival ability (30).

Dryland forests have suffered various types of natural and anthropogenic disturbances, such as, fire, insect outbreak, and drought, in addition to high deforestation rates due to agricultural and livestock expansion (6, 20). In this sense, it is estimated that, globally, about 220,000 km^2 of tree-covered drylands were converted into other land cover types between 1992 and 2015 (29). This suggests the need to sustainably exploit and manage these natural resources, particularly in the actual climate change scenario (16).

The Central Monte Desert (hereafter, CMD) is a dryland biome located in central-west Argentina (2). Along these districts, the algarrobo dulce, *Neltuma flexuosa* (DC.) C.E. Hughes & G.P. Lewis (formerly designated as *Prosopis flexuosa* DC), is a dominant tree species growing on a variety of landform units (20). These woodlands were severely exploited during the first half of the 20th century, mainly for domestic wood demand, railway construction and, afterwards, vineyard expansion, with a resulted extraction of approximately 1 million tons of wood (1, 28).

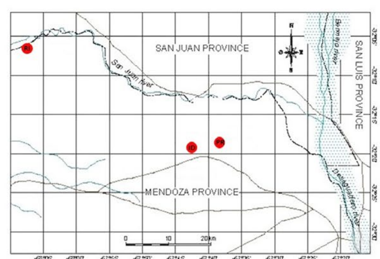
Nowadays, the *N. flexuosa* CMD forests are mostly managed by the local Huarpe native community, through forestry practices that consider the typical low tree growth rates of these woodlands (28). As a result, logging and thinning are extremely rare activities in this area, whereas other silvicultural approaches, such as pruning and deadwood removal, represent valuable forest management alternatives (4, 27). Pruning plays a prominent role due to the high presence of multi-stemmed trees in CMD forests, as well as their higher productivity with respect to one-stemmed individuals (3, 4).

Previous analyses examined productivity in one- and multi-stemmed *N. flexuosa* trees, providing valuable information regarding the CMD algarrobo forest management, but solely at local scale (4). As previously mentioned, the CMD *N. flexuosa* woodlands grow on a mosaic of landform units, expression of soil variability and topographic characteristics (21). This environmental heterogeneity is reflected in differences of tree-ring development, as well as its relation with precipitation regime and disturbance (21, 22). It could be hypothesized, therefore, that the CMD landform variability would represent a factor modulating multi-stemmed *N. flexuosa* tree productivity, as well as stem-cutting cycle periods. Studying how topo-edaphic characteristics influence multi-stemmed algarrobo growth dynamics can enhance CMD silvicultural management by identifying landforms that can sustain intense forest exploitation without ecological imbalance. For this reason, this research analyzed stem growth rates of several multi-stemmed *N. flexuosa* trees distributed along three different landform units, aiming to reconstruct diametric cumulative increment, time (expressed in years) until forest products can be obtained, and biological rotation age according to variations in topography and soil characteristics of the CMD algarrobo forest stands.

Materials and methods

In this study, we examined three sites within the CMD located in the Province of Mendoza, Argentina, representing distinct landform units (figure 1). Along these districts, the algarrobo woodlands grow under semi-arid climatic conditions, with mean annual precipitation of 155 mm, and large variability in temperature at both daily and seasonal timescales (2). Vegetation consists of the typical CMD plant association, with *N. flexousa* dominating the tree layer, occasionally accompanied by *Geoffroea decorticans*, along with shrub presence of *Larrea divaricata* Cav., (Hook. And Arn.), *Atamisquea emarginata* Miers ex Hook. & Arn and *Bulnesia retama* (Hook.) Griseb (28).

a



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b

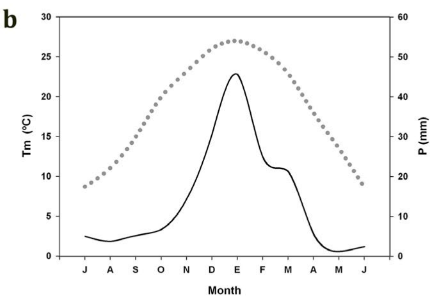


Figure 1. Spatial position of the sampled plots (a), climatic diagram (b), and geographical location of the study area (c).

Figura 1. Ubicación de los sitios de muestreo (a), diagrama climático (b), y localización geográfica del área de estudio (c).

Monthly total precipitation (continuous line) and monthly air temperature (dashed line) data belong to the Encón climatic station (32°15' S, 67°47' W), covering the 1971-1987 period. RI, PR, and ID represent River, Paleo-river, and Inter-dune valley units, respectively.

Los datos de precipitación media mensual (línea continua) y temperatura promedio mensual (línea puntuada) pertenecen a la estación meteorológica de Encón (32°15' S, 67°47' W), para el período 1971-1987. RI, PR, e ID representan respectivamente las unidades Riparia, Paleo-riparia, y de Valle inter-medanoso.

Sites were selected based on prior geomorphological classification (23). In this study, River, Paleo-river, and Inter-dune valley landform units were examined, differing in topographic characteristics and edaphic features (table 1). The selected algarrobo woodlands were in relative proximity (within 50 km), allowing us to assume a common climatic influence upon the species stem growth. Soil types varied among the examined stands, with sandy soils in the River and Interdune valley units and loamy soils in the Paleo-river site (table 1). On the other hand, soil permeability differed among the selected woodlands, showing high to moderate and moderate-hydrophobic characteristics (table 1).

Table 1. Geographical and environmental characteristics of the sampled sites.
Tabla 1. Características geográficas y ambientales de los sitios de muestreo.

m a. s. l.: meters above sea level.
m a. s. l.: metros sobre el nivel del mar.

Landform Unit	Altitude (m a. s. l.)	Latitude (°S)	Longitude (°W)	Soil texture	Soil permeability
River	534	32°06'26,6''	68°07'26,4''	Sandy	Moderate-hydrophobic
Paleo-river	497	32°18'51,9''	67°38'18,1''	Loamy	Moderate
Inter-dune valley	511	32°19'17,1''	67°42'17,0''	Sandy	High

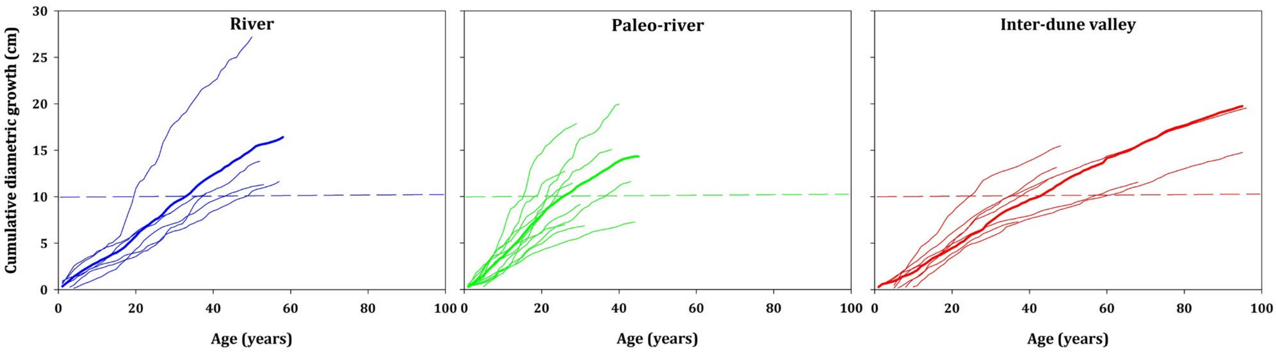
At each site, 1-2 rectangular plots of 1.000m^2 (50m x 20m) were established to examine the algarrobo forest dynamics in terms of tree radial growth relation with rainfall and its response to thinning, results already published (21, 22). The examined stands exhibited variations in structural characteristics, including differences in multi-stemmed tree density, mean basal stem diameter, and tree height, whereas the number of stems per tree was similar among the selected algarrobo forests (table 2).

Table 2. Stand structural characteristics of the sampled sites.
Tabla 2. Características estructurales de los sitios muestreados.

ms: multi-stemmed tree. Dbase: mean multi-stemmed tree basal diameter; H: mean multi-stemmed tree height.
ms: árbol multi-fustal. Dbase: diámetro basal promedio del árbol multi-fustal. H: altura promedio del árbol multi-fustal.

Landform Unit	Density (ms/ha)	Dbase (cm)	H (m)	N° stems/tree
River	60	14,9	4,8	3,8
Paleo-river	110	13,8	5.3	3,2
Inter-dune valley	70	17,2	7,1	3,7

For each multi-stemmed tree, two samples were extracted with a gas-powered drill (TED_262R, Tanaka Kogyo Co. Ltd, Chiba, Japan), at approximately 50 cm above the ground from the stem with the highest basal diameter. Samples were air-drained, mounted on a wooden support, and polished with progressively finer sandpaper to highlight wood anatomy. Rings were dated following the Schulman criteria for the Southern Hemisphere tree species (25). Tree-ring widths were measured from pith to bark with a 0.01 mm resolution Velmex table connected to a computer. The correct dating of these measurements was statistically validated with COFECHA software (13). Then, we estimated individual tree diametric increments by averaging ring measurements from samples belonging to each algarrobo tree and multiplying these values by two. Finally, we calculated the cumulative diametric increment (CDI) as the sum of the current annual increments in diameter for each biological year. This information allowed us to estimate the time, in absolute tree age, required for the stem to reach the minimum diameter corresponding to forest products in CMD algarrobo woodlands, based on available information for the studied area (poles: stem ø= 10 cm) (19). When the core center was not reached, tree age was estimated through a geometric method (10). We used ANOVA with post-hoc Fisher's least significant difference test through the Infostat software (9) to compare tree age data across landform units. Five trees were excluded from this analysis since they did not reach minimum CDI values of 10 cm (figure 2).



Dashed horizontal lines show the minimum stem ø = 10 cm. / Las líneas puntuadas indican el ø mínimo del fuste = 10 cm.

Figure 2. Cumulative diameter increment for the River, Paleo-river, and Inter-dune valley landform units.

Figura 2. Crecimiento diamétrico cumulativo para las unidades de paisaje de Ripario, Paleo-ripario, y valle inter-medanoso.

Biological rotation age of the sampled algarrobo trees was estimated considering raw ring widths converted to basal area increment (BAI). First, tree-ring measurements from the two radii, corresponding to the two samples extracted for each tree, were averaged at tree level to obtain individual ring-width chronologies. Then, the AGE routine included in the DPL software (Dendrochronological Program Library) (14) was used to estimate current (CBAI) and mean (MBAI) basal area, according to the following equation:

$$\mathbf{CBAI_t = \pi * (r_t^2 - r_{t-1}^2)} \text{ and } \mathbf{MBAI_t = \pi * (r_t^2)/t}$$

where:

r_t represents ring width in year *t*. Biological rotation age (cutting cycle period) was determined at the age when MBAI and CBAI intersected (5).

Results

Tree-ring width chronologies were constructed using 36 samples corresponding to 24 *N. flexuosa* multi-stemmed trees. The relatively low number of selected trees at River and Inter-dune valley depended on landowner sampling permission. Multi-stemmed algarrobo site chronologies spanned from 44 (Paleo-river unit) to 96 years (Inter-dune valley unit). Mean annual radial growth rates oscillated between 1.27 (Inter-dune valley unit) and 1.77 mm/yr (Paleo-river unit). Mean correlation values (MC) between individual tree-ring chronologies ranked from 0.446 (Inter-dune valley unit) to 0.490 (Paleo-river unit), with all values being significant at $p < 0.05$ (table 3, page 31).

CDI analysis revealed that multi-stemmed trees achieved, on average, a minimum diameter of 10 cm at different ages: 37 years for River unit, 24 years for Paleo-river environment, and 44 years for Inter-dune valley landform (figure 2).

Table 3. Characteristics of the tree-ring chronologies.

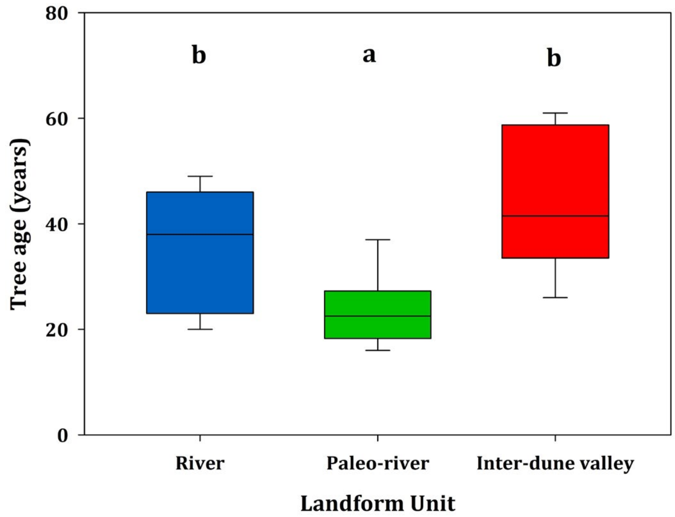
Tabla 3. Características de las cronologías de ancho de anillo.

Landform Unit	N	Period	RW (mm)	MC
River	6 (9)	1954-2011	1.38	0.463
Paleo-river	11 (15)	1967-2010	1.77	0.490
Inter-dune valley	7 (12)	1916-2011	1.27	0.446

N = Number of sampled trees per site (in parenthesis: total number of dendrochronological samples); Period = time range of the sampled cores; RW = mean ring-width value; MC = mean correlation between individual tree-ring series at each stand.

N = número de los árboles muestreados (entre paréntesis: número total de las muestras dendrocronológicas); Period = intervalo temporal de las muestras; RW = valor de ancho de anillo promedio; MC = correlación promedio entre las series dendrocronológicas individuales para cada sitio.

Statistically significant differences emerged regarding tree age corresponding to CDI ø= 10 cm among Paleo-river units on one side, and River and Inter-dune valley landforms on the other (one-way ANOVA, F = 5.40, $p = 0.0161$, $df = 2$, n = 19; figure 3).



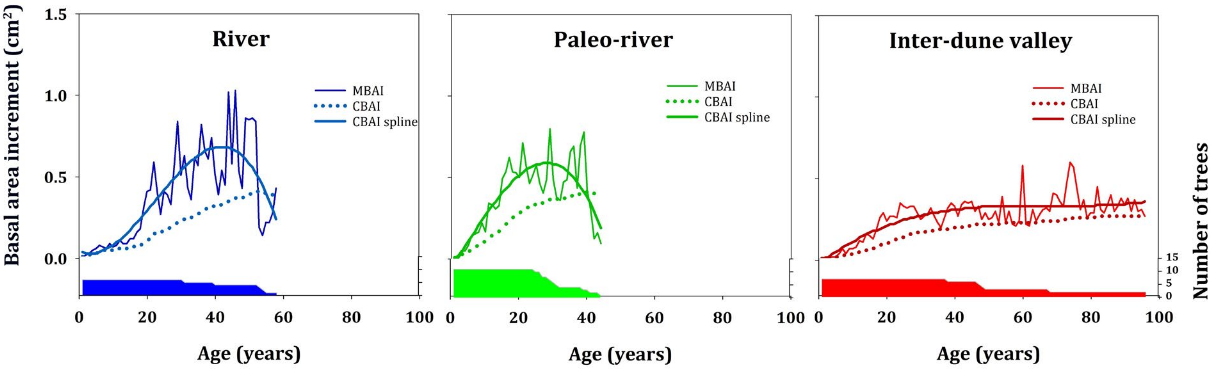
Each box shows the values within one interquartile distance (ID 25% above and below the median). The median is shown as a black horizontal bar in the boxes. Whiskers represent values reaching 1.5 times the IDs. Different letters indicate significant differences at $p < 0.05$.

Cada caja muestra los valores comprendidos en la distancia de un intercuartil (ID 25% por encima y por debajo del promedio). El promedio se muestra como línea negra. Los bigotes corresponden a un valor de 1,5 veces la distancia de un ID y se muestran como líneas negras. Letras diferentes indican diferencias significativas por $p < 0,05$.

Figure 3. Box and whiskers plot for tree age corresponding to the minimum harvestable diameter of 10 cm across landform units.

Figura 3. Gráficos de caja-bigote para los valores del diámetro mínimo maderable de 10 cm según la unidad de paisaje.

Landform heterogeneity was reflected in biological rotation age among the selected units. In this sense, the cutting cycle period occurred at ages 53 and 41 years at River and Paleo-river units, corresponding to stem diameters of 19 and 18 cm, respectively. In contrast, at the Inter-dune valley landform, the culmination age exceeded 96 years (stem ø = 24.5 cm), corresponding to the age of the two oldest sampled trees (figure 4, page 32).



Coloured areas show the number of trees used for estimating MBAI and CBAI.
Las áreas coloreadas indican el número de árboles utilizados en el cálculo de MBAI y CBAI.

Figure 4. Mean (MBAI) and current (CBAI) annual basal area increments in relation to tree ages across landform units.
Figura 4. Incrementos anuales en área basal promedio (MBAI) y corriente (CBAI) en relación a la edad del árbol según la unidad de paisaje.

Discussion

In this study, we employed dendrochronological methods to reconstruct growth dynamics of multi-stemmed *N. flexuosa* across three distinct landform units within the CMD. This research provides pioneering evidence of how topographical and edaphic factors influence growth rates of multi-stemmed algarrobo trees in the studied area. Our investigation delivered novel insights concerning the most important forest resource that sustains local communities residing in arid central-west Argentina. The low number of examined multi-stemmed *N. flexuosa* individuals at two sites is not considered an analytic limitation, aimed to explore for the first time tree growth form-dependent dynamics at regional scale. Future studies increasing site repetitions as well total sampled tree number could validate our findings.

Our analyses demonstrated that landform variations were mirrored by growth rates of multi-stemmed algarrobo trees, evidenced by differences in the time required to attain harvestable stem diameters, and the length of the cutting cycle period. Previous dendrochronological assessments suggested that soil attributes and environmental heterogeneity play pivotal roles in shaping moisture availability in the CMD districts, thereby influencing growth dynamics of algarrobo woodlands (21). In this sense, it is worth mentioning that *N. flexuosa* exhibits characteristics of a facultative phreatophyte species, with distinctive root architecture that enables algarrobo trees to access deep phreatic water while also exploring shallow soil horizons (12). This trait allows *N. flexuosa* trees to use both precipitation and groundwater for tree growth (15). Across the woodlands examined in our study, the phreatic water table consistently lies at similar depths, approximately between 4.5 and 6 meters (26), suggesting that factors beyond water table accessibility, likely soil characteristics and impact on water retention of superficial horizons, probably contributed to the observed variations in tree growth. In arid ecosystems like the CMD, sandy soils tend to facilitate deep water infiltration, whereas loamy edaphic layers promote water retention in superficial horizons, resulting in enhanced stem growth (17, 18, 21). Moreover, soil permeability directly influences water storage capacity, with moderately permeable soils exhibiting better precipitation retention compared to those with higher permeability (18, 21). Both of these edaphic attributes may collectively account for our research outcomes.

Previous analyses have indicated that the biological rotation age of *N. flexuosa* is growth-form dependent, with multi-stemmed trees reaching the cutting cycle period at younger age than their one-stemmed counterparts (4). According to Alvarez *et al.* (2011), multi-stemmed algarrobo trees could be harvested at approximately 80 years of age.

However, our study underscores that landform clearly modulated the cutting cycle period. Our findings revealed different values for biological rotation age across the examined stand. Regarding the discrepancy observed for similar environments, that is, between the Inter-dune valley stand analyzed in this research and the woodland examined by Alvarez *et al.* (2011), belonging to the same landform unit, it could be hypothesized that variations in topographical features, such as the presence (4) or absence (our study) of a complete dune system surrounding the Inter-dune valley site, may affect runoff processes and hence water availability. This landform variability could potentially account for this particular divergent result, although further investigations are warranted to explore the specific topographic influence at a smaller spatial scale within the Inter-dune valley unit, to address this difference more comprehensively.

At local scale, our results indicated that wood extraction from multi-stemmed *N. flexuosa* in CMD districts should consider landform heterogeneity. Specifically, while multi-stemmed algarrobo trees in loamy Paleo-river soil and, to a lesser extent, River units could be managed for pole production, pruning should be avoided in Inter-dune valley *N. flexuosa* forest stands. This recommendation is grounded in the exceptionally extended time required to reach biological rotation age in this landform, which is approximately 100 years. Additionally, the slow radial growth rates in the Inter dune valley environment translated to an extended time window for obtaining forest products used by local inhabitants in the studied area.

Conclusions

This research sheds crucial light on a strategically vital forest resource for the communities residing in the CMD area. These findings should be integrated with the development of future forest management strategies for the semi-arid *N. flexuosa* woodlands located in the central-western region of Argentina. On a broader scale, our study underscores the paramount importance of considering landform heterogeneity in the management of desert resprouting woody vegetation.

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