

A detailed microscopic image of wood tissue, showing a dense arrangement of polygonal cells with thick, dark cell walls. The cells are stained in shades of blue and green, highlighting their intricate structure. A dark, fibrous structure, likely a part of the wood's vascular system, runs diagonally across the lower right portion of the image.

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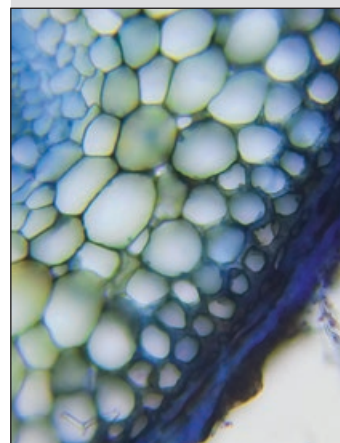
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Coupe transversale d'une racine
mycorrhizée de *Cedrus atlantica* Manetti.
Cross-section of a *Cedrus atlantica*
Manetti mycorrhizal root.
Photo B. El Amrani.



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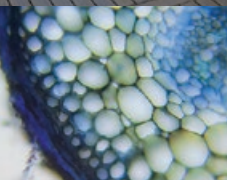
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Light management in tree nurseries to produce *Pithecellobium dulce* for the reforestation of degraded lands in Southern Mexico's tropical dry forests

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Photo 1.
Mature *Pithecellobium dulce* tree chosen as seed source.
Photo E. Basave-Villalobos.

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RÉSUMÉ

Gestion de la lumière dans les pépinières produisant des plants de *Pithecellobium dulce* pour le reboisement de terres dégradées dans les forêts tropicales sèches du sud du Mexique

Le choix des pratiques en pépinière est important pour la production de semis de haute qualité et pour augmenter les taux de survie des plantations de reboisement en milieu tropical sec. Cependant, des pratiques adéquates doivent être établies pour les espèces indigènes pour lesquelles les informations sur la propagation sont rares. La présente étude indique que la gestion de la lumière en pépinière est une pratique et une étape culturelle clé pour le succès futur de la plantation, en raison des changements morpho-physiologiques que les plants subissent habituellement dans différentes conditions de lumière. Nous avons examiné les variations de la morphologie, de l'efficacité de la photosynthèse et de la croissance de plants de *Pithecellobium dulce* produits en pépinière sous quatre niveaux de lumière (20 %, 40 %, 60 % et 100 % du rayonnement photosynthétiquement actif [RPA]). Nous avons également évalué la survie après repiquage en fonction des conditions de lumière dans lesquelles les plants ont été cultivés. Les variables morpho-physiologiques ont été examinées sur des plants de trois mois. Une plantation a été établie sur le terrain avec les plants cultivés en pépinière, et leur taux de survie enregistré tous les mois pendant 17 mois. Les effets des niveaux de lumière en pépinière étaient significatifs pour la morphologie, l'efficacité de la photosynthèse et la croissance des plants. Le niveau de 60 % de RPA était favorable à des résultats optimaux pour la plupart des variables, alors que les résultats les moins bons ont été trouvés pour les plants cultivés à 20 % de RPA. Sur le terrain, le taux de survie des plants varie significativement en fonction du niveau de lumière en pépinière, les meilleurs taux étant observés sur les plants ayant bénéficié d'une plus grande intensité lumineuse en pépinière. Nous avons observé un taux de survie de 100 % pour les plants produits sous 100 % de RPA, tandis que le taux de survie le plus faible (53 %) a été constaté pour les plants cultivés sous 20 % de RPA. La gestion de la lumière apparaît ainsi comme une pratique culturelle clé en raison de son impact sur la qualité des plants de *P. dulce*, qui s'améliore à 60 % de RPA en pépinière. Cependant, le meilleur taux de survie est obtenu pour les plants produits en plein soleil. Ces résultats devraient contribuer à améliorer la gestion des pépinières et la reprise de plants de *P. dulce* utilisés pour les projets de restauration de terres dégradées en milieu tropical sec.

Mots-clés : Balsas River, restauration écologique, transfert au champ, *pinzán*, berges, qualité des plants, Mexique.

ABSTRACT

Light management in tree nurseries to produce *Pithecellobium dulce* seedlings for the reforestation of degraded lands in Southern Mexico's tropical dry forests

The choice of nursery practices is important to the production of high-quality seedlings and to increase the survival rates of reforestation plantations in the dry tropics. However, adequate practices need to be established for native species for which propagation information is scarce. This study suggests that light management in nurseries is a key cultivation practice for future planting success, because of the morpho-physiological changes that plants usually undergo in different light conditions. We examined variations in the morphology, photosynthesis efficiency and growth of *Pithecellobium dulce* plants produced under four levels of light in nursery conditions (20%, 40%, 60%, and 100% of photosynthetically active radiation [PAR]). We also assessed survival after planting out according to the light conditions under which the plants were grown. Morpho-physiological variables were examined in three-month-old plants. A plantation was established in the field using the nursery-grown plants, and their survival was recorded monthly for 17 months. In the nursery, the light levels had significant effects on morphology, photosynthesis efficiency and growth. The 60% PAR level was favourable to optimum results for most of the variables, whereas the least successful results were found in plants grown at 20% PAR. Seedling survival in the field differed significantly according to the nursery light level, increasing with greater light intensity in the nursery during seedling production. 100% survival was observed in seedlings produced under 100% PAR, whereas the lowest survival rate (53%) was found in seedlings grown under 20% PAR. Light management is thus shown as a key cultivation practice by affecting the quality of *P. dulce* seedlings, which is improved in the nursery at 60% PAR. However, better survival after planting out is obtained with plants produced under full sun. These results should help to improve nursery management and establishment in the field of *P. dulce* in projects to restore degraded lands in the dry tropics.

Keywords: Balsas River, ecological restoration, field transplanting, *pinzán*, riverbank, seedling quality, Mexico.

RESUMEN

Manejo de la luz en los viveros de árboles para producir plantío de *Pithecellobium dulce* destinado a la reforestación de tierras degradadas en las selvas secas tropicales del sur de México

La elección de las prácticas de vivero es importante para la producción de plantío de alta calidad y para aumentar las tasas de supervivencia de las plantaciones de reforestación en los trópicos secos. Sin embargo, es necesario establecer prácticas adecuadas para las especies autóctonas sobre las cuales la información de propagación es escasa. Este estudio sugiere que la gestión de la luz en los viveros es una práctica de cultivo clave para el éxito futuro de la plantación, debido a los cambios morfofisiológicos que suelen sufrir las plantas en diferentes condiciones de luz. Examinamos las variaciones en la morfología, la eficiencia fotosintética y el crecimiento de plantones de *Pithecellobium dulce* producidas con cuatro niveles de luz en condiciones de vivero (20 %, 40 %, 60 % y 100 % de radiación fotosintéticamente activa [RFA]). También se evaluó la supervivencia tras la plantación según las condiciones de luz en las que se cultivaron los plantones. Se examinaron las variables morfofisiológicas en plantones de tres meses. Se estableció una plantación en el campo con las plantas cultivadas en vivero y se registró su supervivencia mensualmente durante 17 meses. Los niveles de luz en el vivero tuvieron efectos significativos en la morfología, la eficiencia de la fotosíntesis y el crecimiento. El nivel de RFA del 60 % favoreció la obtención de resultados óptimos para la mayoría de las variables, mientras que los resultados menos satisfactorios se encontraron en las plantas cultivadas con una RFA del 20 %. La supervivencia del plantío en el campo difería significativamente según el nivel de luz del vivero, aumentando con una mayor intensidad de luz en el vivero durante la producción del plantío. Se observó un 100 % de supervivencia en el plantío producido con un 100 % de RFA, mientras que la tasa de supervivencia más baja (53 %) se encontró en el plantío cultivado con un 20 % de RFA. Por lo tanto, el manejo de la luz muestra su potencial como práctica de cultivo al afectar a la calidad del plantío de *P. dulce*, que mejora en el vivero con un 60 % de PAR. Sin embargo, la mejor supervivencia después de la plantación se obtiene con las plantas producidas a pleno sol. Estos resultados deberían ayudar a mejorar la gestión de los viveros y el establecimiento en el campo de *P. dulce* en proyectos de restauración de tierras degradadas en los trópicos secos.

Palabras clave: río Balsas, restauración ecológica, plantación forestal, *pinzán*, ribera, calidad del plantío, México.

Introduction

The deciduous tropical forest, or seasonally dry tropical forest, is widely extended in the dry tropic of Latin America and is characterized by its high biodiversity and endemism (Ceballos *et al.*, 2010). In Mexico, this type of vegetation is mainly present in the biogeographic province known as *Depresión del Balsas* (i.e., Balsas River basin), a priority ecoregion for nature conservation on a global scale (Olson and Dinerstein, 2002).

However, some areas in the Balsas basin have been affected by natural disasters (García *et al.*, 2015). For example, in September 2013, torrential rains caused by tropical cyclone Manuel resulted in flooding and changed the course of the river, affecting large tracts of land in the areas adjacent to the lower Balsas watershed, which includes several municipalities in the state of Guerrero, Mexico (García *et al.*, 2015). Riparian areas lost tree coverage, and debris flows mainly of sand and gravel affected the productivity of agroecosystems in rural populations (García *et al.*, 2015). National statistics show that 55,781 ha of annual crops and perennial plants were affected by floods in Guerrero, and economic losses in the primary sector were as high as one billion Mexican pesos (García *et al.*, 2015).

As a result, carrying out research studies focused on the recovery of damaged areas acquired higher relevance. Reforestation initiatives using pioneer native forest species is the work plan established for that purpose. This decision is based on the fact that plantations of this type of species accelerate vegetation succession and increase the recovery rate of damaged areas in the different stages of ecological restoration (Lamb *et al.*, 2005).

For restoration activities, *Pithecellobium dulce* (Roxb.) Benth. is a suitable local species. This is a typical arboreal element in the deciduous tropical forest of the Balsas watershed (Fernández *et al.*, 1998) recognized as a useful pioneering legume for enhancing reforestation work due to its characteristics of fast growth, atmospheric nitrogen-fixing ability and multiple uses. The main uses of *P. dulce* are as a shade tree, for firewood, as a living fence, for forage, and as wood for construction. It is also a source of food for humans and wildlife (Olivares-Pérez *et al.*, 2011; Palma and González-Rebeles Islas, 2018).

However, according to Bonfil and Trejo (2010), the low representativeness of deciduous tropical forest native species in the nurseries is a significant limitation for reforestation plans. This lack of materials is attributed, in part, to limited knowledge on how to propagate high-quality plants. Producing high-quality plants is crucial to increase the survival of individuals planted in reforestations (Riikonen and Luoranen, 2018). Cultural practices are paramount for this purpose (Vallejo *et al.*, 2012); therefore, it is necessary to improve existing practices and implement alternative techniques using a larger number of species, including deciduous tropical forest native species.

Exploring the potential of sunlight management in forest nurseries is a possible approach to these alternative cultural practices. As a nursery cultural practice, light

management is based on the importance of sunlight on plant growth and development and their acclimation responses at a morpho-physiological level to increase light use efficiency when availability is heterogeneous (Lambert *et al.*, 2008; Pallardy, 2008). Several studies on tropical forest species have been carried out to optimize the establishment and growth of plants in reforestation or forest restoration activities and to define suitable environments and sunlight requirements for their adequate performance (Cheng *et al.*, 2013; Guzmán *et al.*, 2016; Kelly *et al.*, 2009; Kenzo *et al.*, 2011; Tang *et al.*, 2015; Yang *et al.*, 2013); growth, biomass allocation patterns, and photosynthetic capacity are often analyzed under different light conditions. This experimental approach is often carried out in nursery conditions, so there is support to examine nursery light management with a cultural practice approach, focused on its potential to produce high-quality seedlings for reforestation work, thereby increasing the probability of survival in the field after planting (Grossnickle and MacDonald, 2018).

Based on these considerations, analyzing the morphological and physiological changes of deciduous tropical forest species at different light intensities in the nursery and their survival in the field would be an ideal way to develop better management techniques to improve the nursery production and the field establishment of plants in restoration activities in the Balsas watershed. In this context, the present study pursued the following aims: 1) to examine the effects of different light levels in nursery on the morphology, photosynthetic efficiency, and growth of *Pithecellobium dulce* plants; 2) to analyze the survival of the plants in the field as a function of light levels used in nursery.

Materials and Methods

Effect of light intensity level on morphology, photosynthetic efficiency, and growth of *Pithecellobium dulce* seedlings in the nursery

The experiment was conducted in an outdoor nursery located in the village of La Bajada (municipality of Coyuca de Catalán, Tierra Caliente, Guerrero, Mexico, 18°19'01" N and 100°40'19.83" W). During the study period, average maximum, and minimum temperatures of 41 °C and 29 °C were registered between May and August 2018, with an average relative humidity of 32% and an irradiance of 498 W/m² per day. The above information was obtained from the records of the Agrometeorological Station of the *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias* (INIFAP), located in Cutzamala del Pinzón, Guerrero, Mexico (figure 1).

In the nursery, the *P. dulce* seedlings were grown from seeds collected in March 2018 from 10 scattered trees in the municipalities of Arcelia and Coyuca de Catalán (Tierra Caliente, Guerrero, Mexico). Selected trees were vigorous specimens with abundant fruit production and free of pests or diseases (photo 1). Plant production began in May 2018. The seeds were sowed directly into polybags. Black

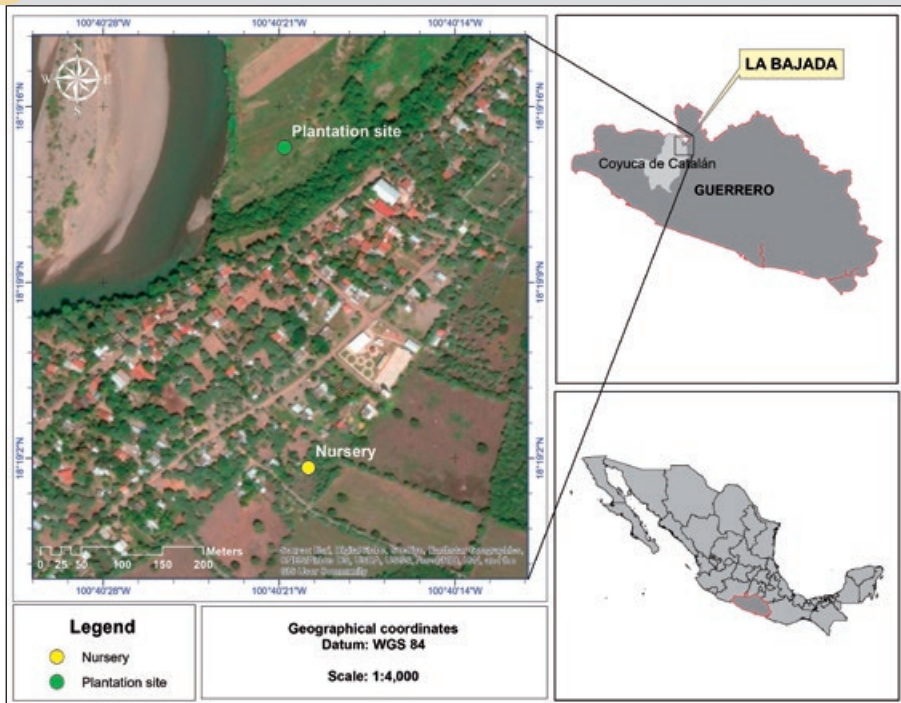


Figure 1.
 Geographical location of the study area.
 Photo E. Basave-Villalobos.

10 × 20 cm (3.9 × 7.8 in) 400-gauge polyethylene bags were used. Growing media consisted of a 2:1:1 mixture of peat moss, perlite, and vermiculite. A controlled-release fertilizer was added (Multicote 8^o,18N, 6P₂O₅, 12K₂O, 2MgO, ME; Haifa Chemicals Ltd.) at a dose of 6 g/L. The collected seeds were mixed, and the larger ones were sowed after soaking them in water at ambient temperature for 12 h to favor rapid and uniform germination. The germination stage was kept under a 20% shade condition. Seedlings emerged 15 days after sowing. Irrigations were applied three times per week at field capacity. Also, a pyrethroid insecticide based on cypermethrin was applied (CIMA[®] 19.6% CE; Química Sagal S. A.) at a dose of 50 mL/L, to control the mealybug (*Planococcus* sp.) when the plants were two-month-old.

Light levels and experimental design

One month after sowing, 256 *P. dulce* plants with average heights of 15 cm were divided in groups of 16 and subjected to four light levels or intensities inside the nursery: 20%, 40%, 60%, and 100% of photosynthetically active radiation (PAR). The placement of individuals followed a completely randomized experimental design composed of four blocks, in each of which the four light levels were represented.

Black monofilament shade clothes were used to reduce sunlight at levels of 20%, 40%, and 60% PAR. These sunlight intensities were defined after determining the transmittance (T; %) of commercial shade-clothes with different percentages of shade based on simultaneous measurements of PAR ($\mu\text{mol}/\text{m}^2/\text{s}$) above and below of them. A light meter was used for this purpose (LightScout[®] Light Sensor Reader, Spectrum Technologies, Inc., USA). Transmittance was determined applying the following formula: $T = \text{PAR under the shading net} / \text{PAR above the shading net}$. Individual domes were built using the shade-cloth for each experimental unit according to the required PAR level. Maxi-

mum and minimum temperature ($^{\circ}\text{C}$) and relative humidity (%) were monitored in each condition using a digital thermo-hygrometer (TER-150, Steren) (table I). Also, PAR levels ($\mu\text{mol}/\text{m}^2/\text{s}$) were recorded throughout an entire sunny day to calculate daily light integral (DLI; $\text{mol}/\text{m}^2/\text{day}$) (table I; photo 2).

Morphology, photosynthetic efficiency, and growth measurement

At the end of the cultivation period in nursery, *i.e.*, when plants were three-month-old, 16 plants per light treatment (four plants per block) were randomly sampled for morphology. First, the growing media was removed carefully from the roots using a water stream; subsequently, shoot height and stem diameter were measured. The shoot height (cm) was recorded from the root-collar to the apex. The stem diameter at the root-collar (mm) was measured with a millimeter ruler and a Digimatic CD-4 "AX Mitutoyo" caliper. Then, all leaves were cut out to measure their area (cm^2) using an LI-3100C leaf area meter (LI-COR Inc., USA). The samples were washed with distilled water and oven dried at 70 $^{\circ}\text{C}$ for 72 h with a forced-air oven (FELISA[®] FE-291AD). Later, dry mass (± 0.0001 g) of leaves, stem, root, and total biomass were determined with an analytical balance (AND[®] GR-120, A & D Company, Ltd.). The following ratios related to biomass allocation patterns were then calculated: leaf mass ratio (LMR [%]; ratio of leaf mass to total dry mass $\times 100$), stem mass ratio (SMR [%]; ratio of stem mass to total dry mass $\times 100$) and root mass ratio (RMR [%] ratio of root mass to total dry mass $\times 100$).

Table I.
 Mean values of climatic variables monitored in each nursery light condition.

Climatic variables	Light level (PAR; %)			
	20	40	60	100
Maximum temperature ($^{\circ}\text{C}$)	40	38.7	40.1	41.4
Minimum temperature ($^{\circ}\text{C}$)	23	23.8	22.7	21.8
Relative humidity (%)	40.1	39.6	34.9	32.8
Daily light integral ($\text{mol}/\text{m}^2/\text{day}$)	10.8	21.7	32.6	54.3



Photo 2.
 Schematic representation of each nursery light condition evaluated during the seedling production of *Pithecellobium dulce*.
 Photo E. Basave-Villalobos.

Additionally, the specific leaf area was determined (cm^2/g) based on leaf area and leaf dry mass.

Concerning photosynthetic efficiency, it was measured in terms of net assimilation rates (NAR; $\text{mg}/\text{cm}^2/\text{day}$). NAR was analyzed according to the following equation (Hunt, 1990):

$$\text{NAR} = \frac{(TDM_2 - TDM_1) (\ln LA_2 - \ln LA_1)}{(LA_2 - LA_1) (T_2 - T_1)}$$

where NAR is the net assimilation rate, TDM is the total dry mass, LA is the leaf area in absolute and logarithmic values (\ln), and T is time. In all cases, 1 and 2 refer to an initial and final evaluation, respectively, which were conducted 60 days apart.

Additionally, growth (total biomass increase) was evaluated in terms of relative growth rates (RGR; $\text{mg}/\text{g}/\text{day}$) and absolute growth rates (AGR; g/day), using the following equation (Hunt, 1990):

$$\text{RGR} = (\ln TDM_2 - \ln TDM_1) / \Delta t \text{ (days)}$$

$$\text{AGR} = (TDM_2 - TDM_1) / \Delta t \text{ (days)}$$

where RGR is the relative growth rate, AGR the absolute growth rate, TDM is the total dry mass in logarithmic values (\ln) and absolute values in the initial (1) and final evaluation (2) Δt = time between both evaluations (60 days).

The initial sampling required for evaluating variables NAR, RGR, and AGR was made at the time the plants were subjected to the different light intensities (June 2018).

The effect of the light levels was examined using a one-way analysis of variance (ANOVA) at a significance

level $\alpha = 0.05$. Prior to the ANOVA, data assumptions of normality and homogeneity of variances were checked. Some variables were log (root and total dry mass) and arcsine (LMR, SMR, RMR) transformed to meet the assumptions. If significant treatment differences were detected, a post-hoc Tukey's test was performed for multiples comparisons. Statistical software InfoStat (2008) was used for all data analysis.

Effect of light intensity on survival of *P. dulce* seedlings in the field

In August 2018, a plantation was set up using *P. dulce* plants issued from each light intensity regime evaluated in the nursery. Previously, the plants growing under the shading nets hardened gradually as they were subjected to full sunlight exposure for one week. The plantation was established in the community of La Bajada (Coyuca de Catalán, Guerrero, Mexico), in an area adjacent to the Balsas River shore at an altitude of 256 masl ($18^\circ 19' 15''$ N and $100^\circ 40' 18''$ W). The land was used for agroforestry until 2013, when the described flood occurred. After the event, most of the surface was covered by natural regeneration with *Ricinus communis* L. and *Muntingia calabura* L. The climate in the area, according to Köppen's classification as modified by García (2004), is tropical dry with a summer rainfall regime (BS_0). Cumulative rainfall per year is 978 mm which occurs between June and September. July and August have the highest precipitation amount, whose average ranges between 220 and 240 mm. Mean annual temperature is 28.6°C (García, 2004). May presents maximum temperatures of 40°C (photo 3).

Plants were planted in a living fence system in a row array and spaced three meters apart from each other. Planting holes were 20 cm wide and 40 cm deep. Weeds were controlled around the planting holes using a machete and a hoe when needed. Auxiliary irrigation was not used: water came only from the regular rain in the season. The soil had a sandy-loam texture with 58.2% sand, 22.3% silt, and 19.4% clay, as well as an apparent density of $1.25 \text{ g}/\text{cm}^3$, $\text{pH} = 7.4$, organic matter = 1.87%, electrical conductivity = $0.14 \text{ dS}/\text{m}$, and total nitrogen = 0.061%. Twenty individuals chosen randomly of each nursery light treatment were planted under a randomized complete block experimental design with four replications and five plants per experimental unit. Possible variability of soil moisture and fertility in the site was assumed as the blocking criterion.

The survival rate of transplanted trees was recorded monthly for 17 months by giving values of 0 and 1 for dead and living plants, respectively.

Differences in survival depending on light levels were analyzed using the Log-Rank test based on survival curves through the Kaplan-Meier method, which defines survival as: $S(t) = P(T \geq t)$

Where $S(t)$ is the probability that a plant dies in a time T greater than or equal to the research study time t (Kaplan and Meier, 1958); this analysis was carried out using the LIFETEST procedure in the SAS (Statistical Analysis System) software version 9.2 (SAS, 2009).



Photo 3.
Conditions of the plantation site before outplanting.
Photo E. Basave-Villalobos.

Table II.
ANOVA results for the effects of different light intensities in nursery on morphological and physiological variables measured in *Pithecellobium dulce* seedlings.

Variables	F-value	P-value
Shoot height	7.62	0.0005
Stem diameter	17.22	< 0.0001
Leaves dry mass	15.10	< 0.0001
Stem dry mass	15.41	< 0.0001
Root dry mass	14.25	< 0.0001
Total dry mass	15.52	< 0.0001
Leaf mass ratio	8.50	0.0002
Stem mass ratio	3.58	0.0235
Root mass ratio	11.79	< 0.0001
Leaf area	15.10	< 0.0001
Specific leaf area	13.79	< 0.0001
Net assimilation rate	25.87	< 0.0001
Relative growth rate	23.14	< 0.0001
Absolute growth rate	15.52	< 0.0001

Results

Effect of light intensity level on morphology, photosynthetic efficiency, and growth of *Pithecellobium dulce* seedlings in the nursery

The ANOVA test showed significant differences ($p < 0.05$) among photosynthetically active radiation levels in all evaluated variables when examining changes in morphology, photosynthetic efficiency, and growth of *P. dulce* plants produced under different light levels in the nursery (table II).

In general, the values for shoot height, stem diameter, leaf, stem, root, and total dry mass, as well as leaf area, specific leaf area, net assimilation rate, and relative and absolute growth rates increased with higher light levels but declined at full sunlight exposure (table III). Plants produced in the 60% PAR level achieved the highest values in most of the variables, except the net assimilation rate, although their values were not statistically different from the values observed for plants in the 100% PAR level (table III); however, 60% of PAR was found to be the optimal light level in the nursery because it promoted the highest values, as opposed to the 20% PAR, which resulted in the lowest values. In the case of the 40% PAR, the different variables measured showed intermediate values between those obtained for 20% and 60% PAR (table III). The *P. dulce* plants subjected to the 60% PAR level had a shoot height and a stem diameter 41% and 70%, respectively, higher than those grown in the 20% PAR level (table III). Similarly, the amount of biomass produced displayed higher values in the 60% PAR level. The amount of dry mass in leaves and stems was between three and four times greater compared to plants subjected to the 20% PAR level, while root dry mass was almost 5-fold larger, thus total dry mass values were also higher when comparing plants subjected to 20% PAR with plants subjected to 60% PAR (table III). Additionally, the plants subjected to 60% PAR had a fourfold increase in the leaf area in relation to the value shown by plants grown at 20% PAR; however, in terms of specific leaf area, the differences between the values of both light levels were lower with a difference of only 16% (table III).

Regarding the biomass allocation patterns, the biomass ratio of aboveground components (leaves and stem combined) increased as the light level received by the plants decreased, at the expense of a reduction in root biomass (figure 2). However, in general, *P. dulce* plants allocated more than 80% of their biomass to the aboveground components (figure 2).

Additionally, photosynthetic efficiency also reduced as light availability decreased. In this regard, the NAR values in plants grown at 20% PAR were smaller by a 2:3 ratio as compared to the NAR values in plants subjected to 60% and 100% PAR, which had similarly high values (table III). Finally, this effect reflects results on relative and absolute growth, where the highest growth rates were observed in plants subjected to the highest light intensities (60% and 100% PAR); specifically, values of *P. dulce* plants subjected to 60% PAR were twice higher in RGR, whereas those of AGR were four times higher than the rates registered by plants subjected to 20% PAR (table III).

Table III.

Mean values (\pm standard error) of the morphological and physiological variables measured in *Pithecellobium dulce* plants growing under different light levels in nursery.

Variables	Light levels of photosynthetically active radiation (PAR; %)			
	20	40	60	100
H (cm)	46.7 \pm 3.1a	48.8 \pm 3.1ab	65.6 \pm 3.3c	59.8 \pm 3.1bc
SD (cm)	3.10 \pm 0.23a	3.34 \pm 0.23a	5.26 \pm 0.25b	4.42 \pm 0.23b
LDM (g)	0.71 \pm 0.22a	0.76 \pm 0.22ab	2.63 \pm 0.24c	1.61 \pm 0.22b
SDM (g)	0.80 \pm 0.25a	0.91 \pm 0.25a	2.86 \pm 0.26b	2.23 \pm 0.25b
RDM (g)	0.23 \pm 0.11a	0.27 \pm 0.11a	1.13 \pm 0.12b	0.83 \pm 0.11b
TDM (g)	1.73 \pm 0.58a	1.94 \pm 0.58a	6.62 \pm 0.61b	4.67 \pm 0.58b
Leaf area (cm ²)	237.7 \pm 85.4a	257.5 \pm 85.4ab	967.5 \pm 90.1c	582.1 \pm 85.4b
SLA (cm ² /g)	321.0 \pm 5.4a	335.2 \pm 5.4a	365.7 \pm 5.7b	357.9 \pm 5.4b
NAR (mg/cm ² /day)	0.27 \pm 0.02a	0.30 \pm 0.02a	0.44 \pm 0.02b	0.45 \pm 0.02b
RGR (mg/g/day)	0.30 \pm 0.00a	0.40 \pm 0.00a	0.60 \pm 0.00b	0.50 \pm 0.00b
AGR (g/day)	0.03 \pm 0.01a	0.03 \pm 0.01a	0.12 \pm 0.01b	0.08 \pm 0.01b

H: shoot height; SD: stem diameter; LDM: leaves dry mass; SDM: stem dry mass; RDM: root dry mass; TDM: total dry mass; SLA: specific leaf area; NAR: net assimilation rate; RGR: relative growth rate; AGR: absolute growth rate; PAR: photosynthetically active radiation. Means in the same line with the same letter do not differ significantly at 5 % of probability by the Tukey's test.

Survival after outplanting of *Pithecellobium dulce* plants produced under different light levels in the nursery

Light intensities (PAR) in the nursery resulted in significant differences in plant survival in the plantation site ($p = 0.0064$). The overall survival of the plantation was 77% at 17 months. Survival increased as the light intensity increased in the nursery during the seedling production, thus 100% probability of survival was observed in plants grown under the highest level of PAR (100%), whereas the lowest probability of survival (53%) was observed in plants subjected to 20% PAR (figure 3). During the study period, most of the mortality events occurred within the first nine months (figure 3).

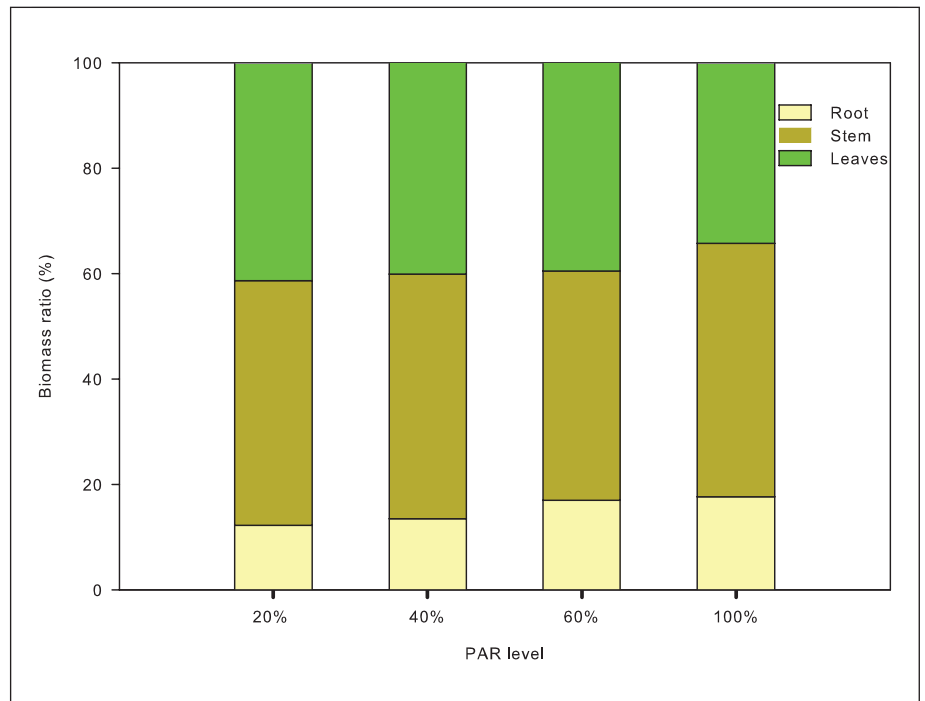


Figure 2.

Biomass allocation patterns in leaves, stem, and roots of *Pithecellobium dulce* seedlings produced under different light intensities in nursery.

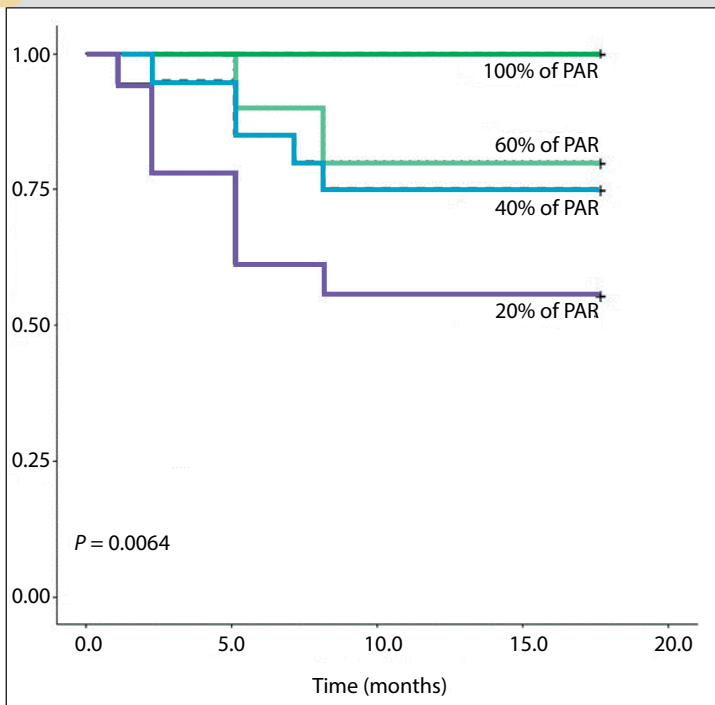


Figure 3. *Pithecellobium dulce* survival curves in the field, according to the Kaplan-Meier estimator, grown under different light levels in nursery (20%, 40%, 60%, and 100% of photosynthetically active radiation [PAR]).

Discussion

Morphology, photosynthetic efficiency, and plant growth of *P. dulce* plants varied according to the light intensity used in the nursery so that light management shows a strong potential to affect morpho-physiological seedling quality. Changes exhibited by *P. dulce* are associated, in general, with functional effects of light acclimation, similar to the changes observed in *Enterolobium contortisiliquum* (Naves *et al.*, 2018). These changes are attributed to the phenotypic plasticity that tree species usually undergo in different light environments (Gong *et al.*, 2016). In the case of *P. dulce*, high light intensities increased the values of each morphological attribute evaluated because of higher biomass gains at whole plant level. This effect suggests that the species needs high light intensities for adequate growth. The observed *P. dulce* response is consistent with Khurana and Singh's (2001) assertions that tropical deciduous species, especially pioneer species, achieve high growth rates under high light intensities. Each species requires an optimal light intensity for favorable growth depending on shade tolerance, succession phase, and acclimation capacity (Cheng *et al.*, 2013; Kelly *et al.*, 2009; Tang *et al.*, 2015). For *P. dulce* 60% of PAR was the light intensity that promoted the best morphology, photosynthetic efficiency, and growth results. Likewise, *Elaeocarpus grandis*, *Flindersia brayleyana* (Kelly *et al.*, 2009) and partially *Copaifera langsdorffii* (Reis *et al.*, 2016) showed high photosynthetic capacity

and growth under this light intensity. In contrast, *Torreya grandis*, a shade-tolerant species, had remarkably higher growth and photosynthetic capacity under a light intensity of 25% (Tang *et al.*, 2015).

Plants tend to produce proportionally more biomass in aboveground components and reduce the amount allocated to the root under low light intensities to increase their exposure to light and maintain a positive carbon balance (Masarovičová *et al.*, 2016); this was also demonstrated in *Cedrela salvadorensis* (Guzmán *et al.*, 2016), and we could confirm it by observing *P. dulce*'s biomass allocation patterns at 20% and 40% PAR. However, leaf area has also significantly changed. Plants increase in leaf area and specific leaf area as a plastic adjustment to the availability of light (Masarovičová *et al.*, 2016). Leaf plasticity adjustment was observed in *Cedrela salvadorensis* (Guzmán *et al.*, 2016), but not in *P. dulce* plants subjected to 20% and 40% PAR, since the low light availability limited leaf formation and growth. On the other hand, increased leaf area and specific leaf area were observed when comparing *P. dulce* plants subjected to 100% and 60% PAR. Shade induced increases in leaf area and specific leaf area in *P. dulce* plants subjected to 60% PAR, possibly as an acclimation strategy to use available light more efficiently, which is a response modulated by the morphological plasticity of the species (Masarovičová *et al.*, 2016). The effect in leaf area observed in *P. dulce* was comparable to the effect observed in *Prosopis laevigata* seedlings (Basave-Villalobos *et al.*, 2017).

The lower growth rates in plants subjected to low light intensities (20% and 40% PAR) compared with plants under high light intensities (60% and 100% PAR) is attributed to the impact of light restrictions on photosynthetic capacity since this is a determining factor in photosynthesis (Pallardy, 2008). Plants of the same species maintain higher photosynthetic rates when growing under high light intensities than when growing at low light intensities (Pallardy, 2008). The low net assimilation rates in plants subjected to 20% and 40% PAR suggests a limited photosynthetic efficiency due to the smaller size of the photosynthetic apparatus, which failed to favor a positive carbon balance to allocate sufficient resources for growth (Lambers *et al.*, 2008). Additionally, the heterogeneous nature of light conditions in which the *P. dulce* plants were grown could have affected other physiological processes, such as the water and nutrients use efficiency, which are also essential factors for growth (Lambers *et al.*, 2008). Although nutrients and water were methodically provided in the same amounts to all plants, the efficiency with which these resources were used might have been inconsistent, and microclimate environments generated by each light condition could have had an impact, as observed in *Pinus pinaster* (Rodríguez-García and Bravo, 2013), since the effects of light intensity are modified by interactions with different environmental factors (Pallardy, 2008). For example, a study using five different tropical shade tolerance species (Gong *et al.*, 2016) supports this assumption concerning nutrient acquisition and use. On the other hand, light intensity affected the effectiveness of the hydrogel used to improve their water status in *Enterolobium contortisiliquum* (Filho *et al.*, 2018). Subsequent stu-



Photo 4.
 Surviving tree of *Pithecellobium dulce* growing
 in the reforested site.
 Photo E. Basave-Villalobos.

dies on *P. dulce* should elucidate the effect of light intensity on the efficiency of water and nutrient use by evaluating its physiological parameters.

In *P. dulce*, nursery results confirm the potential of light management to manipulate the morphological and physiological quality of plants; this response had effects on plant performance in the field, as verified by the survival analysis. In general, *P. dulce* survival in this research study was higher than the 50% survival rate recorded in reforestation programs in Mexico in dry tropics regions, although the planting scales are not comparable in both cases (CONAFOR, 2019). Our results allow for an initial recommendation of *P. dulce* as a suitable species for reforestation work in the study environment or others with similar soil and climate characteristics (photo 4). On the other hand, survival results after outplanting observed for plants growing in the nursery under 100% PAR have important implications, because nursery light management improve the seedling quality of *P. dulce*, but the best nursery plants (those produced at 60% PAR) do not performed better than those produced at full sun, which were apparently of lower quality according to nursery results. Therefore, the use of shade clothes in the nursery may not be a relevant practice for producing *P. dulce*. Nevertheless, shade clothes are often used in forest nurseries in places with high solar radiation and low relative humidity (Pimentel, 2009) to protect plants from damaging heat. Possibly, the field survival response of the

plants produced at 60% PAR could be different under other prevailing environmental conditions and using shading nets could be an important technique to facilitate the establishment of the plants because of its effects on improving plant quality during the nursery phase, which affects the survival after outplanting (Grossnickle and MacDonald, 2018). Therefore, subsequent research studies are needed to explore the survival of plants in other field conditions and to appraise the relationship between initial morpho-physiological plant attributes and their field performance. We attribute the high survival rate of plants subjected to 100% PAR in the research study environment to the fact that plants were fully acclimatized in the nursery. Leaves of plants subjected to 100% PAR were thicker in terms of specific leaf area. Higher leaf thickness results in more cell layers in the palisade parenchyma, which acts as a protection against high irradiance (Lambers *et al.*, 2008). Thus, damage by photoinhibition could have been reduced, as opposite to plants grown under shade, which could have been more prone to this phenomenon in the field (Alves *et al.*, 2002). Even though plants under shade were subjected to a hardening phase before planting, it could not have been enough to acclimatize them, and field stress due to full irradiation or high temperatures could have contributed to the mortality that shaded plants showed during the first nine months after outplanting.

Finally, the decrease in survival during the first nine months after plantation has also important implications for reforestation programs. Results suggest that these first nine months are critical for the survival of reforestations using *P. dulce* in the study environment; for that reason, intensive management actions are suggested for the first nine months after plantation to increase plant survival rates.

Conclusion

Light management in the nursery showed a strong potential as a cultural practice to modify the morphology, photosynthetic efficiency, and growth of *Pithecellobium dulce* seedlings, thereby affecting seedling quality of *P. dulce*. A level of 60% of PAR in the nursery enhances the morphological and physiological quality of plants. In the field, overall plant survival is high, and plants produced under full irradiation (100% PAR) present the highest odds for survival. The critical survival period in the field is the first nine months after plantation. These results have important implications to improve the nursery management and the establishment in the field of *P. dulce* in restoration activities of degraded lands in the dry tropics.

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Access to data

Supplementary datafile can be accessed at: <https://1drv.ms/u/s!ApH0RmNDb-HDp1EpJUZ890ehK0ZS?e=XktizS>.

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References

- da C. A. Alves P. L., Magalhães A. C. N., Barja P. R., 2002. The phenomenon of photoinhibition of photosynthesis and its importance in reforestation. *The Botanical Review*, 68 (2): 193-208. <https://www.jstor.org/stable/4354419>
- Basave-Villalobos E., Rosales-Mata S., Sigala-Rodríguez J. Á., Calixto-Valencia C. G., Sarmiento-López H., 2017. Cambios morfo-fisiológicos de plántulas de *Prosopis laevigata* (Humb. & Bonpl. ex Willd.) M. C. Johnst. ante diferentes ambientes de luz en vivero. *Revista Mexicana de Ciencias Forestales*, 8 (44), 20 p. <https://doi.org/10.29298/rmcf.v8i44.107>
- Bonfil C., Trejo I., 2010. Plant propagation and the ecological restoration of Mexican tropical deciduous forests. *Ecological Restoration*, 28 (3): 369-376. <https://doi.org/10.3368/er.28.3.369>
- Ceballos G., Martínez L., García A., Espinoza E., Bezaury-Creel J., Dirzo R., 2010. Diversidad, amenazas y áreas prioritarias para la conservación de las selvas secas del pacífico de México. Primera edición. México, D.F., Fondo de Cultura Económica-Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, 594 p. https://www.academia.edu/27269090/Diversidad_amenazas_y_%C3%A1reas_prioritarias_para_la_conservaci%C3%B3n_de_las_selvas_secas_del_Pac%C3%ADfico_de_M%C3%A9xico
- Cheng A. X., Yu M., Wang G. G., Wu T., Zhang C., 2013. Growth, morphology and biomass allocation in response to light gradient in five subtropical evergreen broadleaved tree seedlings. *Journal of Tropical Forest Science*, 25 (4): 537-546. <http://www.jstor.org/stable/23616995>
- Close D. C., Beadle C. L., Brown P. H., 2005. The physiological basis of containerised tree seedling “transplant shock”: A review. *Australian Forestry*, 68 (2): 112-120. <https://doi.org/10.1080/00049158.2005.10674954>
- CONAFOR, 2019. Estado que guarda el Sector Forestal en México. Jalisco, México, Comisión Nacional Forestal, 412 p. <https://www.gob.mx/conafor/documentos/estado-que-guarda-el-sector-forestal-en-mexico-2019>
- Fernández N. R., Rodríguez J. C., Arreguín S. M. L., Rodríguez J. A., 1998. Listado florístico de la cuenca del Río Balsas, México. *Polibotánica*, 9: 1-151. <http://www.polibotanica.mx/pdf/pb9/ListadoBalsas.pdf>
- Filho P. R. A., Gondim F. A., Costa M. C. G., 2018. Seedling growth of tree species under doses of hydrogel and two levels of luminosity. *Revista Árvore*, 42 (1): e420112. <https://doi.org/10.1590/1806-90882018000100012>
- García E., 2004. Modificaciones al sistema de clasificación climática de Köppen. México, D.F., Instituto de Geografía, Universidad Nacional Autónoma de México, 90 p. <http://www.publicaciones.igg.unam.mx/index.php/ig/catalog/book/83>
- García A. N. M., Méndez E. K. M., Reyes R. R., Marín C. R. H., 2015. Impacto socioeconómico de los principales desastres ocurridos en la República Mexicana en 2013. México, Secretaría de Gobernación, Centro Nacional de Prevención de Desastres, 80 p. <http://www.cenapred.gob.mx/es/Publicaciones/archivos/324-NO.15-IMPACTOSOCIOECONMICO-DELOSPRINCIPALESDESASTRESOCURRIDOSENMXICOENE-LAO2013.PDF>
- Gong H. D., Wang H., Jiao D. Y., Cai Z. Q., 2016. Phenotypic plasticity of seedlings of five tropical tree species in response to different light and nutrient availability. *Tropical Ecology*, 57 (4): 727-737. http://www.tropecol.com/pdf/open/PDF_57_4/11%20Gong%20et%20al.%202016.pdf
- Grossnickle S., MacDonald J., 2018. Seedling quality: history, application, and plant attributes. *Forests*, 9 (5): 283. <https://doi.org/10.3390/f9050283>
- Guzmán Q. J. A., Cordero S. R. A., Corea A. E., 2016. Biomass allocation and gas exchange are affected by light conditions in endangered *Cedrela salvadorensis* (Meliaceae) seedlings. *Revista de Biología Tropical*, 64 (3): 1143-1154. <https://doi.org/10.15517/rbt.v64i3.19606>
- Hunt R., 1990. Basic growth analysis: plant growth analysis for beginners. London, United Kingdom, Unwin Hyman, 112 p. <https://link.springer.com/book/10.1007/978-94-010-9117-6>
- InfoStat, 2008. Versión 2008. Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina.
- Kaplan E. L., Meier P., 1958. Nonparametric estimation from incomplete observations. *Journal of the American Statistical Association*, 53 (282): 457-481. <https://doi.org/10.2307/2281868>
- Kelly J., Jose S., Nichols J. D., Bristow M., 2009. Growth and physiological response of six Australian rainforest tree species to a light gradient. *Forest Ecology and Management*, 257 (1): 287-293. <https://doi.org/10.1016/j.foreco.2008.09.008>
- Kenzo T., Yoneda R., Matsumoto Y., Azani A. M., Majid M. N., 2011. Growth and photosynthetic response of four Malaysian indigenous tree species under different light conditions. *Journal of Tropical Forest Science*, 23 (3): 271-281. <https://www.jstor.org/stable/23616971>
- Khurana E., Singh J. S., 2001. Ecology of seed and seedling growth for conservation and restoration of tropical dry forest: a review. *Environmental Conservation*, 28 (1): 39-52. <https://doi.org/10.1017/S0376892901000042>

Lamb D., Erskine P. D., Parrotta J. A., 2005. Restoration of degraded tropical forest landscapes. *Science*, 310 (5754): 1628-1632. <http://doi.org/10.1126/science.1111773>

Lambers H., Chapin F. S., Pons T. L., 2008. Plant physiological ecology. New York, NY, USA, Springer, 605 p. <https://link.springer.com/book/10.1007/978-0-387-78341-3>

Masarovičová E., Májeková M., Vykouková I., 2016. Functional traits and plasticity of plants. In: Pessaraki M. (ed.). Handbook of photosynthesis. Third edition. Boca Raton, FL, USA, CRC Press, 487-501. <https://doi.org/10.1201/9781315372136>

Naves V. L., Rambal S., Barbosa J. P. R. A. D., de Castro E. M., Pasqual M., 2018. Recruitment niches of *Enterolobium contortisiliquum* (Vell.) Morong: functional acclimations to light. *Forests*, 9 (5): 1-21. <https://doi.org/10.3390/f9050266>

Olivares-Pérez J., Avilés-Nova F., Albarrán-Portillo B., Rojas-Hernández S., Castelán-Ortega O. A., 2011. Identificación, usos y medición de leguminosas arbóreas forrajeras en ranchos ganaderos del sur del Estado de México. *Tropical and Subtropical Agroecosystems*, 14 (2): 739-748. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1870-04622011000200032

Olson D. M., Dinerstein E., 2002. The Global 200: priority ecoregions for global conservation. *Annals of the Missouri Botanical Garden*, 89: 199-224. <https://www.jstor.org/stable/3298564>

Pallardy S. G., 2008. Physiology of woody plants. Third edition. Burlington, MA, USA, Academic Press, 454 p. <https://www.sciencedirect.com/book/9780120887651/physiology-of-woody-plants>

Palma G. J. M., González-Rebeles Islas C., 2018. Recursos arbóreos y arbustivos tropicales para una ganadería bovina sustentable. Colima, México, Universidad de Colima, 133 p. http://www.uco.mx/content/publicacionesenlinea/adjuntos/Recursos-arboreos-y-arbustivos-tropicales_462.pdf

Pimentel B. L., 2009. Producción de árboles y arbustos de uso múltiple. México, Mundi-Prensa México, 237 p.

Reis S. M., Marimon-Júnior B. H., Morandi P. S., Oliveira-Santos C., Oliveira B. de, Marimon B. S., 2016. Desenvolvimento inicial e qualidade de mudas de *Copaifera langsdorffii* Desf. sob diferentes níveis de sombreamiento. *Ciência Florestal*, 26 (1): 11-20. <https://doi.org/10.5902/1980509821061>

Riikonen J., Luoranen J., 2018. Seedling production and the field performance of seedlings. *Forests*, 9 (12): 740. <https://doi.org/10.3390/f9120740>

Rodríguez-García E., Bravo F., 2013. Plasticity in *Pinus pinaster* populations of diverse origins: comparative seedling responses to light and nitrogen availability. *Forest Ecology and Management*, 307: 196-205. <https://doi.org/10.1016/j.foreco.2013.06.046>

SAS, 2009. Statistical Analysis System Version 9.2. Cary, NC, USA, SAS Institute Inc.

Tang H., Hu Y. Y., Yu W. W., Song L. L., Wu J. S., 2015. Growth, photosynthetic and physiological responses of *Torreya grandis* seedlings to varied light environments. *Trees – Structure and Function*, 29 (4): 1011-1022. <https://doi.org/10.1007/s00468-015-1180-9>

Vallejo R. V., Smanis A., Chirino E., Fuentes D., Valdecantos A., Vilagrosa A., 2012. Perspectives in dryland restoration: approaches for climate change adaptation. *New Forests*, 43 (5-6): 561-579. <https://doi.org/10.1007/s11056-012-9325-9>

Yang W., Liu F., Zhou L., Zhang S., An S., 2013. Growth and photosynthetic responses of *Canarium pimela* and *Nephelium lappaceum* seedlings to a light gradient. *Agroforestry Systems*, 87 (3): 507-516. <https://doi.org/10.1007/s10457-012-9570-0>

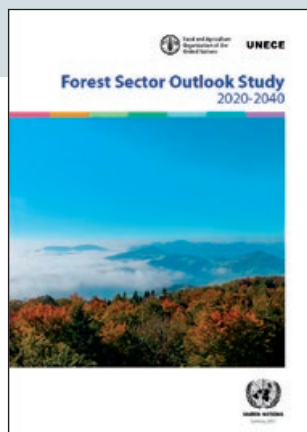
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FAO, UNECE, 2021. **FOREST SECTOR OUTLOOK STUDY 2020-2040**. SWITZERLAND, UNITED NATIONS (UN), UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE (UNECE), FOOD AND AGRICULTURE ORGANIZATION (FAO), 103 P.

The Forest Sector Outlook Study 2020-2040 provides information for the UNECE region that supports decision making by showing the possible medium- and long-term consequences of specific policy choices and structural changes, using scenario analyses whenever possible. The study is the first to cover the entire region and provides results for the main UNECE subregions of Europe, North America and the Russian Federation. The study provides insight on six priority questions which were identified through a transparent and participatory process: (i) How would different demand changes affect the UNECE forest products market? (ii) How would different supply changes affect the UNECE region forest products markets? (iii) How would significant trade restrictions affect the UNECE region forest product markets? (iv) How will UNECE forests be affected by climate change? (v) How could UNECE region forests and the forest sector contribute to climate change mitigation? (vi) How could UNECE forests adapt to climate change? The study contains information on the possible impacts of future trends regarding the future forest carbon sink in tonnes of CO₂ equivalents, and on harvest, production, consumption, net exports and prices of wood products by 2040. The study takes a pragmatic, transparent and objective approach to answering these key questions, sometimes using a modelling approach. It enables stakeholders to evaluate the long-term consequences of policy choices. The study contributes to evidence-based policy formulation and decision making. It is not a forecast of what will happen in the future. Rather, it sheds light on the possible consequences of policy choices and of factors external to the forest sector, most notably anthropogenic climate change. The study draws attention to the following issues emerging from the analysis in the study, and asks questions which policy makers and stakeholders might consider: (i) Disturbances and the

forest sink; (ii) Demand for land for increased carbon sequestration by forests; (iii) Putting substitution in a wider context; (iv) Trade measures, and; (v) Need for a system-wide, holistic approach to strategies and policies.

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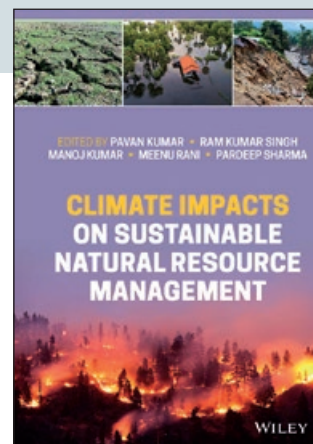


FAO, UNECE, 2021. **FOREST PRODUCTS ANNUAL MARKET REVIEW 2020-2021**. SWITZERLAND, UNITED NATIONS (UN), UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE (UNECE), FOOD AND AGRICULTURE ORGANIZATION (FAO), 103 P.

The Forest Products Annual Market Review 2020-2021 provides a comprehensive analysis of markets in the UNECE region and reports on the main market influences beyond the region. It covers products from the forest to the end user and from roundwood and primary processed products to value-added, housing and wood energy. Statistics-based chapters analyse the markets for wood raw materials, sawnwood, wood-based panels, paper, paperboard and woodpulp. Underlying the analysis is a comprehensive collection of data. The *Review* highlights the role of sustainable forest products in international markets, discusses policies concerning forests and forest products, assesses the main trends and drivers, and analyses the effects of the current economic situation on forest product markets.

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PAVAN KUMAR, RAM KUMAR SINGH, MANOJ KUMAR, MEENU RANI, PARDEEP SHARMA (EDS), 2021. **CLIMATE IMPACTS ON SUSTAINABLE NATURAL RESOURCE MANAGEMENT**. UNITED KINGDOM, WILEY BLACKWELL PUBLISHING, 384 P.

Climate change has emerged as one of the predominant global concerns of the 21st century. Statistics show that the average surface temperature of the Earth has increased by about 1.18 °C since the late 19th century and the sea levels are rising due to the melting of glaciers. Further rise in the global temperature will have dire consequences for the survival of humans on the planet Earth. There is a need to monitor climatic data and associated drivers of changes to develop sustainable planning. The anthropogenic activities that are linked to climate change need scientific evaluation and must be curtailed before it is too late. This book contributes significantly in the field of sustainable natural resource management linked to climate change. Up to date research findings from developing and developed countries like India, Indonesia, Japan, Malaysia, Sri Lanka and the USA have been presented through selected case studies covering different thematic areas. The book has been organized into six major themes of sustainable natural resource management, determinants of forest productivity, agriculture and climate change, water resource management and riverine health, climate change threat on natural resources, and linkages between natural resources and biotic-abiotic stressors to develop the concept and to present the findings in a way that is useful for a wide range of readers. While the range of applications and innovative techniques is constantly increasing, this book provides a summary of findings to provide the updated information. This book will be of interest to researchers and practitioners in the field of environmental sciences, remote sensing, geographical information system, meteorology, sociology and policy studies related to natural resource management and climate change.

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Casuarina species in Algeria: Reviewing identity, distribution and symbiotic status

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Photos 1.

Utilization of *Casuarina* trees in Algeria, *C. cunninghamiana* tree at the North region of Algeria (campus of Houari Boumedienne university, USTHB, district of Algiers). Photo K. Belaid.

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RÉSUMÉ

Espèces de *Casuarina* en Algérie : revisiter l'identité, la distribution et le statut symbiotique

Malgré l'importance prise par les *Casuarina* en Algérie depuis leur introduction au début du 19^e siècle, le nombre d'espèces aujourd'hui présentes dans le pays, leur identité, leur distribution ainsi que leur statut symbiotique sont encore largement méconnus. Une étude menée sur 2 304 arbres dans 96 peuplements répartis dans toute l'Algérie indique qu'ils sont représentés exclusivement par cinq espèces du genre *Casuarina* : *Casuarina cristata* Miq., *C. cunninghamiana* Miq., *C. cunninghamiana* Miq., *C. equisetifolia* L., *C. glauca* Sieber ex Spreng. et *C. junghuhniana* Miq. Deux espèces, *C. cunninghamiana* et *C. glauca*, sont largement prédominantes et différemment réparties, la première étant plus fréquente dans les zones relativement humides et tempérées du pays tandis que la seconde est présente dans les régions les plus arides et les plus chaudes. La production de plants de *C. cunninghamiana* et *C. glauca* dans 12 pépinières situées dans le nord et le sud du pays indique qu'ils présentent de faibles taux de mycorrhization et de nodulation spontanée. Cela suggère qu'il est nécessaire d'inoculer les jeunes plants avec des souches sélectionnées de champignons mycorrhiziens et/ou de *Frankia* au sein des pépinières afin d'améliorer leur installation durable sur le terrain. Cette étude constitue le premier inventaire de la répartition géographique des *Casuarina* en Algérie et peut conduire à une meilleure exploitation des arbres de ce genre largement utilisé en Algérie.

Mots-clés : *Casuarina*, diversité, distribution, mycorrhizes, *Frankia*, nodulation, Algérie.

ABSTRACT

Casuarina species in Algeria: Reviewing their identity, distribution and symbiotic status

Since their introduction at the beginning of the 19th century, *Casuarina* species have become important components of the Algerian landscape, yet the numbers of species present in Algeria and their identity, distribution, and symbiotic status are still not well understood. A survey conducted on 2,304 trees in 96 *Casuarina* stands across Algeria indicates that they are represented exclusively by five species: *Casuarina cristata* Miq., *C. cunninghamiana* Miq., *C. cunninghamiana* Miq., *C. equisetifolia* L., *C. glauca* Sieber ex Spreng. and *C. junghuhniana* Miq. Two species, *C. cunninghamiana* and *C. glauca*, were the most common – the former occurring more often in the relatively humid and temperate areas of the country while the latter is most frequent in the drier and warmer areas. Production of seedlings of *C. cunninghamiana* and *C. glauca* in 12 nurseries resulted in low rates of spontaneous mycorrhizal infection frequency and nodulation, suggesting that inoculation of seedlings with selected mycorrhizal fungi and/or *Frankia* strains in the nursery would be necessary to improve their establishment in the field. This study is the first survey of the geographical distribution of *Casuarina* species in Algeria and should lead to more efficient utilization of this widely used tree genus in Algeria.

Keywords: *Casuarina* trees, diversity, distribution, mycorrhizae, *Frankia*, nodulation, Algeria.

RESUMEN

Especies de *Casuarina* en Argelia: estudio de su identidad, distribución y estatus simbiótico

A pesar de la importancia de *la Casuarina* en Argelia desde su introducción a principios del siglo XIX, el número de especies actualmente presentes en el país, su identidad, su distribución, así como su estatus simbiótico son todavía muy desconocidos. Un estudio realizado a 2 304 árboles en 96 rodales de toda Argelia indica que están representados exclusivamente por 5 especies del género *Casuarina*: *Casuarina cristata* Miq., *C. cunninghamiana* Miq., *C. equisetifolia* L., *C. glauca* Sieber ex Spreng. y *C. junghuhniana* Miq. Dos especies, *C. cunninghamiana* y *C. glauca*, predominan ampliamente y se distribuyen de forma diferente, siendo la primera más común en las zonas relativamente húmedas y templadas del país, mientras que la segunda está presente en las regiones más áridas y cálidas. La producción de plantas de *C. cunninghamiana* y *C. glauca* en 12 viveros del norte y el sur del país indica que tienen bajas tasas de micorrización y nodulación espontánea. Esto sugiere que es necesario inocular las plántulas con cepas seleccionadas de hongos micorrícicos y/o de *Frankia* en el vivero para mejorar su establecimiento duradero en el terreno. Este estudio constituye el primer inventario de la distribución geográfica de *la Casuarina* en Argelia y puede conducir a una mejor explotación de los árboles de este género, ampliamente utilizados en Argelia.

Palabras clave: *Casuarina*, diversidad, distribución, micorrizas, *Frankia*, nodulación, Argelia.

Introduction

Casuarina trees are native to Australia, Southeast Asia, and the Pacific Islands (Wheeler *et al.*, 2011). Due to their economic and ecological importance, they have been introduced to over 100 countries around the world with three species (*C. cunninghamiana*, *C. equisetifolia* and *C. glauca*) becoming invasive in many parts of their introduced range (Potgieter *et al.*, 2014).

The Casuarinaceae family consists of approximately 90 species (though this number is still widely debated in the literature) across four genera: *Allocasuarina*, *Casuarina*, *Ceuthostoma* and *Gymnostoma* (Johnson and Wilson, 1993; Christenhusz and Byng, 2016). The *Casuarina* genus comprises around 14 species (19 taxa) (Potgieter *et al.*, 2014). They are evergreen, monoecious, or dioecious shrubs or tall trees that resemble conifers by their growth habit and shape, needle-like leaves, and cone-shaped woody fruits. Despite this resemblance which made them considered in the past as gymnosperms, they are a group of dicotyledonous angiosperms (Eudicots) classed in the order Fagales and the Rosids group as defined by APG IV (APG, 2016).

Casuarinas are fast-growing, resilient trees that tolerate harsh habitats and many soil types including some of the most inhospitable (NRC, 1984). They have a fair resistance to heat, drought, salinity, wind, and pests and produce good quality timber of high energy value (Benge, 1982; Dawson, 2008). These adaptations are enhanced by their ability to form multi-beneficial mutualistic symbiosis with mycorrhizal fungi and the actinobacteria *Frankia* leading to the formation of nitrogen-fixing root nodules. Thus, these remarkable properties make them pioneer species that are capable of colonizing and enriching poor soils and barren sites, thereby playing a particularly important role in ecological succession (Wall, 2000; Duponnois *et al.*, 2003). Commercially important in reforestation, carbon sequestration, agroforestry, and land rehabilitation programs, casuarinas are now common features in many landscapes around the world (Zhong *et al.*, 2010; Potgieter *et al.*, 2014).

Casuarinas were introduced to Algeria in the first half of the 19th century (around 1835). Four species of *Casuarina* (*C. cunninghamiana*, *C. equisetifolia*, *C. glauca* and *C. junghuhniana*) and four species of *Allocasuarina* (*A. littoralis*, *A. paludosa*, *A. torulosa* and *A. verticillata*) were introduced to Algeria during the French colonization (GGA, 1850, 1865; Trottier, 1872). Since then, they have been continuously propagated at a large scale (Toth, 1965; Houmani, 1997) and have today become a fundamental part of the woody flora in all bioclimatic zones of Algeria (Toth, 1965). They are extensively planted for ornamental purposes along roadsides and as windbreaks, fences or shelterbelts protecting against wind, erosion, sand shifting and rapid drying of irrigated fields, particularly in the southern part of the country (Toth, 1965; Houmani, 1997; Gherbi *et al.*, 2011; Makhlouf *et al.*, 2012). They are also used for reforestation, land reclamation of barren or polluted areas and to fight against desertification (Gherbi *et al.*, 2011; Maity and Pawlowski, 2021). Their branchlets with teeth-like leaves are

used as fodder and organic matter for soil improvement, and their wood is used for firewood, charcoal production or timber (Bensaid, 1995). In addition, they are a source of food, habitat, refuges, and nest material for many species of insects, birds, and small mammals and thus support and even increase the biodiversity in the areas where they are established (Tarai and Doumandji, 2009).

Although *Casuarina* trees are widespread over the country, they rarely disperse naturally and are propagated almost exclusively by the transplantation of individuals produced in nurseries from seed germination or to a lesser extent by cuttings (Houmani, 1997). As a result, few naturalized *Casuarina* populations occur in the country, which might be explained by the more adverse climatic conditions in Algeria compared to their native range (Potgieter *et al.*, 2014).

Despite their considerable importance and increasing application in extensive rehabilitation programs of Saharan lands, the number, identity, importance, and distribution of *Casuarina* species present in Algeria remain largely unexplored.

In this work, we established a comprehensive inventory and distribution of the members of *Casuarina* trees throughout Algerian rangelands. We also assessed the occurrence and frequency of the mycorrhization, and the nodulation of *Casuarina* species cultivated in nurseries across the country. Indeed, since propagation of these trees is done exclusively from nursery stock, the mycorrhization and nodulation of seedlings at the nursery level are crucial both for the successful establishment of the species after transfer into plantation areas and for taking full advantage of their ability to fix nitrogen and to improve soil fertility. This work constitutes the first survey on this family of plants in Algeria and provides valuable data for their utilization in the future.

Materials and Methods

Survey of *Casuarina* trees in Algerian rangelands

To identify the *Casuarina* species present in Algeria, we analyzed plant material collected during the fall of 2014 and 2015 between September and November from 2,304 trees growing in 96 stands of more than 100 individuals of similar size and age (approximately 10-15 meters and 10-30 years), distributed among all the 48 administrative districts of Algeria (figure 1 and table I for GPS coordinates). From each stand, we sampled three branches bearing cones filled with seeds from 24 randomly selected trees. The Random Number Generator v.1.4 software (2XDSOFT) was used to randomly select individuals in each stand. The collected materials were put in large paper envelopes and taken to the laboratory for examination. For each sampled branch, seven measurements were performed on the selected characters (branch length, article length, teeth number and length, stalk length, cone length and diameter). During our prospection, we did not observe *Casuarina* trees that were monoecious with male and female flowers borne on the same individual. All the examined trees were dioecious with male and female flowers on separated individuals.

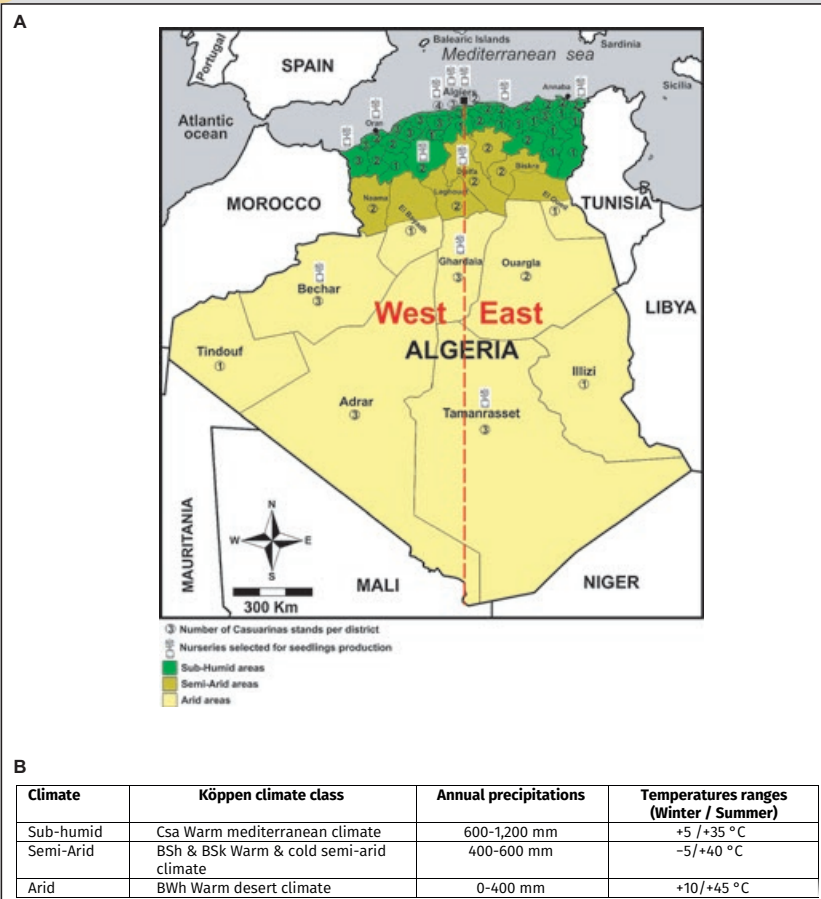


Figure 1.

A. Geographical situation of the *Casuarina* stands and nurseries selected to perform the study. Numbers surrounded by circles represent the number of stands examined for each of the 48 administrative districts of the country. B. Main characteristics of the 3 major climatic zones of Algeria (source: <https://fr.climate-data.org/afrique/algerie-164/>).

Casuarina identification

Casuarina species were identified by their morphometric traits according to the determination key of Wilson and Johnson (1989). Thereby, different traits were considered: the number of sheath teeth (true leaves), the length of branchlets and internodes for the vegetative part, the sizes of inflorescences, cones, and seeds for the floral organs. Macroscopic measurements (length of branchlets, internodes, peduncles, and cones as well as the diameter of cones) were made by using a precision ruler. Microscopic observations and measurements (number and length of teeth by whorls) were carried out under a binocular magnifier (Leica EZ4HD) or a microscope (Premiere MIS-6000T) using (when necessary) a microscope micrometer slide (OPTIKA M-005). However, it should be noted that 0.7% of the individuals (17 of the 2,304 individuals) collected could not be clearly identified on the basis of these morphometric traits, so that they were excluded from the analysis.

Symbiotic status of *Casuarina* grown in nurseries

The occurrence of mycorrhizal and actinorhizal symbioses amongst *C. cunninghamiana* and *C. glauca*, which were found to be the most abundant species in Algeria (see Results), was studied. For this purpose, 12-month-old seedlings of each studied species were produced in 12 selected nurseries from the North and the South of Algeria which regularly produce *Casuarina* seedlings for the local market (figure 1). The seedlings were produced from seeds collected on accurately identified trees growing either in Bâinem arboretum (district of Algiers) for *C. cunninghamiana* or in the district of Tamanrasset for *C. glauca*. For each nursery, plants were analyzed for both mycorrhization and nodulation (24 individuals/species). Germination for young trees production was carried out in March 2015 and symbiotic status were examined in March 2016. The seeds were surface-sterilized by immersion in 5% calcium hypochlorite solution (bleach) for 10 min, rinsed with sterile distilled water and sown on a mixture of nursery soil and thoroughly washed river black sand (2/1: v/v) in perforated polyethylene bags (15 x 25 cm) until they reached 12-month-old.

Mycorrhizal symbiosis

Root systems of seedlings were examined with the naked eye and under a binocular magnifier for the presence of a Hartig net or a hyphal mantle indicating ectomycorrhizal infection (Duponnois *et al.*, 2003). After removing the nodules, the roots of each seedling were excised and stored in ethanol 70° until use. Afterwards, the presence of endomycorrhizal infections was checked and assessed using the method of Phillips and Hayman (1970). For each seedling, five thin roots were randomly chosen, cut into 1 cm segments, and then cleared by soaking in KOH (10%) at 90 °C for one hour followed by soaking in H₂O₂ (9%) for 30 min. Root segments were thoroughly rinsed with distilled water, soaked in HCl (1%) for five minutes and stained with Trypan blue (0.05% Trypan blue in lactophenol (phenol/lactic acid v/v) for 20 min at 90 °C. After removing dye excess by distilled water, segments were incubated in lactophenol for 24 h to enhance their discoloration. To check for the presence/occurrence of dark blue-coloured fungal structures (hyphae, arbuscules, vesicles and spores), 10 stained segments per root (50 root fragments/seedling) were mounted between a microscopic slide and coverslip in a drop of a glycerol solution (20%) and examined under an optical microscope. Endomycorrhizal colonization was scored when fungal structures were found in at least one root segment. The intensity of the mycorrhization (I%) was assessed by counting the number of colonized fragments on the total of roots examined following the

Table I.
 GPS coordinates of the 96 stands from which samples were collected.

Locality	Latitude	Longitude	Elevation
Adrar - Sali	26°57'46,44"N	0°01'45,14"O	217
Adrar - Sbaa	28°13'25,09"N	0°10'17,27"O	263
Adrar - Tamantit	27°44'39,84"N	0°15'45,45"O	244
Ain Defla - Ain Defla	36°15'11,73"N	2°25'39,01"E	248
Ain Defla - El Attaf	36°13'30,07"N	1°41'12,39"E	165
Ain Defla - Khemis Miliana	36°15'00,81"N	2°13'42,08"E	282
Ain Temouchent - Ain Tolba	35°15'51,73"N	1°16'00,02"O	205
Ain Temouchent - El Malah	35°23'47,47"N	1°04'15,51"O	65
Ain Temouchent - Terga	35°25'23,72"N	1°09'38,53"O	51
Algiers - Bainem (INRF)	36°48'14,30"N	2°57'28,03"E	177
Algiers - Ben Aknoun (Zoo parc)	36°45'04,36"N	3°00'56,94"E	253
Algiers - USTHB	36°42'40,65"N	3°42'04,47"E	14
Algiers - Zeralda (F. des planteurs)	36°42'40,24"N	2°51'30,20"E	63
Annaba - Ben Mhidi	36°45'14,57"N	7°55'17,67"E	7
Annaba - Chabbia	36°51'04,52"N	7°42'49,90"E	6
Batna - Bousalh	35°12'31,73"N	6°17'47,86"E	1064
Batna - Tidjdad	35°15'52,15"N	6°05'29,13"E	1225
Bechar - Abadla	31°00'34,75"N	2°44'27,09"O	584
Bechar - Kenadsa	31°33'54,47"N	2°22'25,29"O	763
Bechar - Ouakda	31°39'31,74"N	2°10'29,98"O	808
Bejaia - Djebira	36°42'05,72"N	5°04'14,44"E	36
Bejaia - Oued Ghir	36°42'15,22"N	4°59'01,21"E	15
Biskra - Doucen	34°37'48,01"N	4°58'47,53"E	223
Biskra - Ouled Djellal	34°24'37,07"N	5°04'53,49"E	183
Blida - Boufarik	36°34'31,15"N	2°57'10,57"E	48
Blida - Meftah (Zayane)	36°38'03,74"N	3°16'22,69"E	82
Blida - Sidi Moussa	36°36'09,85"N	3°06'51,13"E	54
Bordj Bou Arreridj - Medjana	36°08'12,67"N	4°41'10,20"E	1061
Bordj Mokhtar city	21°19'41,44"N	0°58'19,64"E	400
Bouira - Ain Bessem	36°20'49,95"N	3°42'22,99"E	738
Bouira - Said Abid	36°21'08,02"N	3°50'36,97"E	525
Boumerdès - Dellys	36°54'23,65"N	3°53'36,67"E	335
Boumerdès - Tadmempt	36°54'07,56"N	3°51'43,34"E	32
Boumerdès - Zaouia	36°53'00,49"N	3°58'42,94"E	193
Chlef - Boukadir	36°04'02,80"N	1°08'17,31"E	83
Chlef - Oued Fodda	36°11'22,87"N	1°31'27,35"E	162
Djelfa - Ain Oussara	35°28'42,35"N	2°53'48,23"E	663
Djelfa - Hassi Bahbah	35°05'08,49"N	2°59'36,33"E	905
El Bayadh - El Abiodh Sidi Cheikh	32°51'01,71"N	0°29'50,01"E	889
El Oued - Hazoua	33°45'20,47"N	7°38'45,19"E	35
El Tarf - Ain Al Assel	36°46'15,07"N	8°22'05,53"E	30
El Tarf - Boutaldja	36°48'00,58"N	8°12'06,75"E	12
Ghardaia - El Meniaa	30°38'49,33"N	2°59'18,83"E	421
Ghardaia - Hassi El Fahl	31°36'49,52"N	3°40'58,91"E	375
Ghardaia - Zelfana	32°25'48,11"N	4°13'40,17"E	364
Illizi City	26°28'53,06"N	8°27'34,00"E	556
Jijel - Airport	36°48'00,43"N	5°52'38,64"E	5
Jijel - Tamila	36°47'40,74"N	5°51'49,66"E	8

Table I (following).

Locality	Latitude	Longitude	Elevation
Laghouat - Al Assafia	33° 49' 53,98" N	2° 58' 52,08" E	750
Laghouat - El Hadjeb Tadjmout	33° 56' 50,75" N	2° 38' 09,92" E	972
Mascara - Froha	35° 17' 47,72" N	0° 07' 46,36" E	469
Mascara - Ghriss	35° 15' 11,04" N	0° 10' 02,47" E	495
Mascara - Tizi	35° 19' 11,04" N	0° 04' 38,94" E	455
Mila - Sidi Mèrouane	36° 30' 51,94" N	6° 15' 45,62" E	342
Mila City	36° 27' 17,57" N	6° 16' 32,43" E	431
Mostaganem - Hassi Mameche	35° 51' 42,91" N	0° 04' 46,06" E	137
Mostaganem - Mazagran	35° 54' 07,58" N	0° 05' 17,64" E	131
Msila - Bou Saada	35° 15' 27,76" N	4° 13' 36,32" E	501
Msila - Ouled Mahdi	35° 34' 07,26" N	4° 31' 28,74" E	407
Naama - Ain Sefra	32° 44' 32,15" N	0° 35' 36,33" O	1081
Naama City	33° 16' 13,89" N	0° 18' 24,61" O	1171
Oran - Es senia	35° 37' 21,52" N	0° 40' 19,46" O	90
Oran - Messerghine	35° 37' 02,82" N	0° 44' 31,56" O	125
Ouargla - Haoud El Hamra	31° 53' 28,69" N	5° 28' 24,17" E	153
Ouargla - Hassi Ben Abdelah	32° 11' 55,52" N	5° 42' 46,37" E	155
Relizane - Belassel Bouzegza	35° 50' 21,34" N	0° 29' 24,11" E	67
Relizane - Chaif El Hassene	35° 40' 58,85" N	0° 33' 50,04" E	90
Relizane - Matmar	35° 43' 45,72" N	0° 28' 29,28" E	69
Saida - Ain El Hadjar	34° 45' 13,68" N	0° 08' 40,22" E	1025
Sidi Bel Abbès - Airport	35° 10' 29,28" N	0° 35' 40,20" O	481
Sidi Bel Abbès - Sidi Brahim	35° 16' 01,99" N	0° 34' 26,26" O	433
Sidi Bel Abbès - Tilmouni	35° 10' 36,43" N	0° 31' 26,75" O	510
Sétif - Fermatou	36° 13' 33,67" N	5° 23' 46,88" E	1048
Skikda - Hamadi Krouma	36° 50' 55,24" N	6° 54' 15,73" E	30
Skikda - Larbi Ben Mhidi	36° 52' 45,26" N	7° 00' 11,20" E	88
Tamanrasset - Djanet	24° 33' 29,96" N	9° 28' 58,16" E	1041
Tamanrasset - Idles	23° 49' 38,29" N	5° 55' 53,70" E	1390
Tamanrasset City	22° 46' 56,36" N	5° 33' 50,64" E	1396
Tebessa - El Ma Labiodh	35° 17' 30,68" N	8° 11' 26,13" E	1103
Tebessa - Oum Ali	35° 00' 32,96" N	8° 15' 15,11" E	916
Tiaret - Frenda	35° 03' 14,05" N	1° 01' 26,86" E	837
Tiaret - Sougueur	35° 10' 50,02" N	1° 28' 44,64" E	1150
Tindouf - Aéroport	27° 41' 49,43" N	8° 09' 19,68" E	438
Tipaza ChercHELL	36° 36' 13,86" N	2° 13' 01,61" E	148
Tipaza Hadjout	36° 32' 09,01" N	2° 25' 39,01" E	79
Tipaza Sidi Amar	36° 32' 52,99" N	2° 18' 42,34" E	54
Tissemsilt - City	35° 35' 18,05" N	1° 49' 01,65" E	937
Tizi Ouzou - Azzefoun	36° 53' 53,90" N	4° 25' 27,24" E	79
Tizi Ouzou - M'letta	36° 53' 22,71" N	4° 22' 10,47" E	24
Tizi Ouzou - Tigzirt	36° 54' 05,29" N	4° 09' 06,29" E	76
Tlemcen - Hennaya	34° 58' 08,84" N	1° 22' 14,12" O	365
Tlemcen - Maghnia	35° 50' 38,57" N	1° 42' 54,59" O	371
Tlemcen - Taffessera	35° 40' 34,89" N	1° 26' 30,32" O	807
Tougourt - El Arfiane	33° 39' 14,96" N	5° 58' 48,54" E	24
Tougourt - El Mansoura	33° 26' 13,07" N	5° 58' 12,26" E	53
Tougourt - Moggar	33° 13' 19,47" N	6° 04' 56,40" E	61

Statistical analyses

method described by Trouvelot *et al.* (1986). This method is based on the range of values from n0 to n5 where n indicates the number of root fragments scored and rating corresponds to: 0 = without colonization of the root segment; 1 = less than 1% is colonized or colonization trace; 2 = less than 10%; 3 = 11 to 50%; 4 = 51 to 90%; 5 = more than 90%. From this, the intensity of mycorrhization is calculated according to the following formula: $I\% = (95n_5 + 70n_4 + 30n_3 + 5n_2 + n_1) / N$, where N is the total of observed root fragments.

Actinorhizal symbiosis

From each of the 12 nurseries investigated, 24 randomly selected plants of *C. cunninghamiana* or *C. glauca* were harvested after 12 months of growth and examined in the laboratory. Root systems of the seedlings were carefully removed from the polyethylene bags, washed thoroughly under a stream of tap water to remove soil and then eye examined for the presence of actinorhizal nodules. Nodules of each seedling were excised, and their dry weights were determined after desiccation at 80 °C until constant weight (1 week).

Canonical Discriminant Analysis (CDA) was performed using the free software Tanagra (Rakotomalala, 2005). CDA is a multivariate statistical method that can highlight differences among groups of individuals (or treatments) and help to better understand of the relationships among the variables measured (branch length, article length, teeth number and length, stalk length, cone length and diameter) within those groups (Cruz-Castillo *et al.*, 1994). We used this method to determine which variables discriminate between two or more naturally occurring groups. Statistical analyses were performed using the free software Past3 (Hammer *et al.*, 2001). Data storage, basic statistics and graphs were performed using Lotus Approach (Lotus Development Corporation, Cambridge, USA).

Data presented in tables II and III were subjected to one-way analyses of variance (ANOVA) and Fisher's Least Significant Difference (LSD) tests to evaluate significant differences for variables at 5% level while the Pearson's χ^2 test was used to assess the homogeneity of proportions in figures 3 and 4 using R Studio v. 2.13 (R Development Core Team, 2016).

Table II.

Endomycorrhizal symbiosis: Percentage of mycorrhized seedlings and mycorrhizal intensity in root tissues (I%) among 12-month-old seedlings of *Casuarina cunninghamiana* and *C. glauca* produced in 12 nurseries located in the North and the South of Algeria. Data of mycorrhizal intensity (I%) were subjected to one-way analyses of variance (ANOVA) and Fisher's Least Significant Difference (LSD) tests at $p = 0.05$ threshold. Mean values \pm SD ($n = 24$) in each column followed by a different letter are significantly different.

Nursery localization	<i>Casuarina cunninghamiana</i>		<i>Casuarina glauca</i>	
	% of mycorrhized seedlings	Mycorrhizal intensity (I %)	% of mycorrhized seedlings	Mycorrhizal intensity (I %)
Algiers - Bainem	100.0	83.1 \pm 2.3 ^a	100.0	83.4 \pm 3.5 ^a
Algiers - Ben Aknoun	100.0	79.4 \pm 3.3 ^a	100.0	72.6 \pm 5.4 ^a
Béjaïa	100.0	64.8 \pm 4.5 ^a	83.3	60.8 \pm 6.6 ^a
El Kala	100.0	84.2 \pm 3.5 ^a	100.0	80.8 \pm 5.5 ^a
Oran	70.8	58.2 \pm 7.1 ^a	100.0	58.5 \pm 9.7 ^a
Tlemcen	100.0	69.8 \pm 1.8 ^a	100.0	80.0 \pm 6.5 ^b
Mean - Northern nurseries	95.1 \pm 4.9 ^a	73.2 \pm 4.3 ^a	97.2 \pm 2.8 ^a	72.7 \pm 4.4 ^a
Adrar	79.2	33.8 \pm 5.5 ^a	91.7	37.0 \pm 5.2 ^a
Biskra	79.2	29.4 \pm 6.9 ^a	91.7	32.2 \pm 8.8 ^a
Djanet	70.8	35.2 \pm 5.0 ^a	87.5	37.5 \pm 7.1 ^a
El Golea	83.3	41.2 \pm 9.3 ^a	100.0	44.0 \pm 5.3 ^a
Tamanrasset	79.2	33.3 \pm 5.2 ^a	87.5	28.7 \pm 7.2 ^a
Tindouf	75.0	22.9 \pm 8.3 ^a	83.3	24.6 \pm 9.1 ^a
Mean - Southern nurseries	77.8 \pm 1.8 ^a	32.6 \pm 2.5 ^a	90.3 \pm 2.3 ^b	34.0 \pm 2.8 ^a
Overall mean value	86.5 \pm 3.6	52.9 \pm 6.5	93.8 \pm 2.0	53.4 \pm 6.3

Table III.

Actinorrhizal symbiosis: Percentage of nodulated seedlings, mean number of nodules per seedling (nodules/seedling) and nodule dry weight per seedling (NDW mg/seedling) among 12-month-old seedlings of *Casuarina cunninghamiana* and *C. glauca* produced in 12 nurseries located in the North and the South of Algeria. Data were subjected to one-way analyses of variance (ANOVA) and Fisher's Least Significant Difference (LSD) tests at $p = 0.05$ threshold for all variables. Mean values \pm SD (n=24) in each column followed by a different letter are significantly different.

Nursery localization	<i>Casuarina cunninghamiana</i>			<i>Casuarina glauca</i>		
	% of nodulated seedlings	Nodule no./ seedling	NDW mg/ seedling	% of nodulated seedlings	Nodule no./ seedling	NDW mg/ seedling
Algiers Baïnem	70.8	6.5 \pm 1.0 ^a	532.7 \pm 81.8 ^a	54.2	4.5 \pm 0.8 ^a	329.7 \pm 74.5 ^b
Algiers Ben Aknoun	37.5	1.8 \pm 0.6 ^a	124.4 \pm 35.7 ^a	41.7	3.0 \pm 0.8 ^b	141.7 \pm 38.4 ^b
Béjaïa	50.0	2.9 \pm 0.6 ^a	243.0 \pm 54.9 ^a	37.5	2.6 \pm 0.8 ^a	202.3 \pm 64.3 ^a
El Kala	54.2	7.0 \pm 1.4 ^a	278.1 \pm 56.2 ^a	29.2	3.0 \pm 1.1 ^b	156.7 \pm 56.7 ^a
Oran	33.3	2.0 \pm 0.6 ^a	97.2 \pm 30.2 ^a	45.8	2.8 \pm 0.7 ^b	100.8 \pm 26.0 ^a
Tlemcen	33.3	1.3 \pm 0.5 ^a	33.9 \pm 13.9 ^a	37.5	2.0 \pm 0.6 ^b	71.2 \pm 21.5 ^b
Mean-Northern nurseries	46.5 \pm 6.0 ^a	3.6 \pm 1.0 ^a	218.1 \pm 73.2 ^a	41.0 \pm 3.5 ^a	3.0 \pm 0.3 ^b	167.1 \pm 37.4 ^b
Adrar	29.2	1.1 \pm 0.4 ^a	16.9 \pm 6.3 ^a	25.0	0.5 \pm 0.2 ^b	12.8 \pm 5.4 ^a
Biskra	20.8	1.0 \pm 0.4 ^a	16.2 \pm 7.1 ^a	25.0	0.6 \pm 0.2 ^a	8.57 \pm 3.4 ^b
Djanet	0.0	0.0 \pm 0.0 ^a	0.0 \pm 0.0 ^a	0.0	0.0 \pm 0.0 ^a	0.0 \pm 0.0 ^a
El Goléa	0.0	0.0 \pm 0.0 ^a	0.0 \pm 0.0 ^a	0.0	0.0 \pm 0.0 ^a	0.0 \pm 0.0 ^a
Tamanrasset	0.0	0.0 \pm 0.0 ^a	0.0 \pm 0.0 ^a	0.0	0.0 \pm 0.0 ^a	0.0 \pm 0.0 ^a
Tindouf	16.7	0.5 \pm 0.2 ^a	6.5 \pm 3.3 ^a	20.8	0.3 \pm 0.2 ^a	6.9 \pm 3.1 ^a
Mean-Southern nurseries	11.1 \pm 5.2 ^a	0.4 \pm 0.2 ^a	6.6 \pm 3.3 ^a	11.8 \pm 5.3 ^a	0.2 \pm 0.1 ^b	4.71 \pm 2.2 ^a
Overall mean value	28.8 \pm 6.5	2.0 \pm 0.7	112.4 \pm 47.3	26.4 \pm 5.3	1.6 \pm 0.4	85.9 \pm 30.3

Results

Casuarina species in Algerian rangelands

Surveys carried out all over Algeria to select sufficiently large and representative tree stands allowed us to observe members of both genera *Casuarina* and *Allocasuarina*. *Casuarina* species are distinguished by their dull and grey to yellow-brown winged seed (samara) body while *Allocasuarina* species are easily recognizable by their shiny red-brown to black samara body.

In all the prospected locations, the examined stands consisted exclusively of representatives of the genus *Casuarina* which are widespread across all Algerian rangelands and bioclimatic areas (figure 1, photos 2). In contrast, only one species of *Allocasuarina* (likely *A. verticillata* (Lam) L.M.S. Johnson), was recorded in a unique site at the arboretum of Baïnem in Algiers indicating that species of this genus are seemingly rare in Algeria.

Casuarina genus is represented by 5 species in Algeria

Casuarina plant material was collected from 2,304 randomly selected trees present in 96 stands (24 individuals per stand) located in the 48 administrative districts of the

country (figure 1). Analyses based on different morphometric traits of the vegetative parts (sheath teeth, length of branchlets and internodes) and of floral organs (size of cones and seeds) allowed us to identify five species: *Casuarina cristata* Miq., *C. cunninghamiana* Miq., *C. equisetifolia* L., *C. glauca* Sieber ex Spreng. and *C. junghuhniana* Miq. (figure 2).

The results of Canonical Discriminant Analysis (CDA) revealed that branch (BR-L) and article (ART-L) lengths were the best discriminating traits since they allow a satisfactory grouping of the individuals from the same species into rather well delineated and cohesive clouds. Nevertheless, except for *C. cunninghamiana*, all the other groups showed some individuals that were scattered far from the centre of their corresponding cloud (figure 2).

Analysis of the 2,304 plants indicated that the composition of the *Casuarina* species present in the 96 stands was not homogeneous (χ^2 test, $p < 0.001$) since more than half (55.2%) included individuals belonging to at least two species (figure 3) and nearly 25% of the stands contained individuals belonging to three species or more. On the other hand, 44.8% of the stands were monospecific (figure 3) and were dominated by either *C. cunninghamiana* or *C. glauca* (figure 2, photos 2).

Species of *Casuarina* that occur in the 96 examined stands are unevenly represented. The proportion

of each species as well as their distribution in the stands were not homogeneous (χ^2 test, $p < 0.001$) (figure 4). Two species, *C. cunninghamiana* (1,101 individuals) (photos 3) and *C. glauca* (1,070 individuals) (photos 4), were largely predominant accounting together for nearly 95% of all 2,304 trees examined (figure 4). The two species are also the most widespread since they were found respectively in 68 and 64 of the 96 stands investigated representing 70.8% and 66.7% of the cases, respectively (figure 4). The three other *Casuarina* species, *C. cristata* (12 individuals), *C. equisetifolia* (42 individuals) and *C. junghuhniana* (62 individuals) are much less frequent and represent altogether only 5.0% of sampled trees (116 out of 2,304). They were found in 4, 16 and 18 stands respectively representing 4.2%, 16.7% and 18.7% of the 96 stands (figure 4). These species can thus be considered as minor in Algeria. In addition, 17 individuals representing 0.7% of the total plants could not be identified (figure 4).

Casuarina cunninghamiana is more common in the northern and eastern parts of the country, which are the wettest and most temperate zones, while *C. glauca* is more abundant in the South and the West, the driest and warmest areas of the country (figure 5).

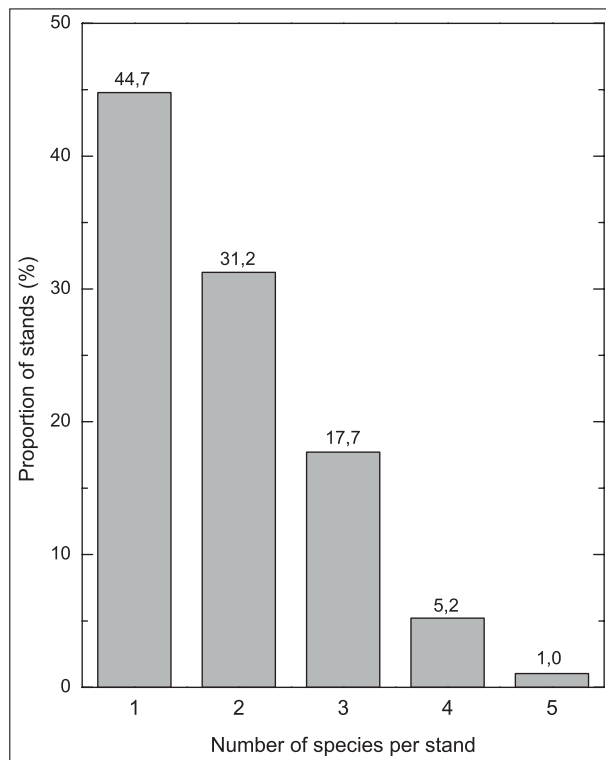


Figure 3. Distribution of the stands studied according to the number of co-occurring *Casuarina* species. The composition in *Casuarina* species present in the 96 stands was not homogeneous (χ^2 test: $\chi^2_{(4)} = 63.58$, $p < 0.001$).

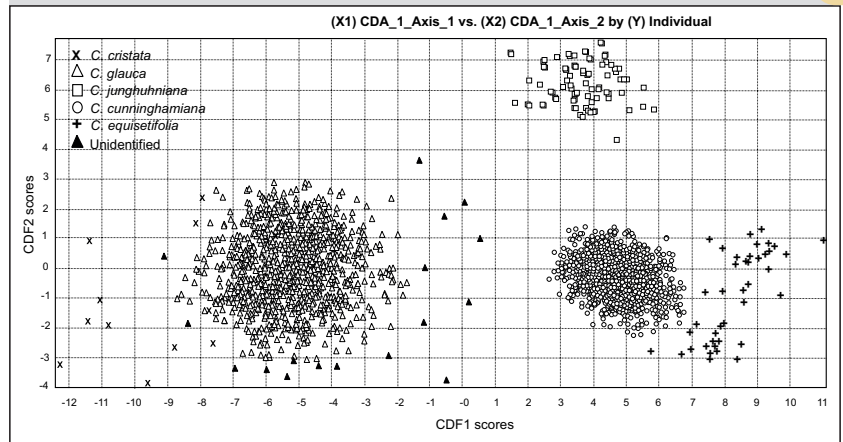


Figure 2. Canonical scores of the first two canonical discriminant functions (CDFs) of the five species of *Casuarina* identified on the basis of their morphometric traits. (X) *C. cristata*, (Δ) *C. glauca*, (□) *C. junghuhniana*, (○) *C. cunninghamiana*, (+) *C. equisetifolia*.



Photos 2. Utilization of *Casuarina* trees in Algeria. A. Roadside delimitation by *C. cunninghamiana* in the coastal zone (El Kaddous, district of Algiers). B. *C. cunninghamiana* tree at the North region of Algeria (campus of Houari Boumedienne university, USTHB, district of Algiers). C. Plantation of *C. glauca* as a windbreak in a palm grove in the South of the country (USTHB experimental field station, El-Golèa, district of Gharðaïa). D. *C. glauca* tree at the South of Algeria (District of Tamanrasset). Photos K. Belaid.

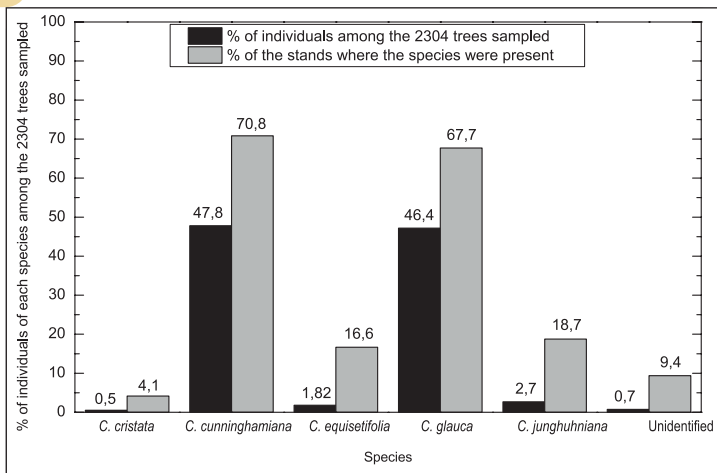


Figure 4.

Distribution of the 2,304 trees analyzed by species and proportion of stands where each species was present (all data are given as % of the total individuals and % of the 96 selected stands). Based on the χ^2 tests, the proportion ($\chi^2_{(11)} = 205$, $p < 0.001$) of each species as well as their distribution ($\chi^2_{(6)} = 3850$, $p < 0.001$) in the stands were not homogeneous.

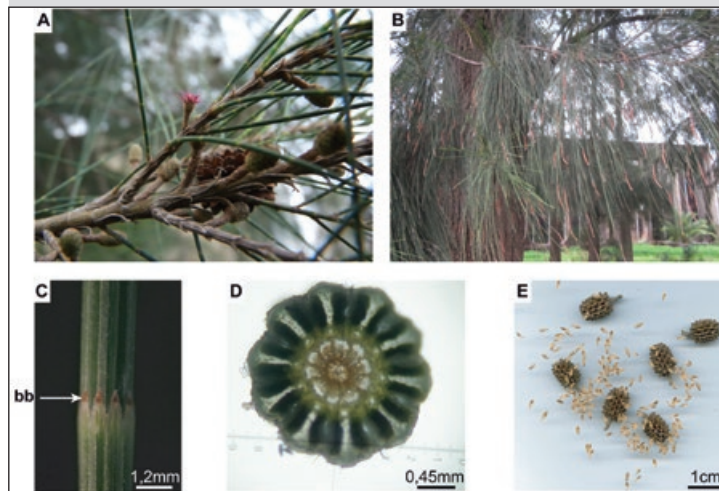
Symbiotic status of the *C. cunninghamiana* and *C. glauca* seedlings grown in nurseries

We examined whether seedlings of *C. cunninghamiana* and *C. glauca* produced in nurseries in Algeria are naturally mycorrhized and nodulated before their dissemination on the local market. For this, we assessed the prevalence of mycorrhizal and actinorhizal symbioses in 12-month-old seedlings produced in 12 nurseries chosen from different areas of Algeria.

Prevalence of mycorrhization

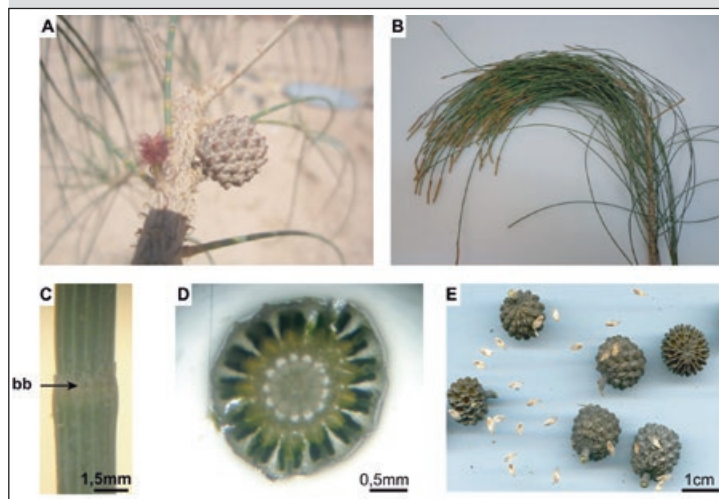
Careful examination of root systems of *C. cunninghamiana* and *C. glauca* plants did not reveal the presence of any ectomycorrhizal structures (Hartig net of hyphal mantle) indicating that these actinorhizal species were unable to form ectomycorrhizal symbiosis in the 12 nurseries from the North and the South of Algeria which regularly produce *Casuarina* seedlings for the local market (figure 1). In contrast, endomycorrhizal structures, mainly in the form of intra- and intercellular hyphae, were observed on most of the root systems of the two *Casuarina* species in all the nurseries included in the analysis. The presence of arbuscules and vesicles was also observed (photos 5A and 5B). The percentage of mycorrhized plants ranged from 70.8% to 100% for *C. cunninghamiana* and from 83.3% to 100% for *C. glauca* (table II). However, seedlings growing in nurseries located in the South were less mycorrhized (table II). These results indicate that both species can interact with endomycorrhizal fungi.

The percentage of mycorrhized plants of *C. cunninghamiana* and *C. glauca* in the nurseries was high (from 86,5% to 93,8%) while the mycorrhizal intensity (I%) had an overall mean of about 53% for both species (table II). Furthermore, I% was more intense in nurseries located in the North than those located in the South of the country (table II). However,



Photos 3.

Morphological characters of *Casuarina cunninghamiana*. A. Branches with female flowers; B. Branches with male flowers; C. Detail of a branch under a magnifying glass highlighting the leaves in whorls with small sharp teeth and a brown transverse band (bb); D. Cross section of a branch observed under a light microscope (10 teeth); E. Female cones and seeds. Photos K. Belaid.



Photos 4.

Morphological characters of *Casuarina glauca*. A. Branches with female flowers; B. Branches with male flowers; C. Detail of a branch under a magnifying glass highlighting the leaves in whorls with small sharp teeth and a brown transverse band; D. Cross sections of a branch observed under a light microscope (13 teeth); E. Female cones and seeds. Photos K. Belaid.

in the nurseries in the North as well as in the South, 1% for both *C. glauca* and *C. cunninghamiana* seedlings were not significantly different (table II).

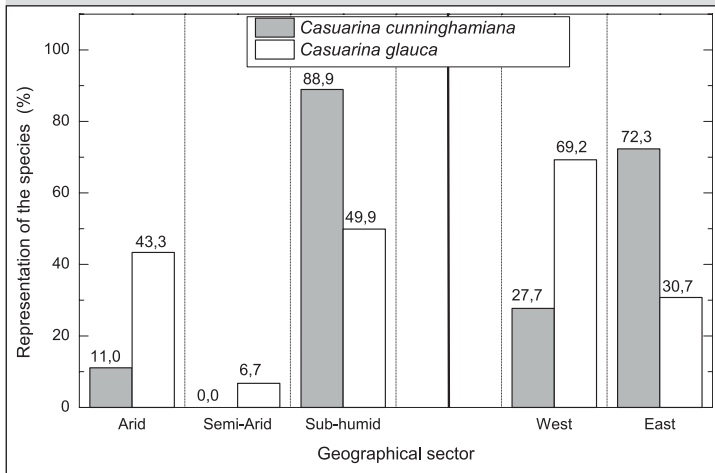
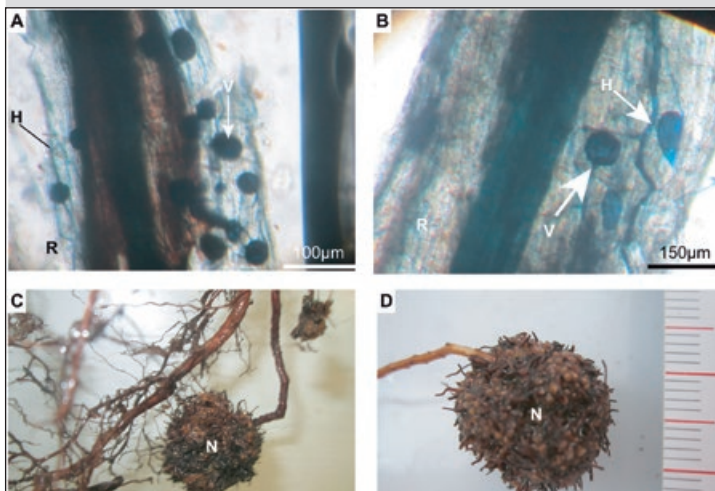


Figure 5. Geographical distribution of the two dominant *Casuarina* species (data are given as % of the total individuals for each geographical zone).



Photos 5. Symbiotic status of *Casuarina cunninghamiana* and *C. glauca*. A. Light microscope photograph of arbuscular mycorrhizal (AM) colonization of the root of *C. cunninghamiana* showing intercellular hyphae in the root cortical tissue and vesicles in the cortical layer; B. Light microscope photograph of arbuscular mycorrhizal colonization of the root of *C. glauca* showing extraradical hyphae of AM attached with the root and vesicles in the cortical layer; C. Root nodules of *C. cunninghamiana*; D. Root nodules of *C. glauca*. H: hyphae; R: root; N: nodule; V: vesicle. Photos K. Belaid.

Prevalence of nodulation

Root systems of *C. cunninghamiana* and *C. glauca* seedlings were examined for the presence of nodules. Results indicate that a low proportion of seedlings produced in the 12 nurseries were nodulated (photos 5C and 5D). The overall mean of nodulation was 28.8% for *C. cunninghamiana* and 26.4% for *C. glauca* with high differences between seedlings growing in northern and southern nurseries (table III). We have observed that seedlings growing in southern nurseries

were much less nodulated (11.1% and 11.8% respectively) than those growing in northern nurseries (46.5% and 50% respectively). In most cases, only a small fraction of seedlings was nodulated except for those growing in the nurseries of Algiers, Béjaia and El Kala located in a wetter zone. In addition, nodulation was absent in three nurseries located in the South (Districts of El Golea, Tamanrasset and Djanet). For both species, the number and dry weight of nodules per seedling were drastically lower in nurseries located in the South than those located in the North of the country. Overall, the two species showed a relatively reduced number of nodules and nodule dry weight per seedling (table III) and had a similar susceptibility to nodulation by *Frankia* in the 12 nurseries.

Discussion

Our survey conducted on 2,304 trees from 96 *Casuarina* stands situated all over Algeria indicates that *Casuarina* trees belong in most cases to the genus *Casuarina*. In Algeria, apart from 12 individuals likely to be *Allocasuarina verticillata* found in a unique site in the arboretum of Baïnem (district of Algiers), we did not find any records of *Allocasuarina* introduction listed in the literature: *A. littoralis*, *A. paludosa* and *A. torulosa* (GGA, 1850, 1865; Trotter, 1872; SGA, 1875; Toth, 1965). Our observations are consistent with those of Maire (1957) who stated that *Allocasuarina* species are very scarce in Algeria with *A. verticillata* (cited as *Casuarina quadrivalvis*) reported as the only species present.

Our investigations throughout the country showed that the genus *Casuarina* is represented by 5 species: *C. cristata*, *C. cunninghamiana*, *C. equisetifolia*, *C. glauca* and *C. junghuhniana*. However, individuals of *C. cunninghamiana* and *C. glauca* are by far the most frequent species in Algeria accounting for nearly 95% of the individuals sampled. These findings contradict previous reports considering *C. equisetifolia* as the most common or the only *Casuarina* species occurring in Algeria (Houmani, 1997). Our results are however partially in line with those of Maire (1957), who reported that only *C. cunninghamiana* and *C. glauca* occur in Algeria and stated that *C. equisetifolia* specimens previously reported from Algeria in the literature were in fact *C. cunninghamiana*, *C. glauca* or *Allocasuarina verticillata* (cited as *Casuarina quadrivalvis*). Such predominance of *C. cunninghamiana* and *C. glauca* is also observed in Morocco, Tunisia, and Egypt (El-Lakany, 1988; Ducousso *et al.*, 2003; Tellal *et al.*, 2008).

Furthermore, the two major species of *Casuarina* highlighted by this study showed a different distribution. *Casuarina cunninghamiana* is more common in the North and East which are the wettest and most temperate areas of the country while *C. glauca* is more represented in drier and warmer areas of the South and West (figure 5). Since there is no detailed history of the spread of *Casuarina* species after their introduction and establishment in Algiers, it is difficult to explain the origin of the current distribution of these

two species throughout Algerian rangelands. However, this difference in their distribution can probably be linked to the ecological properties of the two species. Indeed, *C. glauca* species is characterized by its better tolerance to drought, salinity, frost, and high temperatures (El-Lakany and Luard, 1983) and would have been preferred for plantations in the driest and hottest parts of the country. *Casuarina cunningghamiana* is a more temperate species and less adapted to drought, salinity and high temperatures. This explains why *C. cunningghamiana* is preferably planted in coastal and wet areas of Algeria.

Amongst the list of species highlighted by this study, *C. cristata* has yet to be reported in Algeria or any other North-African country. Its presence should be considered with caution since the CDA resulted in a very scarce grouping of the 12 individuals we attributed to this taxon (figure 2). The misidentification of *C. glauca* as *C. cristata* could have occurred as their morphometric traits are remarkably similar (Wilson and Johnson, 1989). This confusion is common and has led many authors to mistakenly state that *C. cristata* occurs in areas in which it was never introduced such as in Florida, Caribbean Islands, and Taiwan (Woodall and Geary, 1985). A similar misidentification could have occurred by Beddiar *et al.* (2015) who describe *C. obesa* as present in the North-East of Algeria, a species for which no introduction history to the country exists.

In our study, the size of *Casuarina* samples (2,304 individuals) was large enough to limit misidentifications. However, one should not exclude the existence of atypical individuals or hybrids which are quite frequent in nature (El-Lakany and Yunes, 1995; Kamalakannan *et al.*, 2006). In their native range of Australia, *Casuarina* species are typically allopatric - gene flow is limited by ecology (i.e., phenology and spatial distribution), rather than anatomical, biochemical or genetic incompatibilities (Woodall and Geary, 1985). Thus, crosses between species of the genus in which pollen is disseminated mainly by wind are possible as populations of *Casuarina* species with synchronous flowering periods overlap. Crossing between members of *Casuarina* genus has been observed in several areas of the world (Woodall and Geary, 1985; Wilson and Johnson, 1989).

Given that almost all *Casuarina* stands present in the country comprise two or more species and that the species present in Algeria all flower nearly simultaneously in early fall (September and October), the overlap of populations of different species may have favoured the appearance of many hybrids. The presence of hybrids in the stands we explored could explain why in almost all groups delimited by CDA, several individuals were ranged far from the centre of their corresponding cloud (figure 2). This could explain why we attributed some individuals to *C. cristata*, a species for which no introduction history in Algeria has been reported. This also could explain why a small number of individuals (17) could not be identified. Genetic markers could be used to confirm our identifications and to detect possible hybrids that can constitute an interesting plant genetic resource.

Regarding the symbiotic status of *C. cunningghamiana* and *C. glauca*, we observed that young individuals growing in each of the 12 nurseries were unable to deve-

lop ectomycorrhizal symbiosis. By contrast, the two species showed susceptibility to endomycorrhizal fungi with a high proportion of individuals that were colonized (table II). Although *Casuarina* species can interact with both ecto- and endomycorrhizal fungi, our observations are in line with previous reports indicating that they are more susceptible to endomycorrhizal fungi. Indeed, studies conducted by Mejstřík and Cudlín (1983), Nouasria and Beddiar (2010) and Beddiar *et al.*, (2015) reported only endomycorrhizae for *C. equisetifolia*, *C. cunningghamiana* and *C. obesa* growing in Algeria. Furthermore, Duponnois *et al.* (2003) showed that under axenic conditions, isolates of the ectomycorrhizal fungi *Pisolithus* and *Scleroderma* were unable to form a Hartig net on *C. glauca* while they could form ectomycorrhizae on *Allocasuarina verticillata*.

Although the endomycorrhization of *Casuarina* seedlings was globally high, the overall mycorrhizal intensity (1%) was lower. This 1% does not exceed 53% overall, which could be attributed to the reduced concentration of fungal inocula in culture substrates of the nurseries and/or to their composition. For instance, a high phosphate content of the substrate can strongly reduce or inhibit mycorrhization (Duponnois *et al.*, 2003).

Concerning the nodulation by the actinobacteria *Frankia*, our investigations indicate that the presence of root nodules on *C. cunningghamiana* and *C. glauca* seedlings was scarce in the 12 nurseries studied. The overall proportion of nodulated seedlings was less than 30% with a reduced number of nodules and nodule dry weight per seedling (table III). These results are interesting as there is no information about the history of the inoculation of these trees in Algeria. It is known that generally *Casuarina* cannot be nodulated outside their natural range due to the absence of compatible *Frankia* strains (Reddell *et al.*, 1986; Simonet *et al.*, 1999). Nodulated plants observed in the different nurseries indicate that the soils contained viable *Frankia* strains able to nodulate the *Casuarina* plantlets. Since the specificity between *Frankia* and their *Casuarina* hosts results from a long co-evolution process between the two symbionts, it is unlikely that native *actinobacteria* have adapted to *Casuarina*, given their relatively recent introduction to the country. The most probable explanation for the presence of these compatible strains is their co-introduction by *Casuarina* plant material (seedlings, cones, seeds, and solid substrates). Once in Algeria, these strains persisted and spread through the country *via* local exchanges of plant material between central and regional nurseries. The extensive use of *Casuarina* in the country has likely contributed to the spread of actinobacteria (Houmani, 1997).

Nevertheless, overall, the seedlings were scarcely nodulated and showed reduced nodule numbers and nodule dry weights indicating that the symbiosis with *Frankia* was not very effective. This could result from different factors such as the presence of low concentrations of *Frankia* bacteria in the culture substrate in the nurseries (Reddell *et al.*, 1986) or the chemical composition of the culture substrate. A phosphorus deficiency or a high content in nitrogen can also limit the nodulation of the seedlings (Dawson, 2008; Chaia *et al.*, 2010).

Furthermore, in the framework of this study, we could isolate a *Frankia* strain (named B2) from nodules collected from *C. cunninghamiana* seedlings growing in a nursery located at Souk El Tenine (District of Bejaia). The sequencing and the analysis of its genome indicate that the strain B2 is a new Algerian isolate (Belaid *et al.*, 2020).

Conclusion

Since their introduction in Algeria at the beginning of the 19th century, *Casuarina* trees have been rapidly propagated and widely planted for their rapid growth and hardiness and have become an important part of the ligneous flora of the country.

Our analysis revealed that the *Casuarina* trees currently occurring in the country belong to only 5 species with an overwhelming representation (95%) of the 2 species *C. cunninghamiana* and *C. glauca* which displayed distinct distribution. *Casuarina cunninghamiana* is more common in the North and the East while *C. glauca* is more commonly found in the South and the West. In addition, we found that *C. cunninghamiana* and *C. glauca* seedlings produced in nurseries showed low rates of spontaneous mycorrhizal intensity and nodulation. This can have an impact in the successful establishment of the trees in the planting areas where soils are poor or degraded.

Finally, our survey of *Casuarina* in Algeria brings new data and confirms with greater accuracy not only the identity but also the relative abundance and the distribution of a globally important tree genus. Further work is needed to evaluate the presence of putative hybrids (e.g., using genetic markers for the analysis of the morphometric traits), which can have implications for their use as commercially important trees. Similar works are needed in other countries where *Casuarina* have been widely planted, especially in the neighbouring countries in North Africa. This will allow to have an inventory of their distribution and to assess their ecological impact in this region.

References

- APG-The Angiosperm Phylogeny Group, Chase M. W., Christenhusz M. J. M., Fay M. F., Byng J. W., Judd W. S., *et al.*, 2016. An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG IV. *Botanical Journal of the Linnean Society*, 181: 1-20. <https://doi.org/10.1111/boj.12385>
- Beddiar A., Adouane M., Boudiaf I., Fraga F., 2015. Mycorrhizal status of main spontaneous or introduced forest trees in El Tarf province (Algerian North-east). *The Online Journal of Science and Technology*, 5 (2): 40-45. <https://dergipark.org.tr/tr/download/article-file/210262>
- Benge M. D., 1982. *Casuarinas*, "the best firewood in the world": Resources for charcoal, construction poles, windbreaks and shelterbelts and soil erosion and sand dune stabilization. Washington, DC, USA, Agency for International Development, 110 p.
- Belaid K., Swanson E., Carré-Mlouka A., Hoher V., Svistoonoff S., Simpson S., *et al.*, 2020. Draft genome sequence of the symbiotic *Frankia* sp. strain B2 isolated from root nodules of *Casuarina cunninghamiana* found in Algeria. *Journal of Genomics*, 8: 11-15. <https://doi.org/10.7150/jgen.38461>
- Bensaid S., 1995. Bilan critique du barrage vert en Algérie. *Sécheresse*, 3 (6): 247-255.
- Chaia E. E., Wall L. G., Huss-Danell K., 2010. Life in soil by the actinorhizal root nodule endophyte *Frankia*: A review. *Symbiosis*, 51 (3): 201-206. <https://doi.org/10.1007/s13199-010-0086-y>
- Christenhusz M. J. M., Byng J. W., 2016. The number of known plants species in the world and its annual increase. *Phytotaxa*, 261 (3): 201-217. <https://doi.org/10.11646/phytotaxa.261.3.1>
- Cruz-Castillo J. G., Ganeshanandam S., MacKay B. R., Lawes G. S., Lawoko C. R. O., Woolley D. J., 1994. Applications of canonical discriminant analysis in horticultural research. *HortScience*, 29 (10): 1115-1119. <https://doi.org/10.21273/hortsci.29.10.1115>
- Dawson J. O., 2008. Ecology of actinorhizal plants. In: Pawloski K., Newton W. E. (eds). Nitrogen fixation: origins, applications, and research progress. Vol. 6: Nitrogen-fixing actinorhizal symbioses. Dordrecht, Netherlands, Springer, 199-234.
- Ducouso M., Arahou M., Nourissier-Mountou S., Echbab H., Tellal M., Prin Y., *et al.*, 2003. Les microorganismes symbiotiques associés aux racines de *Casuarina cunninghamiana* et de *Casuarina glauca* au Maroc. *Annales de la Recherche Forestière au Maroc*, 36 : 9-25.
- Duponnois R., Diédhiou S., Chotte J. L., Sy M. O., 2003. Relative importance of the endomycorrhizal and (or) ectomycorrhizal associations in *Allocasuarina* and *Casuarina* genera. *Canadian Journal of Microbiology*, 49 (4): 281-287. <https://doi.org/10.1139/w03-038>
- El-Lakany M. H., 1988. Experience with some Australian species as multi-purpose trees in Egypt and North African countries. In: Proceedings of International forestry conference for the Australian bicentenary, Albury Wodonga, Australia, 25th April - 1st May 1988. Vol. V. Albury, Wodonga, Australia, Australian Forestry Development Institute, 16-33.
- El-Lakany M. H., Luard E. J., 1983. Comparative salt tolerance of selected *Casuarina* species. *Australian Forestry Research*, 13: 11-20.
- El-Lakany M. H., Yunes M. I., 1985. Genetic variation in some morphological and growth characteristics in *Casuarina cunninghamiana* and *C. glauca*. In: Eguiluz-Piedra T. (ed.). The State of the Art in Forest Genetics and Breeding. North American Forestry Commission, Universidad Autónoma Chapingo, Mexico, 143 p.
- GGA (Gouvernement Général de l'Algérie), 1850. Catalogue des végétaux cultivés à la pépinière centrale du gouvernement à Alger. Imprimerie du Gouvernement, Alger, 107 p.
- GGA (Gouvernement Général de l'Algérie), 1865. Catalogue des végétaux et graines disponibles et mis en vente au jardin d'acclimatation au Hama (près d'Alger) pendant l'automne 1865 et le printemps 1866. Bastide, Libraire Éditeur, Alger. 152 p.
- Gherbi H., Diagne N., Duponnois R., Bogusz D., Franche C., Bekki A., 2011. Casuarinaceae for soil rehabilitation in Algeria. In: Zhong C., Pinyopusarerk K., Kalinganire A., Franche C. (eds). Improving smallholder livelihoods through improved *Casuarina* productivity. Proceedings of the 4th International *Casuarina* Workshop, Haikou, China, 21-25 March 2010. China Forestry Publishing House, 249 p.
- Hammer Ø., Harper D. A. T., Ryan P. D., 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica*, 4 (1): 1-9. https://palaeo-electronica.org/2001_1/past/issue1_01.htm
- Houmani Z., 1997. Multiplication and utilization of ornamental trees in central Algeria. In: Heywood V. H., Skoula M. (eds). Identification of wild food and non-food plants of the Mediterranean region. Chania, Greece, CIHEAM, 33-42.
- Johnson L. A. S., Wilson K. L., 1993. Casuarinaceae. In: Kubitzki K., Rohrer J. G., Bittrich V. (eds). The families and genera of vascular plants. Volume II. Flowering plants – Dicotyledons. Magnoliid, Hamamelid and Caryophyllid families. Berlin, Germany, Springer Verlag, 237-242.

- Kamalakaran R., Barthwal S., Chezian P., Balasaravanan T., Yasodha R., Gurumurthi K., Ghosh M., 2006. Morphological and molecular diversity among *Casuarina* and *Allocasuarina* species. *Biotechnology*, 5 (3): 301-307. <https://scialert.net/abstract/?doi=biotech.2006.301.307>
- Maire R., 1957. Flore de l'Afrique du Nord : (Maroc, Algérie, Tunisie, Tripolitaine, Cyrénaïque et Sahara). Volume IV, Monocotyledonae : glumiflorae : Cyperaceae, Principes, Spathiflorae, Commelinales. In : L'Encyclopédie biologique. Vol. IV. Paris, France, Éditions Paul Lechevalier, 333 p.
- Maity P. J., Pawlowski K., 2021. Anthropogenic influences on the distribution of the *Casuarina-Frankia* symbiosis. *Symbiosis*, 84: 353-367. <https://doi.org/10.1007/s13199-021-00765-5>
- Makhlouf L., Nedjahi A., Abdellaoui M., Benarar S., 2012. Protection des périmètres agricoles dans les régions arides et semi-arides. Alger, Institut National de la Recherche Forestière, 44 p.
- Mejstřík V. K., Cudlín P., 1983. Mycorrhiza in some desert plant species in Algeria. *Plant and Soil*, 71: 363-366.
- Nouasria D., Beddiar A., 2010. Le statut symbiotique de *Casuarina equisetifolia* (filao) dans le Nord-Est Algérien. *Biodiversité, physiologie et écologie. Tunisian Journal of Medicinal Plants and Natural Products*, 3: 77-83.
- NRC (National Research Council), 1984. *Casuarinas: nitrogen-fixing trees for adverse sites*. Washington, DC, USA, National Academy Press, 118 p.
- Phillips J. M., Hayman D. S., 1970. Improved procedures for clearing roots and staining parasitic and vesicular-arbuscular mycorrhizal fungi for rapid assessment of infection. *Transactions of the British Mycological Society*, 55 (1): 158-161. [https://doi.org/10.1016/S0007-1536\(70\)80110-3](https://doi.org/10.1016/S0007-1536(70)80110-3)
- Potgieter L. J., Richardson D. M., Wilson J. R. U., 2014. *Casuarina*: biogeography and ecology of an important tree genus in a changing world. *Biological Invasions*, 16 (3): 609-633. <https://doi.org/10.1007/s10530-013-0613-x>
- Rakotomalala R., 2005. TANAGRA: un logiciel gratuit pour l'enseignement et la recherche. In: EGC 2005, vol. RNTI-E-3, 697-702.
- R Development Core Team, 2016. *R: A Language and Environment for Statistical Computing*. Vienna, Austria, R Foundation for Statistical Computing. <https://www.R-project.org/>
- Reddell P., Bowen G. D., Robson M., 1986. Nodulation of Casuarinaceae in relation to host species and soil properties. *Australian Journal of Botany*, 34: 435-444.
- SGA (Société Générale Algérienne), 1875. *Jardin du Hamma (près d'Alger) – Végétaux et graines – Catalogue général n° 3*. Imprimerie horticole de E. Donnaud, Paris, 160 p.
- Simonet P., Navarro E., Rouvier C., Reddell P., Zimpfer J., Dommergues Y., et al., 1999. Co-evolution between *Frankia* populations and host plants in the family Casuarinaceae and consequent patterns of global dispersal. *Environmental Microbiology*, 1 (6): 525-533.
- Tarai N., Doumandji S., 2009. Feeding preferences of gregarious nymphs and adults of the Desert locust, *Schistocerca gregaria* Forskal (Orthoptera, Cyrtacanthacridinae) in different habitats at Biskra oasis, Algeria. *Advances in Environmental Biology*, 3 (3): 308-313.
- Tellal M., Qarro M., Arahou M., Abourouh M., Tellal R., Rhazi L., et al., 2008. Effet de l'actinomycète *Frankia* sur la croissance et la fixation de l'azote de *Casuarina glauca* et *Casuarina cunninghamiana*. *Sécheresse*, 19 (3) : 211-216.
- Toth J., 1965. Aspect forestier d'une plantation saharienne. *Revue Forestière Française*, 10 : 674-695.
- Trottier M., 1872. *Les arbres de l'Australie*. Typographie de l'association ouvrière Aillaud et Compagnie, Alger, 20 p.
- Trouvelot A., Kough J. L., Gianinazzi-Pearson V., 1986. Mesure du taux de mycorrhization VA d'un système racinaire. Recherche de méthode d'estimation ayant une signification fonctionnelle. In: Gianinazzi-Pearson V., Gianinazzi S. (eds). *Physiology and genetics aspects of Mycorrhizae*. Paris, France, INRA, 217-221.
- Wall L. G., 2000. The actinorhizal symbiosis. *Journal of Plant Growth Regulation*, 19: 167-182.
- Wheeler G. S., Taylor G. S., Gaskin J. F., Purcell M. F., 2011. Ecology and management of Sheoak (*Casuarina* spp.), an invader of coastal Florida, USA. *Journal of Coastal Research*, 27: 485-492. <https://doi.org/10.2112/JCOASTRES-D-09-00110.1>
- Wilson K. L., Johnson L. A. S., 1989. Casuarinaceae. In: George A. S. (ed.). *Flora of Australia*. 3. Hamamelidales to Casuarinales. Canberra, Australia, Australian Government Publishing Service, 100-174.
- Woodall S. L., Geary T. F., 1985. *Identity of Florida Casuarinas*. USDA, Forest Service, Southeastern Forest Experiment Station, Research Note, 10-12.
- Zhong C., Zhang Y., Chen Y., Jiang Q., Chen Z., Liang J., et al., 2010. *Casuarina* research and applications in China. *Symbiosis*, 50: 107-114. <https://doi.org/10.1007/s13199-009-0039-5>

Belaïd et al. – Author's contributions

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Data access

Data collected as part of the work summarised in the article submitted to *Tropical Timber and Forests* (Excel files) may be used by contacting the corresponding author and citing the article. They are publicly available: <https://drive.google.com/drive/folders/18DGeFPOYfQb68adI4kjudBSOtMjetKSo?usp=sharing>

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Suitability of large-scale tree plantation models in Africa, Asia and Latin America for forest landscape restoration objectives

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Photo 1.

Teak seedling seed orchard, Woningiri, Central Java, Indonesia
Photo H. Baral/CIFOR.

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RÉSUMÉ

Adéquation des modèles de plantation à grande échelle en Afrique, en Asie et en Amérique latine aux objectifs de restauration des paysages forestiers

Les plantations forestières ont aujourd'hui un rôle crucial dans l'approvisionnement en bois et en produits dérivés du bois. Elles répondent à près de la moitié de la demande mondiale, tout en assurant une diversité de services écosystémiques. Dans les zones tropicales et subtropicales, où la croissance des arbres est optimale et où de grandes étendues de terre sont disponibles, la restauration des forêts est présentée comme l'une des stratégies les plus efficaces pour atténuer le changement climatique. Pour ces raisons, les plantations forestières à grande échelle sont encouragées en Afrique, en Asie et en Amérique latine. À partir d'une revue de la littérature et des bases de données publiques sur les plantations forestières, nous avons établi une typologie des plantations à grande échelle en Amérique latine, en Afrique et en Asie à partir de quatre critères : l'objectif de gestion (production ou protection), le nombre d'espèces plantées (plantations multi- ou monospécifiques), l'origine des essences (exotique ou indigène) et le mode de gestion (entreprises industrielles, petits exploitants privés, État). Notre analyse a identifié sept principaux types de plantations et révèle que les deux types les plus courants représentent près de 60 % de la superficie totale plantée : les plantations privées monospécifiques utilisant des espèces exotiques ; les plantations publiques mono-/multispécifiques orientées vers la production et utilisant des essences indigènes. De nombreuses études expérimentales ont été menées dans les années 1950 et 1960 en appliquant un large éventail de modèles de plantations forestières. Cependant, ces modèles ont été peu adoptés par les exploitants car les taux de production et les rendements financiers étaient considérés comme faibles. Les types de plantations majoritaires ne parviennent pas à atteindre la plupart des objectifs de restauration des forêts fixés dans le cadre du Défi de Bonn (productivité, stockage du carbone, conservation de la biodiversité, moyens de subsistance des populations rurales). D'autres modèles de plantations forestières à grande échelle pourraient être favorisés en se concentrant sur les autres biens et services qu'elles peuvent fournir. Cela pourrait se réaliser à condition d'impliquer des parties prenantes plus diversifiées dans les processus de conception et de gestion des plantations et de développer des incitations techniques, financières et institutionnelles appropriées.

Mots-clés : monospécifique, modèles de plantation, typologie, plantations forestières, essences exotiques, essences indigènes, reforestation, Afrique, Asie, Amérique latine.

ABSTRACT

Suitability of large-scale tree plantation models in Africa, Asia and Latin America for forest landscape restoration objectives

Today, tree plantations play a crucial role in supplying wood and wood-based products. They supply almost half of global demand, as well as supporting a diversity of ecosystem services. In tropical and subtropical areas, where tree growth is optimum and large tracts of land are available, forest restoration is presented as one of the most effective strategies for climate change mitigation. For these reasons, large-scale tree plantations are being encouraged in Africa, Asia and Latin America. Based on a review of the literature and of public databases on forest plantations, we drew up a typology of large-scale tree plantations in Latin America, Africa and Asia using four criteria: the management objective (production versus protection), number of species planted (multi-species versus mono-species), origin of species (exotic versus indigenous) and management status (industrial companies, private smallholders, state). Our analysis identified seven main plantation types and reveals that the two most common types represent almost 60% of the total planted area: (1) private mono-species plantations using exotic species; and (2) public production-oriented mono/multi-species plantations of indigenous trees. Numerous experimental studies were conducted in the 1950s and 1960s with a wide range of tree plantation models. However, few were adopted by operators because the production rates and financial returns were considered low. The dominant tree plantation types are failing to meet most of the forest restoration objectives set out in the Bonn Challenge (i.e., productivity, carbon storage, biodiversity conservation, rural livelihoods). Alternative large-scale tree plantation models could be promoted by focusing on the other goods and services that plantations can provide. This could be achieved if more diverse stakeholders were involved in plantation design and management processes, and if appropriate technical, financial, and institutional incentives were developed.

Keywords: mono-species, plantation models, typology, tree plantations, exotic species, native species, reforestation, Africa, Asia, Latin America.

RESUMEN

Idoneidad de los modelos de plantación de árboles a gran escala en África, Asia y América Latina con objetivos de restauración del paisaje forestal

Hoy en día, las plantaciones de árboles desempeñan un papel crucial en el suministro de madera y productos derivados. Suministran casi la mitad de la demanda mundial, además de proporcionar diversos servicios ecosistémicos. En las zonas tropicales y subtropicales, donde el crecimiento de los árboles es óptimo y se dispone de grandes extensiones de terreno, la restauración de los bosques se presenta como una de las estrategias más eficaces para mitigar el cambio climático. Por ello, se están fomentando las plantaciones de árboles a gran escala en África, Asia y América Latina. A partir de una revisión de la literatura y de las bases de datos públicas sobre plantaciones forestales, elaboramos una tipología de plantaciones de árboles a gran escala en América Latina, África y Asia utilizando cuatro criterios: el objetivo de la gestión (producción o protección), el número de especies plantadas (multiespecie o monoespecie), el origen de las especies (exóticas o autóctonas) y la modalidad de la gestión (empresas industriales, pequeños propietarios privados o estado). Nuestro análisis identificó siete tipos principales de plantación y revela que los dos tipos más comunes representan casi el 60 % de la superficie total plantada: (1) plantaciones privadas monoespecie con especies exóticas; y (2) plantaciones públicas monoespecie o multiespecie de árboles autóctonos destinadas a la producción. En los años 50 y 60 se realizaron numerosos estudios experimentales con una amplia gama de modelos de plantación de árboles. Sin embargo, pocos fueron adoptados por los operadores porque los índices de producción y la rentabilidad financiera se consideraron bajos. Los tipos mayoritarios de plantaciones de árboles no logran cumplir la mayoría de los objetivos de restauración forestal establecidos en el Desafío de Bonn (esto es, productividad, almacenamiento de carbono, conservación de la biodiversidad y medio de subsistencia rural). Se podrían promover modelos alternativos de plantación de árboles a gran escala centrándose en el resto de bienes y servicios que pueden proporcionar las plantaciones. Esto podría lograrse si se implicara a partes interesadas más diversas en los procesos de diseño y gestión de las plantaciones, y si se desarrollaran incentivos técnicos, financieros e institucionales adecuados.

Palabras clave: monoespecie, modelos de plantación, tipología, plantaciones de árboles, especies exóticas, especies autóctonas, reforestación, África, Asia, América Latina.

Introduction

In 2020, forests covered 31% of the global land area (4.06 billion hectares) and the vast majority (93%) were considered natural (FAO, 2020). There was a net decrease of 3% in the global forest area between 1990 and 2015. More specifically, the natural forest area worldwide decreased from 3,961 million hectares (M ha) in 1990 to 3,721 M ha in 2015. Most forest loss occurred in tropical regions in Central and South America, South and Southeast Asia and Africa (Keenan *et al.*, 2015). In contrast, the area of planted forests has risen from 4% of the world's total forest area in 1990 to 7% in 2020 (FAO, 2020). In absolute terms, planted forests increased from 167.5 to 294 M ha over the period 1990-2015 (Payn *et al.*, 2015; FAO, 2020). Therefore, planted forests now play a crucial role in roundwood production. They supply 47% of world demand for roundwood (including timber, woodfuel and pulp production) and provide a diversity of ecosystem services (FAO, 2017; Baral *et al.*, 2016).

In the context of climate change and biodiversity loss, well managed tree plantations can reduce pressure on natural forests, capture CO₂, enhance biodiversity conservation, restore degraded land or ecosystems, and improve food security and nutrition for rural populations, by providing a source of income, employment and economic growth (Chazdon, 2008; HLPE, 2017).

Planted forests are not a new phenomenon in Asia, Africa and Latin America. They were developed during the colonial and postcolonial eras (Szulecka *et al.*, 2014). There are various types of plantation, which depend on: (1) species composition (monoculture/mixed); (2) origin of the planted species (native/exotic); (3) plantation purpose (socio-economic and environmental); (4) plantation intended use (pulp, timber, woodfuel, non-timber forest products or ecosystem services); (5) land ownership (public and private, communal); (6) management responsibility (public and private); (7) management intensity (high-medium-low); (8) scale (large-medium-small); (9) original initiator of plantation (external and internal); and (10) level of institutional arrangements (D'Amato *et al.*, 2017; Baral *et al.*, 2016). Overall, three main approaches to planted forest emerge in the existing typologies (CIFOR, 2002; Brockerhoff *et al.*, 2008; Batra and Pirard, 2015): 1) small-scale tree plantations; 2) management of secondary forests (including enrichment); and 3) large-scale industrial plantations.

According to Bastin *et al.* (2019), “the restoration of trees remains among the most effective strategies for climate change mitigation”. Thus, several international processes have been launched, such as the REDD+ process or the Bonn Challenge to support and promote tree plantations around the world, especially in Africa, Asia and Latin America. Forest restoration is also a central component of national commitments to the Paris Agreement and of the United Nations' Sustainable Development Goals and Decade on Ecosystem Restoration (2021-2030). Nowadays, planting programmes are receiving more financial, political and societal support than ever (Holl and Brancalion, 2020). These initiatives largely focus on tropical and subtropical

areas (photo 1), where tree growth is faster (Lewis *et al.*, 2019) and larger tracts of land are available for tree planting (Bastin *et al.*, 2019). However, according to Chazdon and Brancalion (2019), “enormous gaps remain between high-level focus on restoration and implementation on the ground”. This disconnection can be partly explained by the fact that theoretical models of forest restoration are not adapted to the real constraints – particularly economic – encountered by tree plantation managers (Lopez-Sampson *et al.*, 2021). As a matter of fact, it is from a better understanding of actual large-scale tree plantation models and their historical evolution that we can analyse their ability to evolve and apply adapted forms of forest restoration. A better understanding and characterisation of the planted forests in Africa, Asia and Latin America would allow a more detailed analysis of their functions, advantages and limitations, and finally of their suitability to support reforestation efforts in tropical countries (Batra and Pirard, 2015; Malkamäki *et al.*, 2018). In this perspective, based on a literature review, this article aims to: (1) draw up and describe a typology of large-scale tree plantations in Africa, Asia and Latin America; (2) explore the regional dynamics of large-scale tree plantations; and (3) discuss their capacity to contribute to forest restoration.

Methods

Main concepts

A forest is a “land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10%, or trees are able to reach these thresholds *in situ*” (FAO, 2018). The FAO (2018) defines a “Forest Plantation” as a “Planted Forest that is intensively managed and meets all the following criteria at planting and stand maturity: one or two species, even age class, and regular spacing”. A planted forest is defined as a “forest composed mainly of trees established by planting and/or deliberate seeding, where planted and/or seeded trees constitute more than 50% of the mature growing stock”. The FAO definition of a “Forest Plantation” is recent, and no statistics are available for this specific land-use category. Therefore, when referring to planted forests, this article does not differentiate between “planted forest”, “forest plantations” or “tree plantations”. We define a “large-scale tree plantation” as a tree plantation of at least 50 ha on a single plot of land or as a series of small plantations, which may add up to hundreds or thousands of hectares, spread over different plots in the same territory, as the example of the Mampu plantation in Democratic Republic of Congo (photos 2) (Bisiaux *et al.*, 2009). These large-scale plantations can be mono or pluri-specific and even-age or not.

We do not include naturally regenerating forests in our analysis as they are defined by FAO (2018) as “forest predominantly composed of trees established through natural regeneration”.



Photos 2.

The Mampu plantation, in the Democratic Republic of Congo, is mostly constituted by *Acacia auriculiformis* plots belonging to hundreds of smallholders (a) and dedicated to woodfuel and cassava production (b). Photos A. Péroches.

Finally, forest restoration is defined as a “planned process that aims to regain ecological functionality and enhance human well-being in deforested or degraded landscapes” (Gann *et al.*, 2019). Therefore, a tree plantation is one option for forest restoration among others, such as natural regeneration, assisted natural regeneration, agroforestry, or rehabilitation/ reclamation (Chazdon, 2008). Note that according to Lewis *et al.* (2019) and Romijn *et al.* (2019) forest plantations and agroforestry systems represent 79% of forest restoration committed to by 24 countries through 2019.

Geographical scope

This study focuses on countries of Africa, Asia and Latin America. It is in these three continents that we find

most of the Bonn Challenge commitments (Lewis *et al.*, 2019) and where larger tracts of land are available for tree planting (Bastin *et al.*, 2019).

Literature Review

This study is based on a review of existing literature, including peer-reviewed and grey literature from 1990 to the present. The work began with the analysis of 50 references gathered by the co-authors during their past research. This preliminary database was supplemented by additional research using Google Scholar, which yielded 189 documents. The initial database made it possible to establish a first plantation typology and an overview of different geographical situations. Then, additional research was carried out in the second phase, which made it possible to obtain more specific documents by country/geographical region and/or type of plantation and/or specific theme (e.g., yields, pests, questions about sustainability, etc.). After a preliminary reading, 109 documents were discarded because they lacked information or specific relevance to the topic. Ultimately, 79 documents were selected (48 articles, 23 technical reports, 5 conference papers and 3 books).

Choosing variables for defining a typology for large-scale tree plantations

Two steps were followed in selecting the most suitable variables to design a large-scale tree plantation typology: (i) a review of existing tree plantation typologies and a Google Scholar search to identify criteria in order to determine the different types of large-scale plantation for our database, and (ii) identification of the most relevant discriminating factors under the constraint that they can be documented for each tree plantation type.

We identified three existing typologies (CIFOR, 2002; Brockerhoff *et al.*, 2008; D’Amato *et al.*, 2017). The typology proposed by D’Amato *et al.* (2017) is the most complete and uses a coding system of 11 criteria. In comparison, the CIFOR (2002) and Brockerhoff *et al.* (2008) typologies are based on three discriminating factors. These typologies are not specific to large-scale plantations.

All three typologies use the following criteria to define plantation type: the nature of the plantation (species composition: monoculture or mixed and native or exotic), its purpose and management intensity. While the first two criteria are easy to determine, the third is less clear-cut. Consequently, we chose the nature of the plantation (tree type) and the purpose of the plantation as discriminating factors to define the typology for large-scale plantations.

Beyond these three factors, D’Amato *et al.* (2017) stress the importance of other variables, such as: (a) species composition (monoculture or mixed); (b) a plantation’s intended use (provision, regulation and cultural services); (c) land ownership (public and private); (d) management responsibility (public and private); (e) scale (large-medium-small) and composition (monoculture/mixed) in landscape; (f) original initiator of plantation (external and internal); and (g) level of institutional arrangements. Criteria (a) and (d) are easy

to evaluate and have been included in our typology, along with the nature and purpose of the plantation. Criterion (b) is already included in the typologies of CIFOR (2002) and Brockerhoff *et al.* (2008). Criteria (c), (f) and (g) are not easy to determine and were therefore excluded from our definition. Lastly, criterion (e) is not relevant because it does not relate to large-scale tree plantations.

Based on the analysis, four criteria were selected for our typology:

1. Management responsibility (or forest ownership) – The latest FRA report (FAO, 2020) and D’Amato *et al.* (2017) distinguish two main types of forest ownership: public or private. Szulecka *et al.* (2014) state that these two categories are also valid for tree plantations. Del Lungo *et al.* (2006) go further, by separating the private sector into two categories: companies and smallholders. As explained by D’Amato *et al.* (2017), the nature of “ownership and management are relevant to identifying plantation types because it can exert both positive and negative forces on local communities, for instance by influencing the status of, and access to plantation land and surrounding ecosystems and related services, and by influencing community life and relations, livelihoods, education and employment opportunities”. Three categories are distinguished: public plantations, company plantations and plantations owned by smallholders. In the case of private plantations (companies or smallholders), the land may belong to the private person in charge of the plantation or to the state.

2. Planted species – In Africa, Asia and Latin America, most tree plantations are based on even-aged short rotation stands of exotic (non-indigenous) species and intensive management methods (Tassin, 2011; Jürgensen *et al.*, 2014; Payn *et al.*, 2015). In most cases, the main species planted are pine, eucalyptus, acacia and teak (Cossalter and Pye-Smith, 2003; Louppe, 2011; Cateau *et al.*, 2018). These are fast growing exotic species, their seeds are easy to obtain, and their silvicultural techniques are known (Louppe, 2011; INDUFOR, 2017).

3. Species composition – Species can be planted as monocultures or in mixed stands, although mixed plantations are uncommon (Lopez-Sampson *et al.*, 2021). This makes a significant difference in terms of biodiversity and economic returns (D’Amato *et al.*, 2017).

4. Purpose of the plantation – Louppe (2011) points out that the primary objective of planting exotic species is to produce pulp or wood energy, followed by timber. Del Lungo *et al.* (2006) and Szulecka *et al.* (2014) also mentioned that some plantations have protection objectives (protection of soil and water resources, carbon storage, etc.). The fourth discriminating factor used was the objective of the plantation (i.e., timber, pulp or woodfuel production, ecosystem services-oriented or multi-purpose).

Determination of relative weight of each type of plantation

Firstly, in the cited bibliographic sources, all references to the areas covered by large-scale plantations were collected and classified by plantation type, by country and

finally by continent. It is on the basis of these figures that the areas covered, and the relative weight of each type were estimated by continent. When the estimated areas were presented as a range, the middle of the class was retained. Regarding the precision of the available literature, the scale of analysis that seems the most relevant to us is the continent, even if contrasting dynamics can sometimes exist within the same continent.

Key results from the bibliographic summary

Relevant types of large-scale tree plantations in Africa, Asia and Latin America

Based on the four discriminating factors, a “decision tree” was constructed (figure 1). According to figure 1, 60 “theoretical” types of large-scale tree plantations were identified. However, most of these theoretical types do not actually exist or are negligible. The types not mentioned in the literature, or which only cover very small areas (a few thousand hectares) were considered negligible. For example, exotic multi-species stands occupied less than 0.1% of all large-scale plantations worldwide in 2006 (Nichols *et al.*, 2006), and no recent source mentioning the existence of this type of tree plantations has been identified. After eliminating the non-existent theoretical types, we identified seven groups of large-scale tree plantations in Africa, Asia and Latin America (figure 1): Type 1 = Private and production-oriented plantations of monospecific exotic species; Type 2 = Private and production-oriented plantations of mono/multi-specific indigenous species; Type 3 = Public and ecosystem services-oriented plantations of monospecific exotic species; Type 4 = Public and production-oriented plantations of monospecific exotic species; Type 5 = Public and production-oriented plantations of mono/multi-specific indigenous species; Type 6 = Public and ecosystem services-oriented plantations of mono/multi-specific indigenous species; Type 7 = Production-oriented plantations of monospecific exotic species managed by smallholders. The main characteristics of these types are provided in tables I to VII.

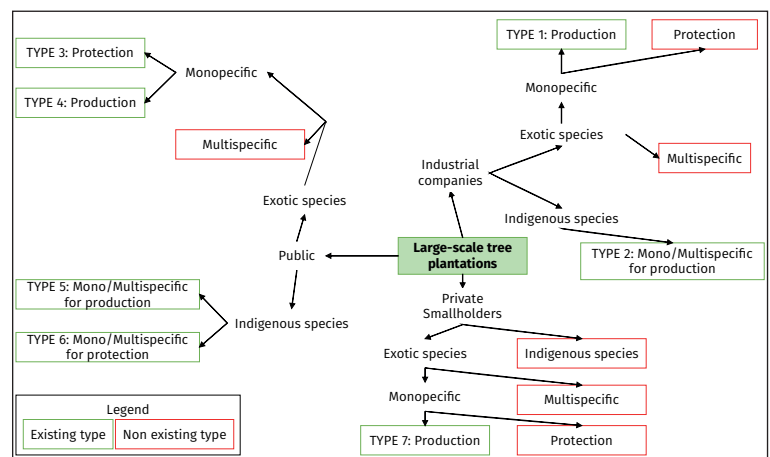


Figure 1. Diagram of relevant types of large-scale tree plantations in Africa, Asia and Latin America.

Table I.

Type 1: Large-scale plantation characteristics – Private and production-oriented plantations of monospecific exotic species.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
25 – 32	Asia (Indonesia, Thailand, India). South America (Brazil, Chile, Argentina, Uruguay). Africa (Mainly South Africa and Congo).	Significant increase, particularly over the last 15 years. It is the dominant model in southern countries.	Most aged from 5 to 10 years, with a harvesting period ranging from 8 to 30 years.	15 – 40 m ³ /ha/year (Exceptionally up to 40).
Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Mainly degraded land and savanna areas. 6 to 7% of the surfaces were deforested for plantation installation. This is particularly true in Chile and Indonesia.	Eucalyptus, acacia (<i>mangium</i> , <i>auriculiformis</i> and <i>parkia</i>), pine and teak.	Significant pressure from pests and diseases linked to monoculture and the cultivation of clones outside their area of origin. For example, over 50 types of pests and diseases, which attack acacias and eucalyptus, have been listed in Vietnam alone.	Model highly criticised for its environmental and social impact: <ul style="list-style-type: none"> ▪ High chemical input use ▪ Low biodiversity ▪ Soil depletion ▪ Pollution and over-consumption of water ▪ Frequent conflicts with local populations, particularly over land ▪ Low job creation per hectare and increasing urban migration ▪ Considered as the secondary cause of deforestation in Southeast Asia and South America. However, this plantation type can alleviate pressure on natural forests due to its high productivity. 	

References: Zobel *et al.*, 1987; Cossalter and Pye-Smith, 2003; Mugo and Ong, 2006; FAO, 2010b; Thu *et al.*, 2010; Tassin, 2011; Kollert and Cherubini, 2012; Elias and Boucher, 2014; Martin, 2014; Nambiar and Hardwood, 2014; Szulecka *et al.*, 2014; Andersson *et al.*, 2015; Payn *et al.*, 2015; WWF, 2015; Cateau *et al.*, 2018.

Table II.

Type 2: Large-scale plantation characteristics – Private and production-oriented plantations of mono/multi-specific indigenous species.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
< 5	Asia. Africa.	An increase in teak plantations in Asia (particularly India), stable due to the low economic interest for other species.	15 to 25 years.	Varies according to species. Generally, relatively low (< 5 m ³ /ha/year) and between 10 and 20 m ³ /ha/year for teak.
Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Generally degraded forest areas.	Several depending on geographical areas. Largely dominated by teak (in native countries) in Asia.	Few documented. Lepidoptera attacks noticed on the genus <i>Khaya</i> in Africa.	Model highly criticised for its environmental concerns because it could potentially reduce harvesting in the natural environment, specifically for certain species, particularly in Central Africa. Few visible impacts on local populations due to the absence of very large-scale plantations, except in the case of teak. Potential land conflicts and value-added sharing identified in the development of this model.	

References: Brunck and Mallet, 1993; Marien and Mallet, 2004; Elias and Boucher, 2014; Karsenty, 2018.

Table III.

Type 3: Large-scale plantation characteristics – Public and ecosystem services-oriented plantations of monospecific exotic species.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
= 5	Asia (Mainly China and India). Africa (Mainly Tunisia).	Significant increase in the late 1990s and 2000s, particularly with Chinese government programmes. Significant increase in Tunisia between 1990 and 2015. Still increasing in Asia and Tunisia.	15 to 15 years.	Approximately 5 m ³ /ha/year.
Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Areas that are degraded / threatened by desertification.	Eucalyptus, acacia, pine, poplar, teak.	In China, some indigenous and exotic forest parasites, such as pine caterpillars, fall worms, spring cankerworms, nematodes, pine mealybugs and rodents destroy large areas of plantations. In Tunisia, eucalyptus plantations are frequently attacked by four types of insects from Australia, including two species of wood borers and two species of gall insects.	Some projects compete with local populations' traditional and agricultural practices, creating tensions. This type of plantation limits biodiversity due to the monoculture of exotic species. Nevertheless, it can help restore very degraded areas and protect some soils from erosion. In addition, it contributes to carbon storage. Risks of the spread of invasive species are occasionally identified.	

References: Chokkalingam *et al.*, 2006; Del Lungo *et al.*, 2006; Dhahri and Ben Jamâa, 2008; Jacovelli, 2014; Duponnois *et al.*, 2013; Liu *et al.*, 2014; Wolosin, 2017.

Table IV.

Type 4: Large-scale plantation characteristics – Public and production-oriented plantations of monospecific exotic species.

Areas concerned (in M ha)	Main geographical areas concerned	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
6 – 8	Asia (mainly China and India) and Africa (Côte d'Ivoire, Ghana, Morocco, Ethiopia, Madagascar, etc.).	Significant growth, particularly in Asia until the 2000s. Since then, growth rate has slowed down because states generally favour the private sector for this type of plantation.	5 to 15 years.	10 – 40 m ³ /ha/year.
Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Degraded or agricultural areas.	Eucalyptus, acacia, pine and teak.	In China, some indigenous and exotic forest parasites, such as pine caterpillars, fall worms, spring cankerworms, nematodes, pine mealybugs, and rodents destroy large areas of plantations.	Some projects compete with local populations' traditional and agricultural practices, creating tensions. This type of plantation limits biodiversity due to the monoculture of exotic species (even if it can participate to local species recolonization). In addition, the regular export of woody material can further deplete poor soils. However, it can protect some soils from erosion, contribute to carbon storage and reduce pressure on natural forests.	

References: Barr and Cossalter, 2004; Del Lungo *et al.*, 2006; Tassin *et al.*, 2011; Kollert and Cherubini, 2012; Liu *et al.*, 2014; Wolosin, 2017; Dubiez *et al.*, 2018.

Table V.

Type 5: Large-scale plantation characteristics – Public and production-oriented plantations of mono/multi-specific indigenous species.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
≈ 20	Asia (Mainly China and India). Africa (Mainly Sudan, over a few tens of thousands of hectares in Gabon or Côte d'Ivoire).	Significant increase, particularly in China since 1990. Weak dynamics in Sudan, where most plantations are old.	15 to 30 years.	Varies according to species. Generally, relatively low (< 5 m ³ /ha/year).
Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Agricultural land, savanna and degraded forest areas.	Chinese fir trees, poplars, acacias from Africa, teak.	In Sudan, most damage to acacias is due to goat and camel alimentation (pruning). Parasite attacks are secondary. Quite variable depending on country and species. Monocultures are generally more sensitive.	Some projects compete with local populations' traditional and agricultural practices, creating tensions. Monospecific plantations (85% of plantations in China), limit biodiversity. Conversely, multi-species plantations have a positive impact on biodiversity. This plantation type can help restore degraded areas, provide carbon storage and provide local resources to the population.	

References: Del Lungo *et al.*, 2006; Gafaar, 2011; Marien *et al.*, 2013; Jacovelli, 2014; Wolosin, 2017; Chevalier, 2018.

Table VI.

Type 6: Large-scale plantation characteristics – Public and ecosystem services-oriented plantations of mono/multi-specific indigenous species.

Areas concerned (in M ha)	Main geographical areas concerned	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
10 – 15	Mainly East Asia (China and India).	Significant increase, particularly in China, as a result of government programmes.	Most range from 10 to 20 years.	Varies according to species. Generally, relatively low (< 5 m ³ /ha/year).
Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Degraded forest and/or agricultural areas.	Chinese fir tree, poplar.	This plantation type does not seem to have too many problems.	Beneficial effects on soil protection, water resource protection and carbon storage.	

References: Del Lungo *et al.*, 2006; Liu *et al.*, 2014; Wolosin, 2017.

Table VII.

Type 7: Large-scale plantation characteristics – Production-oriented plantations of monospecific exotic species managed by smallholders.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
< 5	Africa and Asia.	Little development globally. Development is strongly correlated with the initial public, private or NGO investment.	5 to 10 years based on rotations.	10 – 20 m ³ /ha/year.
Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Degraded forests, wooded savannas.	Eucalyptus, pine and acacia.	Little documentation available.	In many cases, exporting a large part of the woody material at regular intervals can reduce soil fertility (especially in the case of woodfuel production). Given that erosion is usually the main factor involved in soil degradation, this plantation type has positive features. It generally improves the incomes of poor households.	

References: Enters *et al.*, 2004; Del Lungo *et al.*, 2006; Bisiaux *et al.*, 2009; Verhaegen *et al.*, 2014; Dubiez *et al.*, 2018.

Regional trends from 1990 to 2015 by large-scale plantation category/typology

Latin America

Today, Latin America has just over 21.5 M ha of tree plantations (FAO, 2020), of which 80-90% are planted with exotic species (Payn *et al.*, 2015; FAO, 2020). The main planted species are eucalyptus (70%) and pine (25%) (photo 3) (ITTO, 2009; Payn *et al.*, 2015). In this region, the area covered by tree plantations increased by 3.2% per year for the decade 2000-2010. This growth was driven by the private sector and supported by state land and tax policy incentives (ITTO, 2009; EFIATLANTIC *et al.*, 2013). Overall, Type 1 plantations are the most represented category of large-scale plantations.

Wood-based products obtained from South American plantations are generally exported (Cossalter and Pye-Smith, 2003; ITTO, 2009; Cateau *et al.*, 2018). Brazil and Chile have the largest areas of plantations (Jürgensen *et al.*, 2014; Payn *et al.*, 2015), which account for two-thirds of the region's total plantation area (EFIATLANTIC *et al.*, 2013; Payn *et al.*, 2015; Cateau *et al.*, 2018). In both countries, tree plantations produce greater volumes of wood-based products than natural forests (James and Del Lungo, 2005). In Chile, large-scale tree plantations were initially responsible for the deforestation of native forests. However, it seems that since 2001, a shift in tree plantation management combined with changes in forestry policy, have reduced pressure on native forests over time (Heilmayr *et al.*, 2016).

Asia

Asia is the leading continent in terms of forest plantation area, with nearly 123 M ha (EFIATLANTIC *et al.*, 2013). Unlike Latin America, in Asia, plantations of native species are the dominant model (Payn *et al.*, 2015). These native species plantations, such as industrial plantations of teak in India (a native species in the region), are managed according to the same intensive model used for exotic species (ITTO, 2009).

In Asia, historically, the development of tree plantations was based on public projects and funding. One of the main objectives of the plantations was to protect soil and water resources (EFIATLANTIC *et al.*, 2013; Wolosin, 2017). According to FAO (2010a), nearly 30% of the planted area in Asia is geared towards the protection of soil, water resources or biodiversity, more than in any other region of the world. Therefore, a significant proportion of plantations are public and correspond to plantation Types 3, 4, 5 and 6 (Enters *et al.*, 2004; Del Lungo *et al.*, 2006; Wolosin, 2017). Nevertheless, as in most southern countries, since the late 1990s and early 2000s, there has been growing interest in and a major development of industrial production-oriented plantations, particularly in Southeast Asian countries, such as Indonesia and Thailand (Michon, 2003; Enters *et al.*, 2004; Szulecka *et al.*, 2014; Wolosin, 2017). In China, the leading country in terms of planted area, the state has maintained control over plantations (Martin, 2014), which are mainly intended for protection purposes (Liu *et al.*, 2014; Wolosin, 2017).

Then, in Asia, two contrasting situations co-exist: (i) the Chinese model, mostly based on Types 3, 4, 5 and 6; and (ii) the Southeast Asian model, where Type 1 is predominant, as it is in Latin America.



Photo 3.
Clear cutting of a *Pinus patula* plantation in Colombia.
Photo D. Torres.

Africa

Africa has 11.4 M ha of tree plantations (FAO, 2020), of which 80% are indigenous species, mainly *Acacia senegal* and *Acacia nilotica*¹ (Gafaar, 2011; Jacovelli, 2014; Payn *et al.*, 2015). The rate of increase in plantation area on the African continent is one of the lowest in the world (Payn *et al.*, 2015). Apart from the specific case of South Africa, most African plantations are state-owned (EFIATLANTIC *et al.*, 2013). Large planting campaigns in the 1970s and 1980s failed to meet expectations. Since then, there have been few planting campaigns because of a lack of interest or state withdrawal in the 1990s (Marien and Mallet, 2004; Louppe, 2011; Hamel and Dameron, 2011; Chevalier, 2018).

Sudan (and South Sudan) and South Africa are the top two countries in terms of tree plantation area (Jacovelli, 2014; Cateau *et al.*, 2018). However, their large-scale plantation strategies are very different. For example, in Sudan, tree plantations are public plantations of indigenous species to produce gum arabic (Type 5). In South Africa, private industrial plantations of exotic species (pine, eucalyptus and acacia) (Type 1) are the predominant model (Del Lungo *et al.*, 2006; Jacovelli, 2014; Cateau *et al.*, 2018). However, in this country, expansion of Type 1 plantations is limited with planted area remaining stable (Jürgensen *et al.*, 2014) because of poor soil quality, lack of water and competition with other land uses in the country. Tunisia comes in third in terms of tree plantation area, with Eucalyptus being the main species planted to reduce desertification (Type 3) (Jacovelli, 2014). The remaining African countries have less than 0.7 million hectares of plantations combined.

¹ Established by direct sowing and in low density.

Discussion

The typology of tree plantations established in this article is based on the state of available knowledge to provide an operational tool for classifying plantations. Nevertheless, the four criteria retained are relevant for discussing the place of these tree plantation models in relation to forest restoration objectives:

1- Management responsibility (or forest ownership) – This first criterion has indirect impacts on forest restoration objectives. The status, management and access to the plantation land and its related services (ecosystem, social, economic) have an impact on local communities' well-being (D'Amato *et al.*, 2017).

2- Planted species – The recovery of ecological functionality of an area is better in native species tree plantations than in exotic species plantations (Malkamäki *et al.*, 2018).

3- Species composition – The recovery of ecological functionality of an area is better in mixed tree plantations than in monoculture tree plantations (D'Amato *et al.*, 2017).

4- Purpose of the plantation – The four retained objectives of tree plantations (i.e., timber, pulp or woodfuel production, ecosystem services-oriented or multi-purpose) have direct impacts on biodiversity and human well-being.

Considering the three continents analysed, the dominant model for large-scale tree plantations is private industrial monospecific plantations of exotic species (eucalyptus, pine, acacia and teak in non-native areas), which corresponds to our Type 1 (figure 2). These plantations are largely dominant in Latin America and Southeast Asia. In addition, the development of these plantations has been particularly

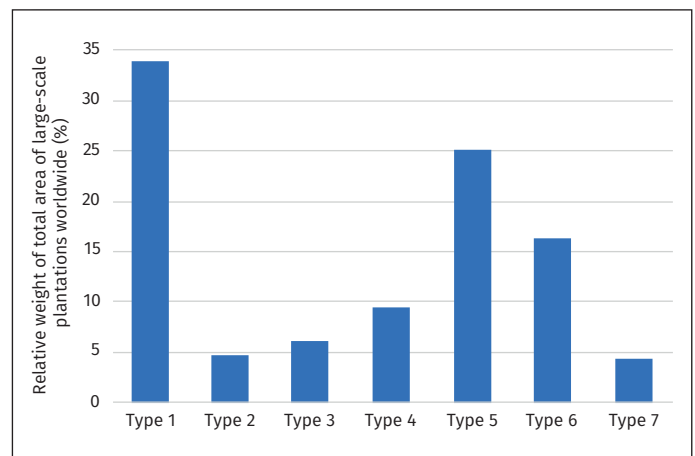


Figure 2.

Relative weight of large-scale plantation typologies worldwide (as %): Type 1 = Private and ecosystem services-oriented plantations of monospecific exotic species; Type 2 = Private and production-oriented plantations of mono/multi-specific indigenous species; Type 3 = Public and ecosystem services-oriented plantations of monospecific exotic species; Type 4 = Public and production-oriented plantations of monospecific exotic species; Type 5 = Public and production-oriented plantations of mono/multi-specific indigenous species; Type 6 = Public and ecosystem services-oriented plantations of mono/multi-specific indigenous species; Type 7 = Production-oriented plantations of monospecific exotic species managed by smallholders.

Table VIII.

Main criticisms of Type 1 – Large-scale plantation model in Africa, Asia and Latin America.

Sustainability parameters	Weaknesses of the dominant model	References
Contribution to the preservation of biodiversity.	Monocultures and pesticide applications are harmful to biodiversity, which is low in plantations. The use of exotic species can cause imbalances (e.g., invasions) in natural biological processes. Fragmentation of natural forest stands is harmful to the survival of sensitive species. In some cases, new plantations may be responsible for the deforestation of natural forests.	Cossalter and Pye-Smith, 2003; Brockerhoff <i>et al.</i> , 2008; Chazdon, 2008; Barua <i>et al.</i> , 2014; Andersson <i>et al.</i> , 2015; Cateau <i>et al.</i> , 2018; Liu <i>et al.</i> , 2018.
Carbon storage.	Land is harvested and cleared for replanting (typically once a decade), which releases carbon as a result of decomposition of plantation waste and products (mostly paper and woodchip boards).	Lewis <i>et al.</i> , 2019.
Preservation of soil quality.	The use of pesticides and intense production methods depletes the soil over time (chemical pollution, compaction and erosion).	Barua <i>et al.</i> , 2014; Andersson <i>et al.</i> , 2015; Cateau <i>et al.</i> , 2018; Liu <i>et al.</i> , 2018; Malkamäki <i>et al.</i> , 2018.
Preservation of the quality of water resources.	The use of chemical pesticides pollutes the water resource. Water resources are overexploited in some cases to irrigate plantations, which reduces river flow rate.	Cossalter and Pye-Smith, 2003; Andersson <i>et al.</i> , 2015; Cateau <i>et al.</i> , 2018; Liu <i>et al.</i> , 2018; Malkamäki <i>et al.</i> , 2018.
Social and economic development of production areas.	Low job creation per hectare compared to other types of plantation. Frequent source of social conflict, particularly relating to land issues. Displacement of local population.	Cossalter and Pye-Smith, 2003; Enters <i>et al.</i> , 2004; Van Bodegom <i>et al.</i> , 2008; Barua <i>et al.</i> , 2014; Andersson <i>et al.</i> , 2015; Cateau <i>et al.</i> , 2018; Liu <i>et al.</i> , 2018; Malkamäki <i>et al.</i> , 2018.
Maintaining production in the long term.	This type of plantation is the most susceptible to pests and diseases, which can be a problem in the medium term. This type of plantation seems to be the least resilient to climatic phenomena and, therefore, to future climate change.	Cossalter and Pye-Smith, 2003; Chazdon, 2008; Barua <i>et al.</i> , 2014; Cateau <i>et al.</i> , 2018; Liu <i>et al.</i> , 2018.

dynamic in Brazil, Southeast Asia and China over the last two decades. This plantation category has various advantages: (i) it stores carbon and produces large quantities of wood products; (ii) it can rehabilitate degraded soils; and (iii) it probably reduces pressure on natural forests – this last point being questionable according to Pirard *et al.* (2016) (Cossalter and Pye-Smith, 2003; Buongiorno and Zhu, 2014; Martin, 2014; Cateau *et al.*, 2018). However, Malkamäki *et al.* (2018) conclude, based on a few examples, that industrial exotic monoculture tree plantations often have a negative environmental and social impact. The main criticisms of this model are summed up in table VIII. Therefore, Type 1 fails to meet the necessary conditions – particularly environmental – for forest restoration objectives in accordance with recent international commitments (Bonn Challenge, UN Decade on Ecosystem Restoration or national commitments to the Paris Agreement). According to Malkamäki *et al.* (2018), these environmental and social impacts of Type 1 plantations should be studied more. This affirmation is confirmed by the study of Pirard *et al.* (2017), which

shows that in Indonesia, these plantations can be perceived as either positive or negative by local populations, and may or may not have social impacts on those populations. In the same way, Tassin *et al.* (2011) explain that planted on degraded land near to natural areas, cloned eucalyptus can facilitate the recolonization of native flora and fauna. That is why a better understanding of various situations could improve the outcomes of large-scale tree plantations on local populations and/or the environment.

This synthesis of literature also shows that regardless of the purpose of a tree plantation, all models are controversial. For example, Bremer and Farley (2010) discuss Type 3, sometimes qualifying it as “green-desert”. The conclusions of their study “suggest that plantations are most likely to contribute to biodiversity when established on degraded lands rather than replacing natural ecosystems, such as forests, grasslands and shrublands, and when indigenous tree species are used rather than exotic species”. Then, the debate is nearer to the one about Type 1, when dedicated to intensive wood production.

From the early 20th century until the 1980s, very diverse mixed plantation models were designed and tested in Africa, Asia and Latin America (Lopez-Sampson *et al.*, 2021). However, they were rarely adopted, primarily because they would probably give low financial returns. Financial returns are documented for exotic monocultures as *Eucalyptus* spp. or *Pinus* spp. (Cubbage *et al.*, 2014), however, financial performance and operation costs of mixed plantations are limited or absent from the literature (Lopez-Sampson *et al.* 2021). According to Cubbage *et al.* (2014), environmental regulations and land rent to governments or local populations reduce plantation investment returns. Then, to promote more socially and environmentally diverse and more efficient tree plantation models, non-financial aspects should be factored in, and the involvement of governments (in both producer and consumer countries) and other stakeholders should be encouraged.

What are the alternatives to Type 1 large-scale tree plantations?

Alternative tree plantation models may be more effective for forest restoration in Africa, Asia and Latin America. According to Brockerhoff *et al.* (2008), native species and long rotation cycles are prerequisites for sustainability. Numerous authors have demonstrated that multi-species plantations improve the sustainability performance of large-scale tree plantations. They optimise environmental resource use, increase productivity and CO₂ storage per hectare, and improve resilience to climatic and biological hazards (Erskine *et al.*, 2005, 2006; Nichols *et al.* 2006; Hung *et al.*, 2011; Louppe, 2011; Pryde *et al.*, 2015; Kelty, 2006; Liu *et al.*, 2018).

Developing alternative plantation types requires funding that will accept a higher risk factor. Funds could be provided by governments or public sources, as illustrated in China (Xu *et al.*, 2004), or by a mix of public incentives, including subsidies, tax benefits and preferential access to credit for private societies as in the Chilean example (Heilmayr *et al.*, 2020). As shown in figures 3 and 4, large-scale tree plantation types are more diverse in Asia and Africa. This can be explained partially by the fact that public funds were allocated to establish plantations. This was not the case in Latin America, where private investment is dominant. Thus, past experiences show the importance of public funds in parallel with or in addition to private investments for developing diverse models of large-scale tree plantations and for considering general interest.

However, alternative tree plantation types have also been criticised. Each type has specific advantages and disadvantages, which are summarised in table IX. Plantation types 1, 4 and 7, which are based on the monoculture of exotic species, may significantly reduce pressure on natural forests, but they are criticised for their frequent (though not systematic) negative ecological impacts, particularly on biodiversity (Holl and Brancalion, 2020). Conversely, types 2, 5 and 6 are more resilient, have fewer negative environmental impacts and promote job creation. However, they are less productive, and mechanisation and processing are more complex.

The diversity of large-scale tree plantation models shows that there are various approaches to achieving the goal of forest restoration. The choice of the appropriate model depends on the results expected from forest restoration, as well as the context. In response to the substantial development of Type 1, current international reforestation initiatives are placing greater emphasis on environmental and social considerations. We now have the knowledge to anticipate these impacts, at least generically, and better prepare new tree plantation projects (Warman, 2014). Today, the major difficulty involved in promoting sustainable tree plantations is clearly identifying the context in terms of decision making and implementation. It is important to consider stakeholders' needs and available knowledge regarding the financial, technical and institutional capacities actually available.

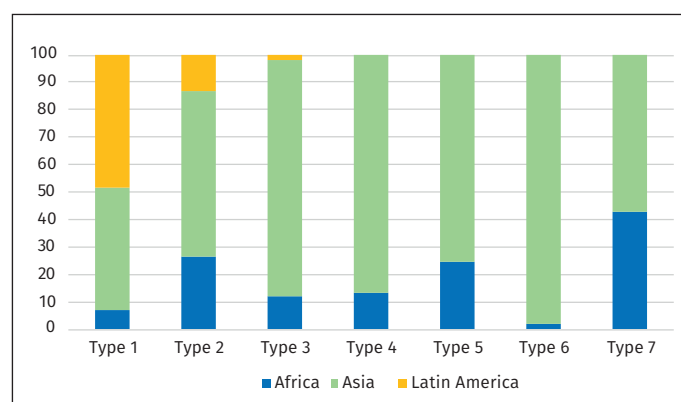


Figure 3. Distribution of large-scale tree plantations by type by geographical areas (as %).

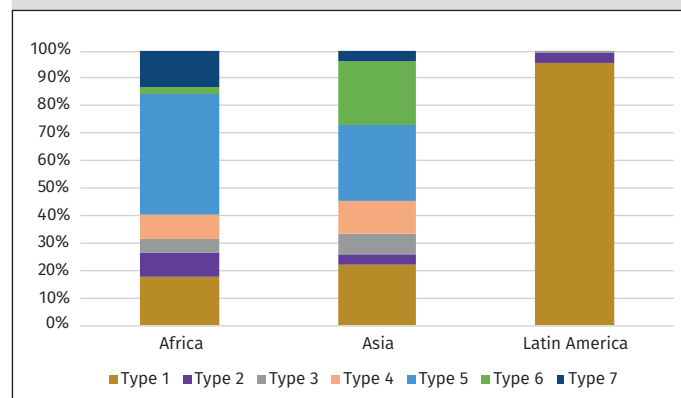


Figure 4. Proportion of large-scale tree plantations by typologies by geographical areas (as %).

Table IX.
 Evaluation of positive and negative impacts of large-scale tree plantations in Africa, Asia and Latin America
 (- - = very negative impact; - = negative impact; + = positive impact; ++ = very positive impact).

	Wood productivity	Carbon storage	Conservation of biodiversity	Preservation of soil quality and water resources	Resilience to climatic and biological hazards	Rural livelihoods
Type 1	++	+	+/-	-	--	+/-
Type 2	+	+	+/- (1 species) or + (few species)	+/-	+/-	+/-
Type 3	--	++	+/-	++	--	-
Type 4	++	+	+/-	+/-	--	--
Type 5	+	+	+/- (1 species) or ++ (few species)	+/-	+/-	+/-
Type 6	--	++	+/- (1 species) or ++ (few species)	++	+/- (1 species) or ++ (few species)	-
Type 7	++	+	+/-	+	-	++

Type 1 = Private and ecosystem services-oriented plantations of monospecific exotic species; Type 2 = Private and production-oriented plantations of mono/multi-specific indigenous species; Type 3 = Public and ecosystem services-oriented plantations of monospecific exotic species; Type 4 = Public and production-oriented plantations of monospecific exotic species; Type 5 = Public and production-oriented plantations of mono/multi-specific indigenous species; Type 6 = Public and ecosystem services-oriented plantations of mono/multi-specific indigenous species; Type 7 = Production-oriented plantations of monospecific exotic species managed by smallholders.

Conclusion

In Africa, Asia and Latin America, large-scale tree plantations are developed in order to: (i) produce forest products (ligneous or non-ligneous); (ii) preserve ecosystems and biodiversity; (iii) act as carbon sinks; and (iv) play a positive social, economic and cultural role, which includes equitable income distribution between the various stakeholders (Cossalter and Pye-Smith, 2003; Louppe, 2011; Payn *et al.*, 2015; Pryde *et al.*, 2015; HLPE, 2017; Cateau *et al.*, 2018; Malkamäki *et al.*, 2018; Bastin *et al.*, 2019; Lewis *et al.*, 2019). None of the existing large-scale tree plantation models can meet these objectives simultaneously, because as Holl and Brancalion (2020) explain “a single tree planting project may achieve multiple goals, but it is rarely possible to simultaneously maximize them all because goals often conflict, and prioritizing one goal may result in other undesirable outcomes”. For instance, the dominant plantation models – private monospecific plantations with exotic species – contribute significantly to roundwood production, but probably generate negative ecological and social externalities in many cases (Malkamäki *et al.*, 2018). Conversely, less intensive models have low yields and financial returns. As Chazdon (2008) and Holl and Brancalion (2020) recall, the choice of a tree plantation model depends not only on the plantation’s main goal, but also on the degree of degradation of the forest ecosystem, the local population’s needs, the available financial and technical resources, and access to land.

Various existing tree plantation management schemes can improve the social, economic, and environmental integration of large-scale tree plantations in landscapes (Pirard *et al.*, 2017). In addition, selecting the most appropriate tree plantation model will be possible if better knowledge about all plantation types is available. For types 1, 3, 4 and 7, studies should be conducted on their social and environmental impacts (Malkamäki *et al.*, 2018), and for the remaining types, more studies are needed on technical and financial performance (Lopez-Sampson *et al.*, 2021).

Rather than focusing on high performance plantations, a change of scale is also possible. Developing mixed-species plantations and including them in multifunctional forest landscapes offer an increasingly popular framework, which combines different types of tree plantations, strengthens their synergies and trade-offs, and involves a broader range of stakeholders, including smallholders (Brockerhoff *et al.*, 2008; Chazdon, 2008; Barua *et al.*, 2014; Payn *et al.*, 2015; WWF, 2015; Lewis *et al.*, 2019). This approach is still difficult to implement because it requires complex institutional planning and organisation (Holl and Brancalion, 2020). However, if tree plantations, and more particularly, large-scale tree plantations, are not integrated at landscape scale, they will continue to respond only to market signals (Pirard *et al.*, 2016) and fail to contribute in forest restoration goals.

References

- Andersson K., Lawrence D., Zavaletas J., Guariguata M. R., 2015. More Trees, More Poverty? The Socioeconomic Effects of Tree Plantations in Chile, 2001-2011. *Environmental Management*, 57: 123-136. <https://doi.org/10.1007/s00267-015-0594-x>
- Barr C., Cossalter C., 2004. China's development of a plantation-based industry: government policies, financial incentives, and investment trends. *International Forestry Review*, 6 (3-4): 267-281. <https://doi.org/10.1505/ifer.6.3.267.59977>
- Baral H., Guariguata M. R., Keenan R. J., 2016. A proposed framework for assessing ecosystem goods and services from planted forests. *Ecosystem Services*, 22: 260-268. <https://doi.org/10.1016/j.ecoser.2016.10.002>
- Barua S. K., Lehtonen P., Pakkasalo T., 2014. Plantation vision: potentials, challenges and policy options for global industrial forest plantation development. *International Forestry Review*, 16 (2): 117-127. <https://doi.org/10.1505/146554814811724801>
- Bastin J. F., Finegold Y., Garcia C., Mollicone D., Rezende M., Routh D., et al., 2019. The global tree restoration potential. *Science*, 365 (6448): 76-79. <https://doi.org/10.1126/science.aax0848>
- Batra P., Pirard R., 2015. Is a typology for planted forests feasible, or even relevant? CIFOR Infobrief, 121: 1-8. http://www.cifor.org/publications/pdf_files/infobrief/5608-infobrief.pdf
- Bisiaux F., Peltier R., Muliele J.-C., 2009. Plantations industrielles et agroforesterie au service des populations des plateaux Batéké, Mampu, en République démocratique du Congo. *Bois et Forêts des Tropiques*, 301 (3) : 21-32. <https://doi.org/10.19182/bft2009.301.a20404>
- Bremer L. L., Farley K. A., 2010. Does plantation forestry restore biodiversity or create green deserts? A synthesis of the effects of land-use transitions on plant species richness. *Biodiversity Conservation*, 19: 3893-3915. <https://doi.org/10.1007/s10531-010-9936-4>
- Brockerhoff E. G., Jactel H., Parrotta J. A., Quine C. P., Sayer J., 2008. Plantation forests and biodiversity: oxymoron or opportunity? *Biodiversity and Conservation*, 17: 925-951. <https://doi.org/10.1007/s10531-008-9380-x>
- Brunck F., Mallet B., 1993. Les problèmes phytosanitaires de l'acajou en Côte d'Ivoire. *Bois et Forêts des Tropiques*, 237 (3) : 9-29. <https://revues.cirad.fr/index.php/BFT/article/view/19783>
- Buongiorno J., Zhu S., 2014. Assessing the impact of planted forests on the global forest economy. *New Zealand Journal of Forestry Science*, Proceedings of the Third International Congress on Planted Forests, 44 (1): 1-9. <https://doi.org/10.1186/1179-5395-44-S1-S2>
- Cateau E., King L., Vallauri D., 2018. Plantations industrielles d'arbres à croissance rapide – Réalités, risques et solutions. *Le Pré-Saint-Gervais, France, WWF-France*, 24 p. <https://bit.ly/2T7JXzW>
- Chazdon R., 2008. Beyond Deforestation: Restoring Forests and Ecosystem Services on Degraded Lands. *Science*, 320 (5882): 1458-1460. <https://doi.org/10.1126/science.1155365>
- Chazdon R., Brancalion P., 2019. Restoring forests as a means to many ends – An urgent need to replenish tree canopy cover calls for holistic approaches. *Science*, 365 (6448): 24-25. <https://doi.org/10.1126/science.aax9539>
- Chevalier J. F., 2018. Étude de capitalisation des acquis de l'expérience en plantations de bois d'œuvre en Côte d'Ivoire. Paris, France, ATIBT, FFEM & FRM, 60 p. <http://bit.ly/2U4zOtb>
- Chokkalingam U., Zaizhi Z., Chunfeng W., Toma T., 2006. Learning lessons from China's forest rehabilitation efforts. National level review and special focus on Guangdong Province. Bogor, Indonesia, CIFOR, 174 p. http://www.cifor.org/publications/pdf_files/Books/BChokkalingam0603.pdf
- CIFOR, 2002. Typology of planted forests. CIFOR Infobrief, 4 p. http://www.cifor.org/publications/pdf_files/Typology/John-ty-pology.pdf
- Cossalter C., Pye-Smith C., 2003. Fast-Wood Forestry – Myths and Realities. Bogor, Indonesia, CIFOR, 60 p. http://www.cifor.org/publications/pdf_files/Books/ForestPerspective.pdf
- Cubbage F., Mac Donagh P., Balmelli G., Morales Olmos V., Bussoni A., Rubilar R., 2014. Global timber investments and trends, 2005-2011. *New Zealand Journal of Forestry Science*, Proceedings of the Third International Congress on Planted Forests, 44 (7): 1-12. <https://doi.org/10.1186/1179-5395-44-S1-S7>
- D'Amato D., Malkamäki N. J., Hogarth N. J., Baral H., 2017. A descriptive plantation typology and coding system to aid the analysis of ecological and socio-economic outcomes. *Current Forestry Reports*, 3: 296-307. <https://doi.org/10.1007/s40725-017-0066-z>
- Del Lungo A., Ball J., Carle J., 2006. Global planted forests thematic study: results and analysis. Rome, Italy, FAO Planted Forests and Trees Working Paper 38, 178 p. <http://bit.ly/2Jmzi8w>
- Dhahri S., Ben Jamâa M. L., 2008. Les insectes ravageurs des eucalyptus en Tunisie. Actes des journées scientifiques de l'INRGREF, Hammamet, Tunisie, 11-13 novembre 2008. <http://bit.ly/2ZiSynm>
- Dubiez E., Freycon V., Marien J.-N., Peltier R., Harmand J.-M., 2018. Long term impact of *Acacia auriculiformis* woodlots growing in rotation with cassava and maize on the carbon and nutrient contents of savannah sandy soils in the humid tropics (Democratic Republic of Congo). *Agroforestry Systems*, 92: 1-12. <https://doi.org/10.1007/s10457-018-0222-x>
- Duponnois R., Baudouin E., Sanguin H., Thioulouse J., Le Roux C., Tournier E., et al., 2013. L'introduction d'acacias australiens pour réhabiliter des écosystèmes dégradés est-elle dépourvue de risques environnementaux. *Bois et Forêts des Tropiques*, 318 (4) : 59-65. <https://revues.cirad.fr/index.php/BFT/article/view/20519>
- EFIATLANTIC, FAO, USSE, 2013. Summary Report of the 3rd International Congress on Planted Forests. EFIATLANTIC, FAO and USSE, 7 p. <http://bit.ly/2ZhshpR>
- Elias P., Boucher D., 2014. Planting for the Future – How Demand for Wood Products Could Be Friendly to Tropical Forests. *Union of Concerned Scientists*, 40 p. <http://bit.ly/2vc71DL>
- Enters T., Durst P. B., Brown C., Carle J., McKenzie P., 2004. What does it take? The role of incentives in forest plantation development in Asia and the Pacific – Executive summary. Rome, Italy, FAO, 280 p. <http://bit.ly/2VKsgll>
- Erskine P. D., Lamb D., Borschmann G., 2005. Growth performance and management of a mixed rainforest tree plantation. *New Forest*, 29: 117-134. <https://doi.org/10.1007/s11056-005-0250-z>
- Erskine P. D., Lamb D., Bristow M., 2006. Tree species diversity and ecosystem function: Can tropical multi-species plantations generate greater productivity? *Forest Ecology and Management*, 233 (2-3): 205-2010. <https://doi.org/10.1016/j.foreco.2006.05.013>
- FAO, 2010a. Global Forest Resources Assessment 2010 (FRA) – Main Report. Rome, Italy, FAO, 37 p. <http://www.fao.org/3/a-i1757e.pdf>

- FAO, 2010b. What woodfuels can do to mitigate climate change. Rome, Italy, FAO Forestry Paper 162, 98 p. <http://www.fao.org/3/i1756e/i1756e00.pdf>
- FAO, 2017. Planted forest, sustainable wood for a sustainable world. FAO, Sustainable wood for a sustainable world Congress, 31 October - 1 November 2017, Rome. <http://www.fao.org/forestry/sustainable-wood/en/>
- FAO, 2018. Terms and Definitions – FRA 2020. Rome, Italy, FAO, Forest Resources Assessment Working Paper 188, 32 p. <http://www.fao.org/3/i8661en/i8661en.pdf>
- FAO, 2020. Global Forest Resources Assessment 2020 – Key findings. Rome, Italy, FAO, 184 p. <http://www.fao.org/3/CA8753EN/CA8753EN.pdf>
- Gafaar A., 2011. Forest plantations and woodlots in Sudan. African Forest Forum, 76 p. <https://www.fao.org/sustainable-forest-management/toolbox/cases/case-detail/en/c/214343/>
- Gann G. D., McDonald T., Aronson J., Nelson C. R., 2019. International principles and standards for the practice of ecological restoration. Second edition. Restoration Ecology, 27 (1): 1-46. <https://doi.org/10.1111/rec.13035>
- Hamel O., Dameron V., 2011. Dynamiques de plantations et disponibilités des terres en Afrique. Dynamiques historiques [1970/2010], opportunités nouvelles, perspectives [2010/2050]. CASCADe (UNEP, FFEM & CIRAD), 38 p. <http://agritrop.cirad.fr/572043/>
- Heilmayr R., Echeverria C., Fuentes R., Lambin E. F., 2016. A plantation-dominated forest transition in Chile. Applied Geography, 75: 71-82. <http://dx.doi.org/10.1016/j.apgeog.2016.07.014>
- Heilmayr R., Echeverria C., Lambin E. F., 2020. Impacts of Chilean forest subsidies on forest cover, carbon and biodiversity. Nature Sustainability, 3: 701-709. <https://doi.org/10.1038/s41893-020-0547-0>
- Holl K. D., Brancalion P. H. S., 2020. Tree planting is not a simple solution. Science, 368 (6491): 580-581. <https://doi.org/10.1126/science.aba8232>
- HLPE, 2017. Sustainable forestry for food security and nutrition. Rome, Italy, High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, 137 p. <http://www.fao.org/3/a-i7395e.pdf>
- Hung T. D., Herbohn J. L., Lamb D., Nhan H. D., 2011. Growth and production varies between pair-wise mixtures and monoculture plantations in North Viet Nam. Forest Ecology and Management, 262 (3): 440-448. <https://doi.org/10.1016/j.foreco.2011.04.010>
- INDUFOR, 2017. Future Trends in Smallholder Plantation Forestry. Helsinki, Finland, INDUFOR, 8 p. <https://induforgroup.com/future-trends-in-smallholder-plantation-forestry/#>
- ITTO, 2009. Encouraging industrial forest plantations in the tropics – Report of a global study. Yokohama, Japan, ITTO, 143 p. <http://bit.ly/2JwBeHl>
- Jacovelli P. A., 2014. The future of plantations in Africa. International Forestry Review, 16 (2): 144-159. <https://doi.org/10.1505/146554814811724748>
- James R., Del Lungo A., 2005. The potential for fast-growing commercial forest plantations to supply high value roundwood. Rome, Italy, FAO, 49 p. <http://bit.ly/2UfkY9r>
- Jürgensen C., Kollert W., Lebedys A., 2014. Assessment of industrial roundwood production from planted forests. Rome, Italy, FAO, 40 p. <http://www.fao.org/3/a-i3384e.pdf>
- Karsenty A., 2018. Is sustainable logging possible in Africa's dense forest? Bois et Forêts des Tropiques, 336 (2): 3-5. <https://doi.org/10.19182/bft2018.336.a31615>
- Keenan R. J., Reams G. A., Achard F., De Freitas J. V., Grainger A., Lindquist E., 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment. Forest Ecology and Management, 352: 9-20. <http://dx.doi.org/10.1016/j.foreco.2015.06.014>
- Kelty M. J., 2006. The role of species mixtures in plantation forestry. Forest Ecology and Management, 233 (2-3): 195-204. <https://doi.org/10.1016/j.foreco.2006.05.011>
- Kollert W., Cherubini L., 2012. Teak resources and market assessment 2010. Rome, Italy, FAO, 52 p. <http://www.fao.org/3/a-an537e.pdf>
- Lewis S. L., Wheeler C. E., Mitchard E. T. A., Koch A., 2019. Regenerate natural forests to store carbon. Nature, 568 (7750): 25-28. <https://media.nature.com/original/magazine-assets/d41586-019-01026-8/d41586-019-01026-8.pdf>
- Liu S., Wu S., Wang H., 2014. Managing Planted Forests for Multiple Uses in a Changing China. New Zealand Journal of Forestry Science, 44 (3): 1-10. <https://doi.org/10.1186/1179-5395-44-S1-S3>
- Liu C. L. C., Kuchma O., Krutovsky K. V., 2018. Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. Global Ecology and Conservation, 15: 1-13. <https://doi.org/10.1016/j.gecco.2018.e00419>
- Lopez-Sampson A., Baral H., Chesnes M., 2021. Mixed timber plantations and their potential role in innovative production systems for forest restoration: Lessons from Latin America, Sub-Saharan Africa and Asia/Pacific. FTA Program, 35 p. *Being edited.*
- Loupe D., 2011. Plantations forestières : un sujet d'actualité ? Bois et Forêts des Tropiques 309 (3) : 4-7. <https://doi.org/10.19182/bft2011.309.a20465>
- Malkamäki A., D'Amato D., Hogarth N. J., Kanninen M., Pirard R., Toppinen A., et al., 2018. A systematic review of the socio-economic impacts of large-scale tree plantations, worldwide. Global Environmental Change, 53: 90-103. <https://doi.org/10.1016/j.gloenvcha.2018.09.001>
- Marién J.-N., Mallet B., 2004. Nouvelles perspectives pour les plantations forestières en Afrique centrale. Bois et Forêts des Tropiques, 282 (4) : 67-79. <https://revues.cirad.fr/index.php/BFT/article/view/20221>
- Marién J.-N., Gourlet-Fleury S., Peltier R., Daïnou K., Vermeulen C., Doucet J.-L., et al., 2013. Les plantations forestières en Afrique centrale : des sylvicultures nouvelles pour répondre aux nouveaux besoins des sociétés. In : De Wasseige C., Flynn J., Loupe D., Hiol Hiol F., Mayaux P. (éds). Les forêts du bassin du Congo – État des forêts 2013. Neuchâteau, France, Weyrich, 197-212. https://www.observatoire-comifac.net/docs/edf2013/FR/EDF2013_FR_chap8.pdf
- Martin B., 2014. Le bois futur viendra des plantations. Revue Forestière Française, 66 : 337-350. <http://bit.ly/2Kcc9LZ>
- Michon G., 2003. Déforestation et reconstructions forestières en Indonésie : de la transformation des paysages aux recompositions sociales et politiques. Bois et Forêts des Tropiques, 278 (4) : 65-75. <https://revues.cirad.fr/index.php/BFT/article/view/20179>
- Mugo F., Ong C., 2006. Lessons of eastern Africa's unsustainable charcoal trade. Nairobi, Kenya, ICRAF Working Paper 20, 34 p. <http://bit.ly/2FbCJHj>
- Nambiar E. K. S., Harwood C. E., 2014. Productivity of acacia and eucalypt plantations in Southeast Asia. 1. Bio-physical determinants of production: opportunities and challenges. International Forestry Review, 16 (2): 225-248. <https://doi.org/10.1505/146554814811724757>

Nichols J. D., Bristow M., Vanclay J. K., 2006. Mixed-species plantations: Prospects and Challenges. *Forest Ecology and Management*, 233 (2-3): 383-390. <https://doi.org/10.1016/j.foreco.2006.07.018>

Payn T., Carnus J. M., Freer-Smith P., Kimberley M., Kollert W., Liu S., *et al.*, 2015. Changes in planted forests and future global implications. *Forest Ecology and Management*, 352: 57-67. <http://dx.doi.org/10.1016/j.foreco.2015.06.021>

Pirard R., Dal Secco L., Warman R., 2016. Do timber plantations contribute to forest conservation? *Environmental Science & Policy*, 57: 122-130. <http://dx.doi.org/10.1016/j.envsci.2015.12.010>

Pirard R., Petit H., Baral H., 2017. Local impacts of industrial tree plantations: An empirical analysis in Indonesia across plantation types. *Land Use Policy*, 60: 242-253. <http://dx.doi.org/10.1016/j.landusepol.2016.10.038>

Pryde E., Holland G. J., Watson S. J., Turton S. M., Nimmo D. G., 2015. Conservation of tropical forest tree species in a native timber plantation landscape. *Forest Ecology and Management*, 339: 96-104. <https://doi.org/10.1016/j.foreco.2014.11.028>

Romijn E., Coppus R., De Sy V., Herold M., Roman-Cuesta R. M., Verchot L., 2019. Land Restoration in Latin America and the Caribbean: An Overview of Recent, Ongoing and Planned Restoration Initiatives and Their Potential for Climate Change Mitigation. *Forests*, 10 (510): 1-17. <https://doi.org/10.3390/f10060510>

Szulecka J., Pretzsch J., Secco L., 2014. Paradigms in tropical forest plantations: a critical reflection on historical shifts in plantation approaches. *International Forestry Review*, 16 (2): 128-143. <https://doi.org/10.1505/146554814811724829>

Tassin J., 2011. Les plantations forestières industrielles à l'épreuve des représentations de la nature. *Bois et Forêts des Tropiques*, 309 (3) : 9-16. <https://revues.cirad.fr/index.php/BFT/article/view/20469>

Tassin J., Missamba A. P., Marien J.-N., 2011. Biodiversité des plantations d'eucalyptus. *Bois et Forêts des Tropiques*, 309 (3): 27-35. <https://revues.cirad.fr/index.php/BFT/article/view/20463>

Thu P. Q., Griffiths M. W., Pegg G. S., McDonald J. M., Wyllie F. R., King J., *et al.*, 2010. Healthy plantations: a field guide to pests and pathogens of Acacia, Eucalyptus and Pinus in Vietnam. Brisbane, Australia, State of Queensland, 124 p. <http://era.daf.qld.gov.au/id/eprint/2049/>

Verhaegen D., Randrianjafy H., Rakotondraoelina Andriatsitohaina H., Trendelenburg Rakotonirina M. C., Montagne P., Rasamindisa A., *et al.*, 2014. *Eucalyptus robusta* pour une production durable de bois énergie à Madagascar : bilan des connaissances et perspectives. *Bois et Forêts des Tropiques*, 320 : 15-30. <https://doi.org/10.19182/bft2014.320.a20541>

Warman R. D., 2014. Global wood production from natural forests has peaked. *Biodiversity and Conservation*, 23: 1063-1078. <https://doi.org/10.1007/s10531-014-0633-6>

Wolosin M., 2017. Large-scale forestation for climate mitigation – Lessons from South Korea, China and India. *Climate and Land Use Alliance*, 62 p. <http://bit.ly/2KHWLxK>

WWF, 2015. Chapter 5 – Saving forests at risk. *In: WWF Living Forests Report*, 1-54. http://awsassets.panda.org/downloads/living_forests_report_chapter_5_1.pdf

Xu Z., Bennett M. T., Tao R., Xu J., 2004. China's Sloping Land Conversion Programme four years on: current situation and pending issues. *International Forestry Review*, 6 (4): 317-326. <https://doi.org/10.1505/ifor.6.3.317.59976>

Zobel B. J., Van Wyk G., Stahl P., 1987. *Growing Exotic Forests*. New York, USA, John Wiley & Sons, 508 p.

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Access to data

As this work is a bibliographic synthesis, there is no database. Internet links to sources are available in the bibliographic list.

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Dynamics of *Pinus* wood prices for different timber assortments: comparison of stochastic processes

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Photo 1.
Planted forests *Pinus* in Brazil.
Photo R. A. Munis, J. C. Martins, D. A. Camargo, D. Simões.

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RÉSUMÉ

Dynamique du prix des bois de *Pinus* selon différents assortiments d'essences : comparaison entre processus stochastiques

La compréhension de la dynamique des prix du marché pour le bois de *Pinus* est une condition préalable aux décisions stratégiques concernant les plans d'investissement forestier puisque, du point de vue du marché, le risque exogène d'un projet dépend des assortiments d'essences forestières. Il faut donc connaître le processus stochastique qui représente la meilleure façon d'évaluer l'actif sous-jacent. À l'aide de tests économétriques, la présente étude vise à comparer le mouvement brownien fractionnaire et le mouvement brownien géométrique pour déterminer le modèle stochastique qui représente le mieux le comportement du prix du bois de *Pinus* provenant de forêts plantées dans l'État de Santa Catarina, au Brésil, afin d'évaluer l'actif sous-jacent et les options réelles intrinsèques aux projets d'investissement forestier. Les séries chronologiques de prix, pour la période allant de juin 2017 à juillet 2019, concernent trois assortiments de bois de *Pinus* utilisés pour de multiples produits. Les tests économétriques recommandés pour analyser les séries chronologiques portaient sur la normalité des données, la tendance, l'autocorrélation, la stationnarité et l'estimation différentielle fractionnelle. Les séries chronologiques ont ensuite été modélisées au moyen de processus stochastiques conformément aux tests économétriques. Les séries chronologiques ont indiqué un comportement normal, la présence d'une tendance positive et la non-stationnarité des données. En outre, une mémoire longue a été trouvée dans toutes les séries. Le mouvement brownien fractionnaire s'est avéré être le processus stochastique le plus approprié pour modéliser les prix de trois assortiments de bois forestiers, étant donné les caractéristiques non stationnaires et la mémoire longue des séries chronologiques pour les prix du bois de *Pinus*.

Mots-clés : évaluation des actifs, processus stochastique, mouvement brownien fractionnaire, mouvement brownien géométrique, test économétrique.

ABSTRACT

Dynamics of *Pinus* wood prices for different timber assortments: comparison of stochastic processes

Understanding the dynamics of market prices for *Pinus* wood is a prerequisite for strategic decisions concerning forest investment plans since, in terms of the market, the exogenous risk to a project depends on timber assortments. The stochastic process that represents the best way of pricing the underlying asset therefore needs to be known. This study set out to compare Fractional Brownian Motion and Geometric Brownian Motion, through econometric tests, to understand the stochastic model that best represents the price behaviour of *Pinus* wood from planted forests in the state of Santa Catarina, Brazil, for the pricing of the underlying asset and valuation of the real options intrinsic to forest investment projects. The time series of prices, for the period from June 2017 to July 2019, relate to three assortments of *Pinus* wood used for multiple products. The recommended econometric tests to analyse the time series were for normality of the data, trend, autocorrelation, stationarity and fractional differential estimation. The time series were then modelled by means of stochastic processes in line with the econometric tests. The time series showed normal behaviour and indicated the presence of a positive trend and non-stationarity in the data. In addition, a true long memory was found in all series. Fractional Brownian Motion proved to be the most suitable stochastic process for modelling the prices of three forest timber assortments, given the non-stationary characteristics and true long memory of the time series for *Pinus* wood prices.

Keywords: asset pricing, stochastic process, fractional Brownian motion, geometric Brownian motion, econometric test.

RESUMEN

Dinámica de los precios de la madera de *Pinus* para distintos surtidos de madera: comparación de procesos estocásticos

Comprender la dinámica de los precios de mercado de la madera de *Pinus* es un requisito previo para las decisiones estratégicas relativas a los planes de inversión forestal, ya que, en términos de mercado, el riesgo exógeno de un proyecto depende de los surtidos de madera. Por lo tanto, es necesario conocer el proceso estocástico que representa la mejor forma de fijar un precio al activo subyacente. Este estudio se propuso comparar el movimiento browniano fraccional y el movimiento browniano geométrico, a través de pruebas econométricas, para entender el modelo estocástico que mejor representa el comportamiento del precio de la madera de *Pinus* de bosques plantados en el estado de Santa Catalina, Brasil, con el fin de evaluar los precios del activo subyacente y las opciones reales intrínsecas a los proyectos de inversión forestal. Las series temporales de precios, para el periodo comprendido entre junio de 2017 y julio de 2019, se refieren a tres surtidos de madera de *Pinus* utilizados para múltiples productos. Las pruebas econométricas recomendadas para analizar las series temporales fueron la normalidad de los datos, la tendencia, la autocorrelación, la estacionalidad y la estimación diferencial fraccional. A continuación, las series temporales se modelaron mediante procesos estocásticos de acuerdo con las pruebas econométricas. Las series temporales mostraron un comportamiento normal e indicaron la presencia de una tendencia positiva y la no estacionariedad de los datos. Además, se encontró una memoria a largo plazo en todas las series. El movimiento browniano fraccional resultó ser el proceso estocástico más adecuado para modelar los precios de tres surtidos de madera forestal, dadas las características no estacionarias y la memoria a largo plazo de las series temporales de los precios de la madera de *Pinus*.

Palabras clave: fijación de precios de activos, proceso estocástico, movimiento browniano fraccional, movimiento browniano geométrico, test econométrico.

Introduction

Stochastic modelling of wood prices provides information to improve the commercial use and strategic planning of companies in the forestry sector and, consequently, enables decision making based on reliable models that do not undervalue or overestimate the expectations of financial revenues.

Among the alternatives of stochastic models for the real options valuation, there is the use of Geometric Brownian Motion (GBM) for price modelling (Berk and Podhraski, 2018) with a linear stochastic solution using the Itô's lemma (Maeda and Watts, 2019). In addition, the GBM simulates the prices of the underlying asset following a random walk with constant volatility (Ardian and Kumral, 2020), assuming a lognormal probability distribution when the ratio between the expected price and the present price has independence from the past price history (Angstmann *et al.*, 2019).

Another stochastic model with useful characteristics for price modelling is the Fractional Brownian Motion (FBM), which according to Gajda and Wyłomańska (2014), is a generalization of classic Brownian Motion and, in the understanding of Xu *et al.* (2019), this model belongs to the family of Gaussian processes and assumes that increments are not necessarily independent. FBM is also a long memory process (Kozachenko *et al.*, 2015) and, according to Le Breton (1998), it can be considered one of the simplest stochastic processes that exhibit long-range dependence.

It is noteworthy that both stochastic models are Gaussian, however, the GBM has independent increments, while the FBM has correlated increments in series, thus, the historical trajectory of the process becomes fundamental when predicting its future evolution (Wang *et al.*, 2018).

Insley (2002) demonstrated that the assumption that wood prices follow a process of reversion to the average, instead of GBM, can make a significant difference in the valuation of forest stand and the ideal harvest time. Likewise, FBM may be more appropriate than GBM to model timber prices over time because the fractional integration is the discrete counterpart of FBM (Manley and Niquidet, 2017).

In the analysis of investment projects, the stochastic process to be used in price modelling is fundamental in obtaining the value of flexibility. Furthermore, according to Matias *et al.* (2005), price modelling is one of the most important and delicate challenges of the process, as it influences future revenue that is commonly based on the behaviour of prices over time, which combined with econometric analysis, provide statistical information about the behaviour of the market under analysis (Olsson *et al.*, 2011).

In this context, the time series of *Pinus* wood prices presents an additional component of complexity since they are normally sold in assortments. In agreement with Silva *et al.* (2017) and Kohler *et al.* (2015), the characterization of assortments describes the classification of logs according to their quality, dimensions, possibilities of use, and economic value.

Thus, it is justified to analyse more than one time series of *Pinus* wood prices since each forest assortment has different prices. Hence, the stochastic models used to forecast prices provide more plausible information, for example, the timing of the timber harvest and the application of capital for the expansion of planted forests.

However, Cordeiro *et al.* (2010) and Niquidet and Sun (2012) point out that despite the expectation of the price of wood being a fundamental factor for adequate forest management and for informing the development of the wood market, there is a lack of adjustment of models in relation to the stochastic properties of prices.

Therefore, in line with Manley and Niquidet (2010), there is a lack of consensus on how to specify the stochastic process of wood prices. According to Plantinga (1998) forest owners could more accurately value planted forests from the approach of stochastic price variations. That said, the need to select stochastic models to characterize the series of wood price and to pricing the underlying asset for *Pinus* assortments planted in Brazil is confirmed.

In this perspective, we analyse the prices of *Pinus* wood for different forest assortments in order to identify the behaviour of the wood prices time series and, therefore, compare Fractional Brownian Motion and Geometric Brownian Motion, and then, indicate the stochastic model recommended for the underlying asset pricing and the intrinsic real options valuation of forest investment projects.

Material and Methods

Study support

We carried out the econometric characterization of *Pinus* wood price time series from planted forests in the state of Santa Catarina, Brazil, according to data provided by the Centre for Socioeconomics and Agricultural Planning (2019). We used a time series of the monthly prices of *Pinus* wood from June 2017 to July 2019. The prices were derived from the average obtained from producers for different forest assortments, or rather, which supply wood to the processing industries with a view to obtaining multiproducts, characterized as:

Cellulose: first forest assortment of a *Pinus* plantation with diameter at breast height of the standing tree ranging between 8 cm and 17 cm, used as a raw material for the manufacture of cellulose pulp;

Sawmill I: second forest assortment of a *Pinus* plantation with diameter range of the standing tree defined between 18 cm to 24 cm, used as sawn wood;

Sawmill II: third forest assortment of a *Pinus* plantation with tree diameter range between 25 cm to 34 cm, for the supply of sawn wood.

Econometric tests of the price time series

To improve the accuracy of the projected wood prices, note the importance of using temporary wood price limits, which, by estimate, provide the application of stochastic models used with a price trajectory.

In this sense, in order to verify the behaviour of the price of wood, we performed econometric tests, using software R, to confirm normality, trend, autocorrelation, stationarity and the fractional differential estimate or true long memory of the wood price time series from the *Pinus* assortments.

Normality of the price time series data

The normality of the data should be the first parameter analysed, especially for economic data, since it acts as an indication in the selection of parametric or non-parametric tests, and, thus, it reduces large deviations and increases the accuracy of the results (Chen and Cheng, 2007).

Therefore, we test the normality of the data and the residuals of the regression analysis using the Jarque Bera test (Jarque and Bera, 1980) with a null hypothesis of normal data distribution at the 5% significance level.

Trend of the price time series

Trend time series models have gained attention in the past two decades due to many applications in corporate finance (Cai, 2007). When we approach the application of time series of prices, it is essential to verify the presence of trends and, therefore, their configuration, whether increasing, decreasing or stationary (Antunes and Cardoso, 2015). For this, we applied the Cox Stuart test (Cox and Stuart, 1955) with a null hypothesis that the time series does not trend to the 5% significance level.

Autocorrelation of the price time series

Through the linear regression of linearized prices at the present moment (t) with the past price ($t-1$), we verified whether the behavior of prices has any memory, or whether it actually meets Markov's property (Matias *et al.*, 2005). Therefore, it is highly recommended to confirm the regression adjustment by analyzing the normality of the residuals.

Trend of the price time series

Once the normality of the data was indicated, we opted for applying the Dickey-Fuller parametric test (Dickey and Fuller, 1979), with a null hypothesis of unit root, $I(1)$, at the level of 5% significance. In addition, we also opted for the application of the KPSS test (Kwiatkowski *et al.*, 1992), with null hypothesis of stationarity, $I(0)$ at the level of 10% of significance since it allows to verify the presence of true long memory in the time series.

Fractional differential estimate

Usually, economic time series exhibit cycles with orders of several quantities, thus, the spectra of a sample of these series do not show an accentuated pure period, but a spectral density (Mandelbrot and Ness, 1968).

Thus, using the Geweke and Porter-Hudak (GPH) estimator that returns Hurst's H parameter of a time series suggested by Geweke and Porter-Hudak (1983) we obtained the fractional differential parameter (d) of the linearized time series.

Modelling the price of *Pinus* wood

Supported by the econometric tests of the three *Pinus* assortments' wood price time series, we performed the modelling of the underlying asset, in order to estimate the dynamics of this price through the FBM and the GBM.

In this way, we estimated the values of drift (α) and volatility (σ) in annual terms, using the average and standard deviation of the series of linearized returns. Thus, for the valuation of real options, we model the price of *Pinus* wood for the three assortments by applying the stochastic model FBM (Equation 1) as described by Gu *et al.* (2012).

$$P_t = P_{t-\tau} e^{\left(\alpha t - \frac{\sigma^2 t^{2H}}{2}\right)} e^{\alpha \sqrt{\Delta t} W^H} \quad [\text{Equation 1}]$$

where: P_{t-1} is the initial condition; P_t is the price of wood in the subsequent period; α is the constant growth rate (drift); σ is the standard deviation (volatility); t is the period; H is the Hurst coefficient; W^H is the fractional Gaussian noise; Δt is the time increment.

Furthermore, based on the inputs of the FBM stochastic model, that is, on drift and volatility, we model the price of *Pinus* wood, when subject to adjustment, using the GBM stochastic model (Equation 2) according to Ossenbruggen and Laflamme (2019).

$$P_t = P_{t-\tau} e^{\left(\alpha - \frac{\sigma^2}{2}\right) \Delta t} e^{\sigma \varepsilon \sqrt{\Delta t}} \quad [\text{Equation 2}]$$

where: ε is the random error with standard normal distribution.

In addition, the determination of the best fit for wood price modelling was done through the Mean Absolute Error and the root mean square error (RMSE), both used as performance indicators. Associated, the coefficient of determination (R^2) was used as a performance measure.

Results

For the price series used, we accept the assumptions of normality and trend of each assortment of *Pinus* wood prices (table 1), with a view to valuing their Real Options. It means the incorporation of managerial flexibilities in forest investment projects. Moreover, we obtained the trend of price time series to check the discrepancy in relation to observed prices.

Table I.
 Normality and trend of the *Pinus* wood prices time series for different forest assortments.

Forest assortment	Data normality	Trend in the <i>Pinus</i> wood prices time series
Cellulose	0.705	0.0009*
Sawmill I	0.324	0.0009*
Sawmill II	0.169	0.0117*

* At the 5% level of significance.

After the application of the natural logarithm (\ln) in the *Pinus* wood price time series, since as the errors of the stochastic models are normally distributed, the variable could assume negative values, which does not match the economic approach, we obtained the autocorrelation found through regression analysis (table II). Consequently, the adjustment confirmed by the Jarque Bera test, with the normality of the residuals, however, occurred only for the cellulose assortment.

In view of this, through the Dickey-Fuller and KPSS tests, we found that the time series of *Pinus* is non-stationary, except for the current time dependence, confirmed through the GPH estimate (table III).

In view of the values we obtained for Hurst's H parameters from the time series of the *Pinus* wood price and, also, the presence of true long memory in all-time series, since through this KPSS test it is possible to verify if the second derivative of a series follows a process $I(0)$, identifying a true long memory against spurious long memory (Niquidet and Sun, 2012), we performed three simulations of wood price modelling through the FBM for the Cellulose forest assortment (figure 1a), Sawmill I (figure 1b) and Saw mill II (figure 1c).

In view of this, the GBM has a Hurst index of 0.5 and is considered a particular type of FBM, therefore, Manley and Niquidet (2017) indicate that there are no material differences in modelling the asset through GBM compared to FBM, when the Hurst index is 0.49. Given the same amplitude of the Hurst index found by these authors, that is, 0.51

Table III.
 Stationarity tests, GPH estimate, fractional memory and Hurst coefficient of *Pinus* wood prices for different forest assortments.

Forest assortment	Dick-Fuller (Pt)	KPSS (Pt)	d (Pt)	H (ln(Pt)-ln(Pt-1))
Cellulose	-2.4143*	0.1**	0.55	0.05
Sawmill I	-2.4906*	0.1**	1.01	0.51
Sawmill II	-2.4699*	0.1**	1.32	0.82

*At the 5% level of significance.
 **p-value = 0.1 represents p-value \geq 10%.

Table IV.
 Model performance evaluation.

Multiproduct	Model	R ²	MAE (USD)	RMSE (USD)
Cellulose	FBM	0.53	0.85	0.91
	GBM	0.33	0.94	1.01
Sawmill I	FBM	0.64	1.07	1.31
	GBM	0.36	1.27	1.58
Sawmill II	FBM	0.73	2.37	2.68
	GBM	0.19	1.42	2.09

for the Sawmill II forest assortment, we also performed three simulations, but modelled using the GBM (figure 1d).

Thus, it was inferred the best performance of *Pinus* wood price modelling in the different assortments evaluated by the FBM, mainly due to the fact that the MAE and the RMSE are inferior to the GBM, with the exception of Sawmill II. However, the coefficient of determination allowed inferring that when modelled by the FBM, it can better explain the variation of the data than obtained by the GBM (table IV).

Table II.
 Regression analysis results of the of *Pinus* wood prices for different forest assortments.

Forest assortment	R ² adjusted	t-value	Characteristic line equation	Data normality
Cellulose	0.83	10.43	$\ln(P_t) = 0.081 + 0.8663 \cdot \ln(P_{t-1})$	0.62
Sawmill I	0.83	11.00	$\ln(P_t) = 0.219 + 0.9037 \cdot \ln(P_{t-1})$	$1.72 \cdot e^{-06*}$
Sawmill II	0.75	8.16	$\ln(P_t) = 0.330 + 0.8839 \cdot \ln(P_{t-1})$	$1.28 \cdot e^{-07*}$

* At the 5% level of significance.

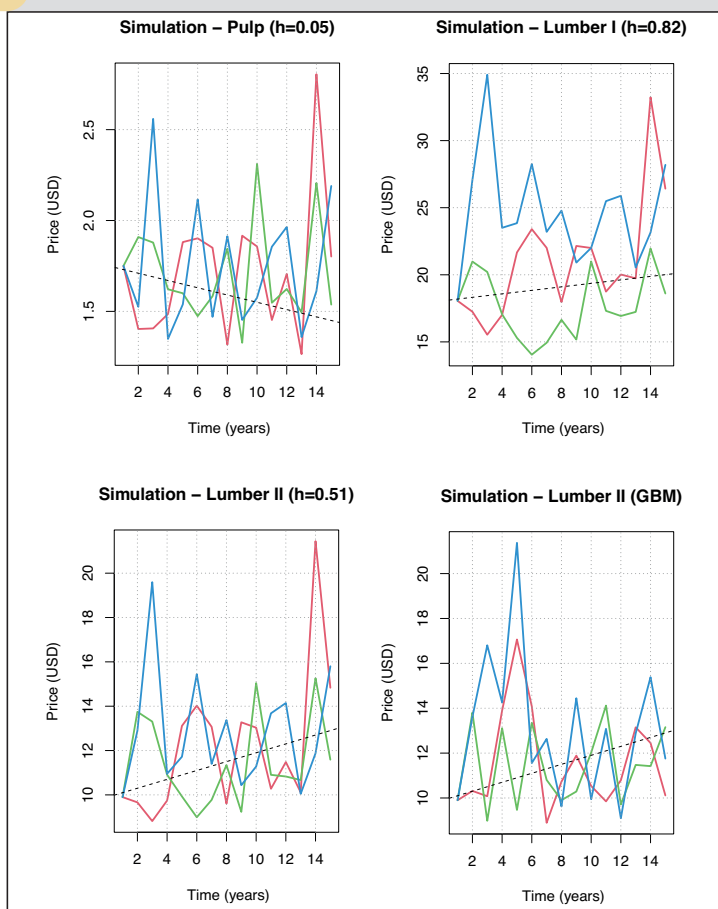


Figure 1. Representation of the simulations with the *Pinus* wood price modelling for different forest assortments. The solid lines represent the results of the three different simulations performed for each condition. The dotted line is the series drift.

Discussion

Pinus planted forests emerge due to the increased demand for wood, used as raw material for various segments, providing economic and social benefits. In this sense, when we compare *Pinus* wood price series modelling criteria, we are providing inputs to managers so that they can discern among the most viable options for providing effective property rights, insurance, stocking price policy, governance and forest management.

Our econometric treatment of the *Pinus* wood price time series evidenced a normal distribution of price data over two years of observation. Furthermore, trend parameters were identified, which underlie the organizational strategy of forest-based transformation industries, in addition to enhancing the economic results of the projected time horizons.

Zhang *et al.* (2015) point out that planted forests develop in response to economic instruments, which require an understanding of this scenario, as well as its evolution. Therefore, we verified, through the Dickey-Fuller and KPSS test,

the temporal dependence in the evolution of *Pinus* wood prices for the assortments used in the production of pulp and wood splitting in Sawmill I Sawmill II.

Niquidet and Manley (2007) add that fluctuations in these prices are intrinsically related to market volatility and trends. Therefore, the proper management of the *Pinus* genus, added to the application of taper models provided, in the same planted forest, different recipes, confirming the study developed by Kohler *et al.* (2015), because the same forest individual can generate the sale of several by-products.

Therefore, the generation of future income must be adequate for silvicultural management. In this way, we characterize the use of forest assortments of the *Pinus* genus by modelling the different price series and allocating the obtained wood, based on its diameter, to different industrial sectors, aiming at the fundamental adaptation to maximize the biological asset.

According to Figueiredo Filho *et al.* (2015) and Kohler *et al.* (2015), as they are classified based on the minimum diameter of use and the length of the logs, the evaluation of the forest assortment depends on the industrial purpose of the *Pinus* wood. We observe that the different price series, coming from different market segments, also have different dynamics.

The economic forecast of investment projects in planted forests requires an understanding of the market dynamics in which it operates. Simultaneously, the planning and adequacy of productive capacity must be conditioned to the silvicultural management system, as well as to the moment of implantation and commercialization of the planted forest.

In this type of segment, it is useful to predict future values based on previous data, since the prediction implies having an evolution model, even when there is randomness. According to Herrmann and Otesteanu (2016), GBM is considered a stochastic process based on random processes. However, Varnosfaderani and Verly (2017) reinforce that, to obtain more accurate results applying the GBM, the price logarithms must have a normal distribution and be independent.

Assuming independence in prices over time may impact erroneous projections of economic models, which are related to the volatility of wood products markets. FBM is also a stochastic process, and, like regular Brownian motion, it is generated by adding a series of random steps with a Gaussian distribution. However, according to Addison *et al.* (1998), in the FBM the sum is weighted over the previous Brownian steps.

As noted, in addition to the econometric analysis having evidenced the dependency structure in the data, the performance metrics of the models indicated the superiority of FBM in modelling the *Pinus* wood price series in the different assortments. In line with Zhang *et al.* (2015), as a premise, it is essential to identify the pattern of evolution of biological asset prices. We add, however, that the proper silvicultural management of forest species includes prior planning of the time horizon to be explored, through projections that, when properly measured, imply the creation of value associated with biological assets.

The consistent and exclusive potential of the Fractional Brownian Motion in modelling the prices of *Pinus* wood from different forest assortments, based on a series of two years of observations, provides important details for reproducing the results. Our experimental procedures can be revised or incorporated in other analyses considering historical data series for longer periods, mainly due to the lack of definition of the ideal size of these series.

Conclusions

Fractional Brownian Motion is the most suitable stochastic process for modelling *Pinus* wood prices for different forest assortments due to the time series showing non-stationarity and true long memory.

For *Pinus* plantation forests, the eligibility of Fractional Brownian Motion offers better accuracy for the pricing of the underlying asset, and consequently, consistent results for the valuation of real options intrinsic to forest investment projects.

The econometric analysis and stochastic modelling of forest assets from forest assortments intended for multi-products must occur for each class of tree diameter, since the economic and financial interferences are different for this sector.

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References

Addison P. S., Qu B., Nisbet A., Pender G., 1998. A non-Fickian, particle tracking diffusion model based on fractional Brownian motion. *International Journal for Numerical Methods in Fluids*, 25: 1373-1384. [https://doi.org/10.1002/\(SICI\)1097-0363\(19971230\)25:12%3C1373::AID-FLD620%3E3.0.CO;2-6](https://doi.org/10.1002/(SICI)1097-0363(19971230)25:12%3C1373::AID-FLD620%3E3.0.CO;2-6)

Angstmann C. N., Henry B. I., Mcgann A. V., 2019. Time-fractional geometric Brownian motion from continuous time random walks. *Physica A: Statistical Mechanics and its Applications*, 526: 02-13. <https://doi.org/10.1016/j.physa.2019.04.238>

Antunes J. L. F., Cardoso M. R. A., 2015. Uso da análise de séries temporais em estudos epidemiológicos. *Epidemiologia e Serviços de Saúde*, 24: 565-576. <https://www.scielo.br/j/ress/a/zzG-7bfRbP7xSmqgWX7FfGZL/abstract/?lang=pt>

Ardian A., Kumral M., 2020. Incorporating stochastic correlations into mining project evaluation using the Jacobi process. *Resources Policy*, 65: 1-9. <https://doi.org/10.1016/j.resourpol.2019.101558>

Berk A. S., Podhraski D., 2018. Superiority of Monte Carlo simulation in valuing real options within public-private partnerships. *Risk Management*, 20: 1-28. <https://doi.org/10.1057/s41283-017-0025-9>

Cai Z., 2007. Trending time-varying coefficient time series models with serially correlated errors. *Journal of Econometrics*, 136: 163-188. <https://doi.org/10.1016/j.jeconom.2005.08.004>

Centre for Socioeconomics and Agricultural Planning, 2019. Mercado Agrícola. CEPA, EPAGRI, website. <https://cepa.epagri.sc.gov.br/index.php/precos-agricolas-mensais-indice/>

Chen H., Cheng Y., 2007. Non-normality effects on the economic-statistical design of \bar{x} charts with Weibull in-control time. *European Journal of Operational Research*, 176: 986-998. <https://doi.org/10.1016/j.ejor.2005.08.022>

Cordeiro S. A., Soares N. S., Braga M. J., Silva M. L., 2010. Previsões do preço de exportação da madeira serrada de *Pinus* no Brasil. *Scientia Forestalis*, 38: 205-214. <http://www.bibliotecaforestal.ufv.br/handle/123456789/16452>

Cox D. R., Stuart A., 1955. Some quick sign tests for trend in location and dispersion. *Biometrika*, 42: 80-95. <https://doi.org/10.1093/biomet/42.1-2.80>

Dickey D. A., Fuller W. A., 1979. Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association*, 74: 427-431. <https://doi.org/10.2307/2286348>

Figueiredo Filho A., Retslaff F. A. S., Kohler S. V., Becker M., Brandes D., 2015. Efeito da idade no afilamento e sortimento em povoamentos de *Araucaria angustifolia*. *Floresta e Ambiente*, 22: 50-59. <https://doi.org/10.1590/2179-8087.080114>

Gajda J., Wytomańska A., 2014. Fokker-Planck type equations associated with fractional Brownian motion controlled by infinitely divisible processes. *Physica A: Statistical Mechanics and its Applications*, 405: 104-113. <https://doi.org/10.1016/j.physa.2014.03.016>

Geweke J., Porter-Hudak S., 1983. The estimation and application of long memory time series models. *Journal of Time Series Analysis*, 4: 221-238. <https://doi.org/10.1111/j.1467-9892.1983.tb00371.x>

Gu H., Liang J. R., Zhang Y. X., 2012. Time-changed geometric fractional Brownian motion and option pricing with transaction costs. *Physica A: Statistical Mechanics and its Applications*, 391: 3971-3977. <https://doi.org/10.1016/j.physa.2012.03.020>

Herrmann M., Ottesteanu M., 2016. A MAP estimator based on geometric Brownian motion for sample distances of laser triangulation data. *Optics and Lasers in Engineering*, 86: 98-105. <https://doi.org/10.1016/j.optlaseng.2016.05.009>

Insley M., 2002. A Real Options approach to the valuation of a forestry investment. *Journal of Environmental Economics and Management*, 44: 471-492. <https://doi.org/10.1006/jeem.2001.1209>

Jarque C. M., Bera A. K., 1980. Efficient tests for normality, homoscedasticity and serial independence of regression residuals. *Economics Letters*, 6: 255-259. [https://doi.org/10.1016/0165-1765\(80\)90024-5](https://doi.org/10.1016/0165-1765(80)90024-5)

Kohler S. V., Koehler H. S., Figueiredo Filho A., Arce J. E., Machado S. A., 2015. Evolução do sortimento em povoamentos de *Pinus taeda* nos estados do Paraná e Santa Catarina. *Floresta*, 45: 545-554. <https://doi.org/10.5380/rev.v45i3.35746>

Kozachenko Y., Melnikov A., Mishura Y., 2015. On drift parameter estimation in models with fractional Brownian motion. *Statistics: a journal of theoretical and applied statistics*, 49: 35-62. <https://doi.org/10.1080/02331888.2014.907294>

Kwiatkowski D., Phillips P. C. B., Schmidt P., Shin Y., 1992. Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root? *Journal of Econometrics*, 54: 159-178. [https://doi.org/10.1016/0304-4076\(92\)90104-Y](https://doi.org/10.1016/0304-4076(92)90104-Y)

Le Breton A., 1998. Filtering and parameter estimation in a simple linear system driven by a fractional Brownian motion. *Statistics & Probability Letters*, 38: 263-274. [https://doi.org/10.1016/S0167-7152\(98\)00029-7](https://doi.org/10.1016/S0167-7152(98)00029-7)

Maeda M., Watts D., 2019. The unnoticed impact of long-term cost information on wind farms' economic value in the USA – a real option analysis. *Applied Energy*, 241: 540-547. <https://doi.org/10.1016/j.apenergy.2018.11.065>

Mandelbrot B., Ness V., 1968. Fractional Brownian motions, fractional noises and applications. *SIAM Review*, 10: 422-437. <https://www.jstor.org/stable/2027184>

Manley B., Niquidet K., 2017. How does real option value compare with Faustmann value when log prices follow fractional Brownian motion? *Forest Policy and Economics*, 85: 76-84. <https://doi.org/10.1016/j.forpol.2017.08.017>

Manley B., Niquidet K., 2010. What is the relevance of option pricing for forest valuation in New Zealand? *Forest Policy and Economics*, 12: 299-307. <https://doi.org/10.1016/j.forpol.2009.11.002>

Matias M. A., Silva C. A. T., Vieira L., 2005. Analysis of price behaviour patterns for revenue projections: statistical tests of a copper price time series. *Brazilian Business Review*, 2: 108-123. <https://doi.org/10.15728/bbr.2005.2.2.2>

Niquidet K., Manley B., 2007. Price dynamics in the New Zealand log market. *New Zealand Journal of Forestry*, 52: 4-9. <https://www.semanticscholar.org/paper/Price-dynamics-in-the-New-Zealand-log-market-Niquidet-Manley/2737d0ad12774546b953722311533624819547a4>

Niquidet K., Sun L., 2012. Do forest products prices display long memory? *Canadian Journal of Agricultural Economics*, 60: 239-261. <https://doi.org/10.1111/j.1744-7976.2012.01244.x>

Ossenbruggen P. J., Laflamme E. M., 2019. Explaining freeway breakdown with geometric Brownian motion model. *Journal of Transportation Engineering, Part A: Systems*, 145: 1-9. <https://doi.org/10.1061/JTEPBS.0000255>

Olsson O., Hillring B., Vinterbäck J., 2011. European wood pellet market integration – A study of the residential sector. *Biomass and Bioenergy*, 35: 153-160. <https://doi.org/10.1016/j.biombioe.2010.08.020>

Plantinga A. J., 1998. The optimal timber rotation: an option value approach. *Forest Science*, 44: 192-202. <https://academic.oup.com/forestscience/article/44/2/192/4627423>

Silva C. A., Klauberg C., Hudak A. T., Vierling L. A., Jaafar W. S. W. M., Mohan M., et al., 2017. Predicting stem total and assortment volumes in an industrial *Pinus taeda* L. forest plantation using airborne laser scanning data and random forest. *Forests*, 8: 1-17. <https://doi.org/10.3390/f8070254>

Varnosfaderani P. E., Verly J. G., 2017. Geometric Brownian motion (GBM) random process model appears to be an excellent choice for modeling realizations of perclos signals. *Sleep Medicine*, 40: 86. <https://doi.org/10.1016/j.sleep.2017.11.246>

Wang L., Zhang R., Yang L., Su Y., Ma F., 2018. Pricing geometric Asian rainbow options under fractional Brownian motion. *Physica A: Statistical Mechanics and its Applications*, 494: 8-16. <https://doi.org/10.1016/j.physa.2017.11.055>

Xu P., Huang J., Zang C., 2019. Ergodicity of stochastic Rabinovich systems driven by fractional Brownian motion. *Physica A: Statistical Mechanics and its Applications*, 546: 122955. <https://doi.org/10.1016/j.physa.2019.122955>

Zhang D., Stenger A., Harou P. A., 2015. Policy instruments for developing planted forests: theory and practices in China, the U.S., Brazil, and France. *Journal of Forest Economics*, 21: 223-237. <https://doi.org/10.1016/j.jfe.2015.09.004>

Munis et al. – Author's contributions

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Writing – Review & Editing	D. A. Camargo, J. C. Martins, R. A. Munis

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Access to data

We used a time series of pine wood prices (USD) from planted forests in the state of Santa Catarina, Brazil, as per BRL prices provided by the Center for Socioeconomics and Agricultural Planning (link: <https://cepa.epagri.sc.gov.br/index.php/produtos/mercado-agricola/precos-agricolas-mensais-indice/>).

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Importance des cultes dans la préservation des espèces d'arbre, le cas du samba (*Triplochiton scleroxylon* K. Schum.) au Bénin

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Photos 1.

Triplochiton scleroxylon en forêt sacrée dans la région guinéo-congolaise du Bénin.
Triplochiton scleroxylon in the sacred forest in the Guinean-Congolese region of Benin.
Photos G. Ganka.

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RÉSUMÉ

Importance des cultes dans la préservation des espèces d'arbre, le cas du samba (*Triplochiton scleroxylon* K. Schum.) au Bénin

Triplochiton scleroxylon K. Schum. est l'une des espèces vénérées des écosystèmes sacrés du Bénin qui revêt une importance socioculturelle. Toutefois, les peuplements naturels de l'espèce sont en déclin et les informations sur ses usages sont quasi non documentées. Cette étude évalue les connaissances locales sur les usages de l'espèce et la distribution desdites connaissances entre groupes ethnolinguistiques, culturels et cultuels au Bénin. Des enquêtes ethnobotaniques individuelles ont été réalisées auprès de 411 adeptes des divinités liées à la conservation de l'espèce au Bénin. Les indices ethnobotaniques tels que la fréquence relative de citation (FRC), la valeur d'usage (VU) total et par organe, et l'indice d'importance culturelle (IC) ont été utilisés pour quantifier la popularité, l'utilisation et l'importance socioculturelle de *T. scleroxylon*, respectivement. Un modèle linéaire généralisé avec la distribution de la binomiale négative a été réalisé pour examiner la variation de la VU entre groupes ethnolinguistiques, culturels et cultuels. Au total, 36 usages spécifiques catégorisés en neuf types d'usages ont été rapportés. Les usages cultuels, médicaux, artisanaux et comme bois d'œuvre sont les plus cités. Toutes les parties de la plante sont prisées dans la tradition du culte *Oro*. Les feuilles, racines et écorces sont les organes utilisés pour traiter diverses affections dont les plus populaires sont les affections digestives et gynécologiques. Les connaissances et les usages de l'espèce varient significativement entre les groupes ethnolinguistiques et cultuels. Une singularité des connaissances de *T. scleroxylon* a été observée chez les adeptes du culte *Oro*. La disparition de cette espèce pourrait avoir des conséquences majeures sur l'identité et la stabilité culturelle et cultuelle des peuples pratiquant cette tradition. Les usages médicaux populaires rapportés offrent aussi des perspectives pour la valorisation médicinale de l'espèce.

Mots-clés : *Triplochiton scleroxylon*, samba, connaissances traditionnelles, valeur d'usage, importance culturelle, forêts sacrées, Bénin.

ABSTRACT

On the importance of the sacred in the preservation of tree species: the case of Samba (*Triplochiton scleroxylon* K. Schum.) in Benin

Triplochiton scleroxylon K. Schum. is a species of socio-cultural importance as one of the trees that are venerated in the sacred ecosystems of Benin. However, natural stands of the species are declining and virtually no detailed information on its local uses has been documented. The aim of this study was to assess local knowledge on uses of the species and its distribution among ethnolinguistic, cultural and faith groups in Benin. Individual ethnobotanical interviews were conducted with 411 believers in deities associated with conservation of this tree species. Ethnobotanical indices such as relative frequency of citation, use value (total and per tree organ), and the cultural importance index were used to quantify the popularity, uses and socio-cultural importance of *T. scleroxylon*. A negative binomial generalized linear model was used to examine the variations in use value between ethno-linguistic, cultural and faith groups. A total of 36 specific uses classified into nine use types were reported. Cultural, medicinal, food, artisanal and timber uses were the most popular. All parts of the plant are valued in the tradition of *Oro* worship. Leaves, roots and bark are the organs of *T. scleroxylon* used to treat various ailments, the most common being digestive and gynaecological. Knowledge and uses of the species vary significantly among the groups surveyed. We found singular knowledge, uses and importance of *T. scleroxylon* among followers of the *Oro* cult. The disappearance of this species could have major consequences for the identity and the cultural and religious stability of the people practising this tradition. The popular medicinal uses reported also offer prospects for promoting the medicinal properties of the species.

Keywords: *Triplochiton scleroxylon*, Samba, traditional knowledge, use value, cultural importance, religious importance, sacred forests, Benin.

RESUMEN

Importancia de los cultos en la conservación de las especies arbóreas, el caso de la samba (*Triplochiton scleroxylon* K. Schum.) en Benín

El *Triplochiton scleroxylon* K. Schum. es una de las especies veneradas de los ecosistemas sagrados de Benín, con una gran importancia sociocultural. Sin embargo, las masas forestales naturales de la especie están disminuyendo y la información sobre sus usos está casi sin documentar. Este estudio evalúa los conocimientos locales sobre los usos de la especie y la distribución de dichos conocimientos entre los grupos etnolingüísticos, culturales y cultuales en Benín. Se realizaron encuestas etnobotánicas individuales entre 411 devotos de deidades vinculadas a la conservación de la especie en Benín. Para cuantificar la popularidad, el uso y la importancia sociocultural de la *T. scleroxylon* se utilizaron índices etnobotánicos como la frecuencia relativa de citación (FRC); el valor de uso (VU) total y por órgano, y el índice de importancia cultural (IC), respectivamente. Se realizó un modelo lineal generalizado con la distribución binomial negativa para examinar la variación del VU entre los grupos etnolingüísticos, culturales y cultuales. En total, se recogieron 36 usos específicos, clasificados en nueve tipos de uso. Los usos más citados son cultuales, medicinales, artesanales y como madera de construcción. Todas las partes de la planta se valoran en la tradición del culto *Oro*. Las hojas, las raíces y las cortezas son los órganos utilizados para tratar diversas afecciones, las más populares de las cuales son las digestivas y las ginecológicas. El conocimiento y uso de la especie varían significativamente entre los grupos etnolingüísticos y cultuales. Se ha observado una singularidad en el conocimiento de la *T. scleroxylon* entre los devotos del culto *Oro*. La desaparición de esta especie podría tener importantes consecuencias para la identidad y la estabilidad cultural y cultural de los pueblos que practican esta tradición. Los usos medicinales populares señalados también ofrecen perspectivas para la valorización medicinal de la especie.

Palabras clave: *Triplochiton scleroxylon*, samba, conocimientos tradicionales, valor de uso, importancia cultural, bosques sagrados, Benín.

Introduction

Depuis les temps anciens, l'humanité dépend de différents produits des forêts pour les besoins quotidiens. Les forêts représentent une importante source de satisfaction des besoins élémentaires des populations, notamment s'alimenter et se soigner (Cavendish, 2000 ; Maxted *et al.*, 2007 ; FAO, 2018). Les communautés résidant dans les villages et à proximité des forêts dépendent essentiellement des plantes et des produits végétaux pour leurs revenus et leurs moyens de subsistance car elles jouissent d'un droit spécifique sur les forêts et leurs produits (Rajesh et Nair, 2018). Les plantes ne sont pas seulement un moyen de subsistance ; les communautés locales sont aussi souvent engagées dans différentes pratiques magico-religieuses et rituelles où les plantes sont vénérées comme des dieux et déesses. La dépendance des sociétés, surtout rurales, vis-à-vis de ces ressources forestières peut constituer une menace pour l'équilibre des écosystèmes (Kalinganire *et al.*, 2008 ; Fandohan *et al.*, 2017). Prévenir la disparition de ces ressources nécessite de prendre en compte les considérations sociales dans les stratégies de conservation et de gestion durable des essences forestières.

En Afrique, les communautés rurales ont des traditions anciennes de collecte et d'utilisation de plusieurs espèces de plantes. Grâce à ces pratiques, ces communautés ont acquis des connaissances traditionnelles substantielles sur les propriétés des plantes et l'importance nutritionnelle, médicinale et spirituelle de la biodiversité locale (Johns *et al.*, 1996). Bien que la modernisation ait été impliquée dans la réduction des connaissances et de l'utilisation de la biodiversité, ces savoirs endogènes ont été transmis de génération en génération (Pilgrim *et al.*, 2008). Toutefois, de nombreuses études ont démontré la difficulté des générations plus âgées à transmettre de nos jours les connaissances traditionnelles à la jeune génération (Saynez-Vaquez *et al.*, 2016) ; ce qui conduit à l'aliénation de cette génération quant à son environnement immédiat, et à la perte d'informations liées à la nature.

La recherche ethnobotanique prend en compte la relation entre les peuples et les plantes, y compris les croyances et les pratiques culturelles associées à diverses formes d'utilisation et de conservation de l'environnement naturel, conformément aux connaissances des communautés locales (Nolan et Turner, 2011). Ces connaissances permettent de comprendre les valeurs sociales, culturelles et économiques que ces communautés associent aux ressources autochtones avec lesquelles elles interagissent et partagent des liens séculaires. Elles sont donc devenues essentielles dans la biologie de la conservation (Pilgrim *et al.*, 2008). Cependant, malgré la diversité des études ethnobotaniques sur plusieurs espèces autochtones d'Afrique au cours des deux dernières décennies, les informations sur plusieurs autres espèces de valeur restent éparées et non documentées, malgré leur statut d'espèce menacée dans certaines régions. C'est le cas du samba (*Triplochiton*

scleroxylon K. Schum.) pour lequel les informations sur sa structure démographique et spatiale, son écophysiologie et sa sylviculture particulière restent encore fragmentaires.

Triplochiton scleroxylon, de la famille des Malvacées, est une espèce de l'étage dominant des forêts tropicales denses semi-décidues (Akoegninou *et al.*, 2006). Troisième essence la plus exploitée en Afrique centrale pour la qualité de son bois (Bayol *et al.*, 2012), *T. scleroxylon* fait également partie des premières plantes médicinales les plus utilisées au Nigeria pour guérir le diabète (Onoagbe *et al.*, 1999). Au Bénin, elle est traditionnellement utilisée pour la fabrication d'objets d'art. Elle fait partie des essences les plus vénérées dans les couvents (Kokou et Sokpon, 2006). Arbre sacré du fétiche « Oro » chez les peuples Nagot au sud du Bénin (Palla et Louppe, 2002 ; Kokou et Sokpon, 2006 ; Adomou *et al.*, 2011), son aire de distribution se réduit de plus en plus aux forêts sacrées d'Oro. Elle fait partie des centaines de plantes rituelles commercialisées sur les principaux marchés de plantes en Afrique de l'Ouest (Quiroz et van Andel, 2015). En raison des pouvoirs surnaturels qui sont souvent attribués aux arbres sacrés, leur récolte à des fins commerciales est devenue une entreprise rentable en Afrique (Quiroz et van Andel, 2015). Au Bénin, l'espèce fait face à de fortes menaces d'extinction (Adomou *et al.*, 2011). Suivant les critères d'évaluation de la vulnérabilité des espèces de l'UCN, elle fait partie des 105 espèces menacées du Bénin (Adomou *et al.*, 2011). L'une des principales menaces sur l'espèce est la fragmentation des reliques de forêts denses semi-décidues qui constituent son habitat naturel. Son caractère sacré fait de *T. scleroxylon* une espèce inféodée à certains groupes ethnolinguistiques et culturels dont les connaissances sur les usages de l'espèce, et l'importance culturelle, ne sont pas suffisamment développées.

La présente étude vise à évaluer les connaissances ethnobotaniques sur l'espèce et examiner la distribution de ces connaissances entre groupes ethnolinguistiques, culturels et culturels au Bénin. En effet, plusieurs hypothèses ont été testées concernant la dynamique des connaissances des plantes. L'ensemble de ces hypothèses considère que le niveau de connaissance individuelle d'une plante est corrélé avec certains facteurs socioculturels et démographiques comme le sexe, l'âge, les us et coutumes (Sundriyal *et al.*, 2004 ; Souto et Ticktin, 2012 ; Gaoué *et al.*, 2017). Les femmes et les personnes âgées auraient ainsi tendance à avoir plus de connaissances sur les plantes médicinales ; de même, les personnes avec un fort niveau d'alphabétisation ou ayant un meilleur accès à l'éducation formelle détiennent moins de connaissances sur l'usage des plantes (Voeks, 2007). Elles considèrent aussi que l'accumulation de connaissances sur les ressources naturelles, en particulier les plantes, est un processus dans le temps, de sorte qu'il est attendu que les personnes âgées aient plus de connaissances que les personnes jeunes (Hanazaki *et al.*, 2013 ; Gaoué *et al.*, 2017).

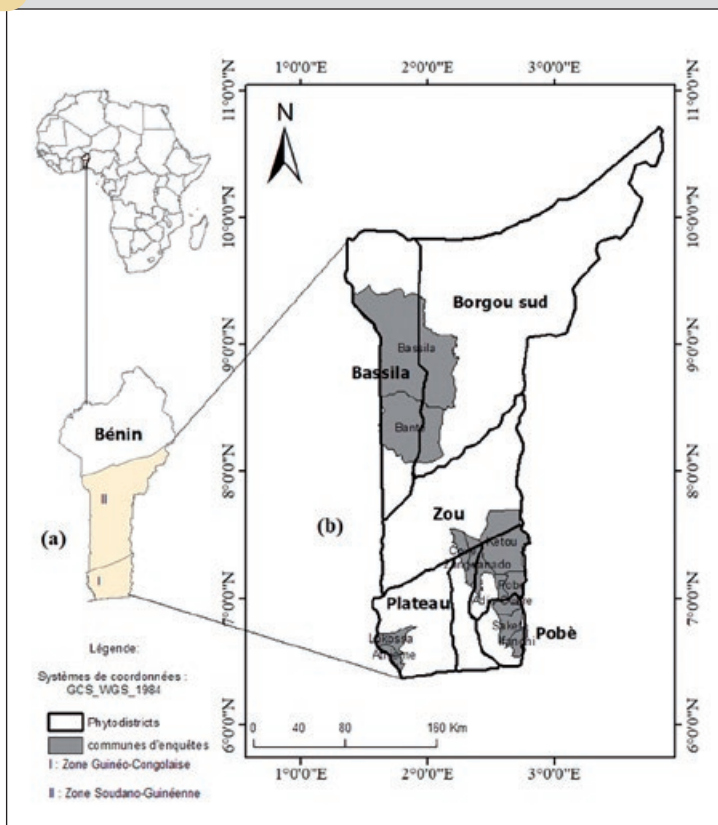


Figure 1.
Localisation géographique de la zone d'étude.
Geographical location of the study area.

Plusieurs travaux ont testé l'objectivité de ces hypothèses. Cependant, le contexte dans lequel se fait la transmission des savoirs locaux peut influencer les résultats. Par exemple, les tabous et interdictions relatifs à certaines espèces sacrées dans certaines communautés en Afrique par rapport à la gente féminine ne permettent pas de vérifier ces hypothèses. Les hommes et les femmes peuvent posséder différents types de connaissances des usages des plantes en raison de leurs différents rôles définis culturellement. Le type de connaissance a de l'importance dans l'évaluation de la dynamique des connaissances sur l'usage des plantes (de Albuquerque *et al.*, 2011 ; Souto et Ticktin, 2012 ; Gaoué *et al.*, 2017). Il peut également être difficile de comparer les connaissances de toutes les plantes suivant l'âge car, dans les couvents, le niveau de responsabilité n'est pas forcément fonction de l'âge. Aussi la durée d'adhésion à un culte ou à une divinité peut-elle être un meilleur prédicteur de la dynamique des connaissances locales sur les plantes rituelles que l'âge. Il est donc clair que le degré des connaissances sur l'usage de *T. scleroxylon* pourrait varier indépendamment de l'âge, du sexe et du niveau d'instruction. Quels sont alors les facteurs prédicteurs de la dynamique des connaissances sur l'usage traditionnel de *T. scleroxylon*, un arbre sacré et vénéré au Bénin ?

Matériel et méthode

Modèle biologique d'étude

Triplochiton scleroxylon est une espèce d'arbre de grande taille, à feuilles caduques, et ayant une faible densité de bois (320-440 kg/m³) (Palla et Louppe, 2002), qui avec de grands contreforts à la base de son tronc peut dépasser 50 m de hauteur et 2 m de diamètre (Siepel *et al.*, 2004). Elle fait partie des espèces principales de l'Afrique subsaharienne, dont l'aire de répartition s'étendait entre la Sierra Leone et le Congo (Fayolle *et al.*, 2012). L'espèce est plus abondante sur les sols bien drainés, ferrugineux et fertiles, à une altitude inférieure à 500 m. Les zones de son aire de répartition géographique ont un climat saisonnier avec des précipitations comprises entre 1 100 et 1 800 mm et une température oscillant entre 20 et 35 °C (Hall et Bada, 1979). Au Bénin, il existe à ce jour peu d'évaluations quantitatives de l'abondance de l'espèce, de même que pour la structure de son peuplement ; toutefois, sa principale zone d'occurrence au Bénin est l'espace guinéo-congolais, avec quelques individus dans la zone soudano-guinéenne, et principalement dans les forêts sacrées et quelques forêts classées (Akoegninou *et al.*, 2006).

Milieu d'étude

La présente étude a été réalisée dans la zone de distribution de *T. scleroxylon* que sont le centre d'endémisme régional guinéo-congolais et la zone de transition régionale soudano-guinéenne au Bénin (figure 1). La région guinéo-congolaise du Bénin (6°25'N à 7°30'N) représente la partie sud du pays. Le climat qui y règne est de type subéquatorial avec des précipitations annuelles moyennes de 900-1 300 mm. Le sol dominant dans cette région est de type ferrallitique profond, couvert par les forêts semi-décidues (Adomou, 2005). Les groupes ethno-linguistiques dominants sont les *Pédah*, *Idatcha*, *Nagot*, *Fon* et *Mahi*.

La zone de transition soudano-guinéenne (7°30'N-10°30'N) représente la région méridionale du pays. Un climat subhumide y prévaut avec un régime à tendance unimodale de saison des pluies (1 000-1 300 mm/an). Les sols ferrugineux couverts par les forêts sèches sont les types de sol dominants de cette zone. On y rencontre principalement les peuples *Fon*, *Kotafon*, *Nagot/Yorouba*, *Goun*, *Wemé*, *Aïzo*, *Xwla*, *Tofin* et *Pédah* (Adomou, 2005). Cependant, il est à noter que les forêts sacrées existent un peu partout au Bénin, dont l'ensemble représente une superficie non négligeable.

Échantillonnage et collecte des données

Une étude exploratoire a été conduite dans la zone de distribution de *T. scleroxylon* au Bénin (figure 1.a). Tous les villages à proximité des forêts sacrées abritant *T. scleroxylon* ont été retenus. Au total, 11 communes ont été considérées (figure 1.b). Cette première phase a permis d'identifier tous les couvents des cultes associés à la conservation des



Photos 2.

Quelques couvents de forêts sacrées liées à la conservation de *Triplochiton scleroxylon* au Bénin.
Some sacred forest convents linked to the conservation of Triplochiton scleroxylon in Benin.

Photos G. Ganka.



Photos 3.

Quelques organes (graine, feuille, tronc) et arbre de *Triplochiton scleroxylon*.
Some organs (seed, leaf, trunk) and tree of Triplochiton scleroxylon.

Photos G. Ganka.

forêts sacrées abritant *T. scleroxylon* (photos 2) ainsi que les adeptes qui connaissent l'espèce et sont à même de citer différents critères de reconnaissance de celle-ci. Cette phase a montré que tous les adeptes des cultes associés à la conservation de *T. scleroxylon* connaissent et utilisent l'espèce. Ces adeptes sont tous de sexe masculin.

À la fin de la première phase, une permission a été demandée auprès du chef de village et du *Adjana* (chef dignitaire de *Oro*) de chaque site d'étude avant la conduite des enquêtes et ceci en respect du code d'éthique établi par la Société internationale d'ethnobiologie (International Society of Ethnobiology, 2006). Les enquêtés ont été identifiés et leur permission a été aussi obtenue avec l'aide des autorités locales avant l'administration du guide d'entretien conçu à cet effet.

Pour ce faire, les autorités locales et traditionnelles de chaque localité ont été informées de l'étude et des intermédiaires ont été engagés. Des photos des feuilles et des fruits de *T. scleroxylon* (photos 3) ont été montrées aux enquêtés pour faciliter la reconnaissance de l'espèce.

Compte tenu de la distribution de *T. scleroxylon* et de son caractère sacré au Bénin, l'approche d'échantillonnage non aléatoire par la technique de la boule de neige (Cochran, 1977) a été adoptée en vue d'identifier les informateurs clés parmi les acteurs des forêts sacrées du culte *Oro* et des divinités autres qu'*Oro*. Cette technique consiste à approcher un informateur compétent pour l'étude, qui, après avoir été enquêté, indique à son tour une autre personne compétente de la même communauté ; le processus évolue ainsi jusqu'à l'investigation de toutes les personnes compétentes pour le sujet d'étude. Cela nous a permis d'approcher directement des informateurs qui sont réputés détenir des connaissances sur *T. scleroxylon* au sein de leur communauté. En effet, l'estimation de l'effectif des

informateurs clés a été considérée comme représentative lorsque la limite de saturation (point auquel plus aucun nom d'informateur clé n'est mentionné par le dernier enquêté) a été atteinte au terme de l'enquête (Cochran, 1977).

Le nombre d'enquêtés était de 297 au sein du groupe ethnolinguistique *Nagot* (72,26 %), 57 chez les *Mahi* (13,87 %), 3 chez les *Fon* (0,73 %), 50 parmi les *Kotafon* (12,17 %) et 4 pour les *Anii* (0,97 %), soit 411 individus au total. Cependant, compte tenu de la faible représentativité des groupes ethniques *Anii* (0,97 %) et *Fon* (0,73 %), les informateurs *Anii* et *Fon* n'ont pas été pris en compte dans les analyses statistiques. Ainsi, 404 enquêtés appartenant à trois groupes ethniques (*Kotafon*, *Mahi*, et *Nagot*) ont été retenus.

Les données ont été collectées à travers des entretiens semi-structurés individuels et des observations directes sur le terrain. Les données collectées sont structurées en trois parties. La première partie est relative aux caractéristiques de l'enquêté, notamment le groupe ethnique, l'âge et le groupe culturel d'appartenance (communauté de culte à laquelle il appartient). La deuxième partie est relative aux appellations locales de l'espèce et leur signification ainsi qu'aux connaissances sur les usages spécifiques de l'espèce, et les parties ou organes utilisés. La troisième partie porte sur l'importance culturelle de la plante. Les données préliminaires ont permis d'identifier neuf catégories d'usage : alimentaire, médicinale, brosse végétale, culturelle, cultuelle, artisanale, bois énergie, bois d'œuvre et agropastoralisme. Pour évaluer l'importance des catégories d'usage et des organes, il a été demandé à chaque enquêté d'évaluer leur niveau d'importance.

Pour les besoins de l'analyse, les enquêtés ont été répartis suivant l'âge (adultes, 18-60 ans ; personnes âgées, plus de 60 ans), l'appartenance à un culte lié à la conservation de *T. sclerocyton* et l'activité socioprofessionnelle (tableau I). Les catégories socioprofessionnelles identifiées étaient les agriculteurs (56,68 %), les sculpteurs (5,19 %) et les tradithérapeutes (les prêtres des divinités et guérisseurs traditionnels) (24,26 %). Une quatrième catégorie regroupe les autres activités (13,63 %) et inclut les fonctionnaires, mécaniciens, pépiniéristes, etc. (tableau I).

Traitement et analyse des données

Trois indices ethnobotaniques ont été utilisés pour l'analyse des données. Il s'agit de la fréquence relative de citation d'une utilisation u (FRC _{u}), la valeur d'usage de la plante entière (VU _{e}) et par organe (VU _{org}) et l'indice d'importance culturelle (IC). Ces indices ont permis d'examiner les connaissances des personnes interviewées sur l'espèce ainsi que son importance socioculturelle suivant les différents groupes.

La FRC mesure la popularité de chaque usage spécifique de la plante par les répondants d'un groupe donné (Friedman *et al.*, 1986). Les valeurs élevées de la FRC pour une utilisation spécifique reflètent une popularité et généralement un consensus (partage des connaissances) pour cette utilisation de l'organe dans la communauté. Elle a été calculée par :

$$FRC_u = \frac{Nu}{N} \times 100$$

où N_u représente le nombre de répondants qui ont déclaré l'utilisation u et N le nombre total de répondants.

Les utilisations rapportées par plus de 20 % des répondants (FRC > 20 %) ont été considérées comme des connaissances partagées (TRAMIL, 1989). Cependant, les connaissances rapportées par moins de 20 % des répondants peuvent être importantes dans certains groupes ethnolinguistiques. Une utilisation u a été considérée comme importante pour un groupe ethnolinguistique lorsque la FRC _{u} est supérieure à 5 % (Gouwakinnou *et al.*, 2011).

La VU _{T} a été exprimée en termes de nombre moyen d'usages rapportés (Gomez-Beloz, 2002) :

$$VU_T = \frac{\sum_{i=1}^N UR_i}{N}$$

où UR _{i} représente le nombre d'usages spécifiques rapporté par l'enquêté i du groupe considéré et N le nombre total d'enquêtés du groupe.

Compte tenu de la nature des données initiales de VU _{T} (données de comptage), un modèle linéaire généralisé (GLM) basé sur la distribution binomiale négative a été utilisé pour tester l'influence des facteurs âge, groupe ethnolinguistique, culturel et professionnel sur sa variation. Le modèle saturé a été d'abord spécifié, puis progressivement simplifié en utilisant la valeur du critère d'information d'Akaike (Akaike, 1973 ; Johnson et Omland, 2004) jusqu'à la

Tableau I.

Répartition des enquêtés par groupes ethnolinguistiques et culturels.
Distribution of respondents by ethnolinguistic and cultural groups.

Groupe ethnolinguistique et domaine d'activité	Groupe socioculturel	Adulte	Vieux	Proportion (%)
Groupe ethnolinguistique Nagot	Acteur du culte Oro	92	33	72,26
	Acteur d'autres divinités	97	75	
Mahi	Acteur du culte Oro	20	6	13,87
	Acteur d'autres divinités	21	10	
Kotafon	Acteur du culte Oro	0	0	12,17
	Acteur d'autres divinités	33	17	
Domaine d'activité Agriculture	Acteur du culte Oro	42	19	56,7
	Autre acteur	106	62	
Tradithérapie	Acteur du culte Oro	52	22	24,2
	Autre acteur	4	20	
Autre	Acteur du culte Oro	12	0	13,6
	Autre acteur	26	18	
Sculpture	Acteur du culte Oro	4	0	5,2
	Autre acteur	17	0	

Critères d'âge : adulte, 18-60 ans ; vieux, plus de 60 ans.

Tableau II.
 Appellations locales de *Triplochiton scleroxylon* au Bénin.
 Local names for *Triplochiton scleroxylon* in Benin.

Groupe ethnolinguistique	Appellation utilisée	Signification
Kotafon	Athiwé	Bois blanc
Mahi	Whètin	
Nagot/Yoruba	Aréré ; Egui Aréré	L'arbre de l'étage dominant de toute forêt
	Egui alassa	
	Egui Oro	L'arbre sacré du fétiche Oro
	Egui ogù	L'arbre sacré

sélection du meilleur modèle (modèle ayant le plus faible nombre de facteurs avec des effets significatifs) (Johnson et Omland, 2004).

La VU_{org} est exprimée en termes de nombre moyen d'usages par enquêté et par organe. Elle a été calculée en utilisant la formule ci-dessous (Gomez-Beloz, 2002) :

$$VU_{org} = \frac{\sum_{i=1}^N UR_{org,i}}{N}$$

où VU_{org} est la valeur d'usage d'un organe donné, $UR_{org,i}$ est le nombre d'usages mentionné pour cet organe par l'enquêté i et N est le nombre de personnes enquêtées du groupe.

Les organes ayant une VU_{org} élevée sont considérés comme les parties ayant le plus d'usages connus et implicitement les organes les plus exploités par la population. La VU_{org} a été comparée entre organes en utilisant un modèle linéaire général (GLM) basé sur la distribution de Poisson.

L'indice d'importance culturelle (IC) désigne la valeur allouée culturellement à la plante ainsi que celle rattachée à ses organes (Houehanou *et al.*, 2011). L' IC des catégories d'usage (IC_{cu}) et des organes (IC_{org}) a été calculée en utilisant les deux formules ci-dessous (Houehanou *et al.*, 2011) :

$$IC_{cu} = \frac{\sum_{i=1}^N S_{cu,i}}{N}$$

$$IC_{org} = \frac{\sum_{i=1}^N S_{org,i}}{N}$$

Pour une catégorie d'usage donnée, $S_{cu,i}$ est le score d'importance culturelle attribué par l'enquêté i à cette catégorie. Pour un organe donné, $S_{org,i}$ est le score d'importance culturelle attribué par l'enquêté i à cet organe. N est le nombre de personnes enquêtées du groupe. Ces scores ont été obtenus par la conversion des niveaux d'importance en termes de « pas important », « peu important », « moyennement important » et « très important », respectivement en 0, 1, 2 et 3. Des diagrammes en radar ont été construits pour analyser la variation de l' IC_{cu} et de l' IC_{org} suivant les groupes ethniques. Toutes les analyses statistiques ont été réalisées sous le logiciel R version 3.5.0 (R Core Development, 2020)¹.

¹ <https://cran.r-project.org/bin/windows/base/old/3.5.0/>

Résultats

Appellations locales

Les appellations utilisées par les enquêtés pour désigner *T. scleroxylon* et leur signification varient suivant les groupes ethnolinguistiques rencontrés (tableau II).

Diversité des usages de *Triplochiton scleroxylon*

Triplochiton scleroxylon présente 36 usages spécifiques catégorisés en neuf types d'utili-

sation (tableau III). Seul l'usage comme bois énergie présente une faible fréquence de citation (FRC = 0,97 %). L'usage culturel est le plus rapporté par les enquêtés (FRC = 96,1 %). La diversité des usages de *T. scleroxylon* varie en fonction des organes de la plante. Les organes les plus impliqués dans les usages sont les feuilles (11 usages), les écorces (6), les racines (6), le tronc (8) et les tiges et branches (5) (tableau III).

Usages médicaux

Triplochiton scleroxylon est utilisé dans le traitement de 14 maladies et symptômes. Le recours à *T. scleroxylon* dans le traitement des troubles digestifs et des affections gynécologiques est le plus connu de la population, respectivement 53,3 % et 38,9 % des enquêtés (tableau IV). *T. scleroxylon* est aussi sollicité pour soigner de multiples maladies : diabète (17,3 %), épilepsie (10,2 %), varicelle (12,9 %), asthme (23,3 %), prostate (17,8 %) et cancer du sein (10,7 %), mais il reste peu utilisé pour le traitement des maladies cardiaques (3,6 %).

Relation entre les facteurs ethnolinguistiques, culturels et socio-professionnels et la valeur d'usage de *Triplochiton scleroxylon*

Les connaissances et usages de *T. scleroxylon* varient significativement suivant les groupes ethnolinguistiques (GSC) et la catégorie d'adeptes (CA). Le facteur âge n'a pas d'effet significatif sur la variation des connaissances et usages de *T. scleroxylon*.

La valeur d'usage totale de *T. scleroxylon* était plus élevée chez les Nagot (12,14 ± 0,34) suivis des Mahi (7,71 ± 0,56) (figure 1a). Au sein des groupes culturels, les acteurs du culte Oro utilisent plus l'espèce que les acteurs des autres divinités (figure 2b). Les tradithérapeutes et les sculpteurs détiennent également plus de connaissances que ceux des autres domaines d'activité (figure 2c).

Afin d'évaluer la relation entre les facteurs socio-démographiques et le niveau de connaissance des usages de *T. scleroxylon*, différents modèles ont été testés (tableau V).

Tableau III.Catégorie d'usage de *Triplochiton scleroxylon* au Bénin.
Category of use of Triplochiton scleroxylon in Benin.

Catégorie d'usage	FRC (%)	Observations	Parties utilisées
Alimentaire	71	Utilisé pour préparer la sauce gluante	Feuille
Médicinale	72,7	Traitement des maladies et symptômes	Feuille, racine, écorce
Brosse végétale	18	Utilisé comme cure-dent	Tige/branche, racine
Culturelle	96,1	Émondage des feuilles par le fétiche <i>Oro</i> , usage du bois dans la fabrication des tam-tams et masque du culte « <i>Guèlèdè</i> » et de bâton de guide de <i>vodoun Egoun-goun</i>	Feuille, fruit/graine, racine, branche, tronc
Cultuelle	36,5	Usage dans les cérémonies de sortie de fétiche <i>Oro</i> , usage dans l'art divinatoire, la fabrication de tam-tam sacré <i>Oro</i> , fabrication des statuètes de jumeaux et de protection spirituelle et autres usages spirituels dans les couvents du culte <i>Oro</i>	Feuille, tronc, branche/tige, racine
Artisanale	74,4	Fabrication d'objets d'art, de palettes de cuisine	Branche, tronc
Bois énergie	0,9	Utilisé comme bois de feu et charbon	Branche, tronc
Bois d'œuvre	88,1	Fabrication de meubles, pirogues monoxyles, objets sculptés, mortiers, tam-tams	Tronc
Agropastoralisme	5,1	Alimentation et soins du bétail	Feuille

Tableau IV.Usages médicaux de *Triplochiton scleroxylon* au Bénin.
Medicinal uses of Triplochiton scleroxylon in Benin.

Catégorie d'affection	Maladie et symptôme	Organes	Mode de préparation	Mode d'admission	Groupe sociolinguistique	FRC
Digestive	Constipation	Feuille	Décoction	Boisson	<i>Anii ; Fon ; Kotafon ; Mahi ; Nagot</i>	32,6
	Maux de ventre	Feuille	Décoction	Boisson	<i>Anii ; Fon ; Kotafon ; Mahi ; Nagot</i>	53,3
Gynécologique	Accouchement compliqué	Feuille	Décoction	Boisson	<i>Anii ; Fon ; Kotafon ; Mahi ; Nagot</i>	38,9
	Irrégularité des menstrues	Feuille	Trituration	Boisson		31,4
	Menstrues intermittentes	Feuille	Décoction	Boisson		30,6
	Pertes blanches	Feuille	Trituration	Boisson		28,7
	Fibrome	Racine	Poudre	Mélange alcoolique	<i>Nagot ; Mahi</i>	18,2
Cardiologique	Hypotension artérielle	Écorce	Décoction	Boisson	<i>Nagot</i>	3,6
Endocrinienne	Diabète	Écorce	Décoction	Boisson	<i>Nagot ; Mahi</i>	17,3
Neurologique	Épilepsie	Racine	Poudre	Lapement	<i>Nagot</i>	10,2
Dermatologique	Varicelle	Écorce	Poudre	Application locale	<i>Nagot ; Mahi</i>	12,9
Cancéreuse	Cancer du sein	Écorce	Poudre	Mélange alimentaire	<i>Nagot</i>	10,7
Autres	Asthme	Écorce	Poudre	Lapement	<i>Nagot ; Mahi</i>	23,3
	Prostate	Écorce	Macération	Boisson	<i>Nagot ; Mahi</i>	17,8

Le modèle incluant l'interaction des facteurs groupe ethnolinguistique (GSC) et catégorie d'adeptes (CA) est le modèle adéquat du fait de sa faible valeur de l'AIC (tableau V). La variation du degré de connaissance des usages de *T. scleroxylon* est seulement déterminée par les groupes culturels et ethnolinguistiques.

Les connaissances des usages de *T. scleroxylon* sont significativement plus élevées chez les *Nagot* et les *Mahi* que chez les *Kotafon*. Les adeptes du culte *Oro* possèdent plus de connaissances sur les usages de *T. scleroxylon* que les adeptes des autres divinités (tableau VI).

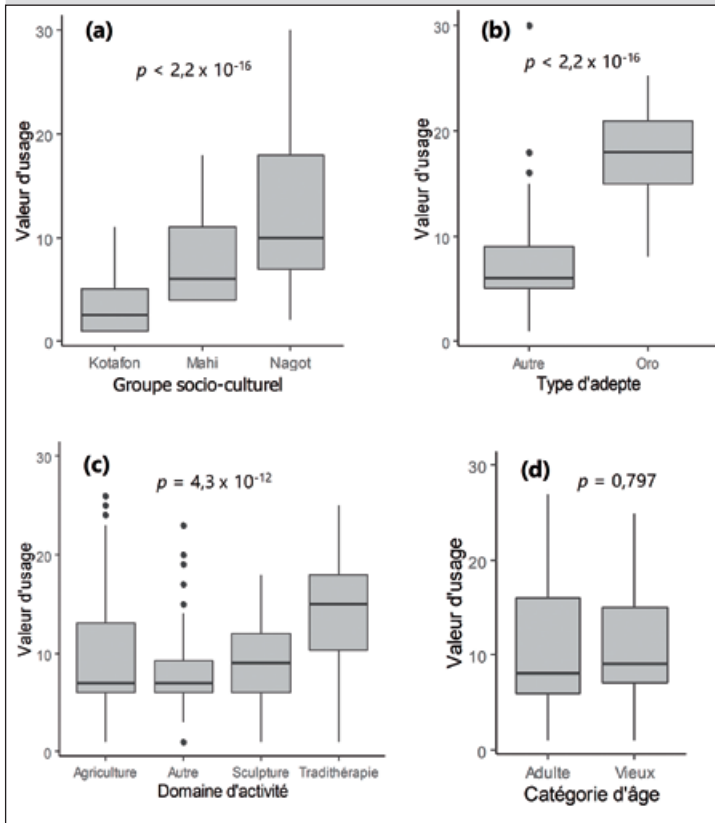


Figure 2.
 Variation des valeurs d'usages ethnobotaniques de *Triplochiton scleroxylon* suivant les groupes sociodémographiques.
Variation in ethnobotanical use values of Triplochiton scleroxylon according to socio-demographic groups.

Variation des VUR de *Triplochiton scleroxylon* au sein de la communauté Nagot

Les deux catégories de cultes existent au sein du groupe ethnolinguistique *Nagot*, contrairement aux groupes *Kotafon* et *Mahi* caractérisés uniquement soit par le culte *Oro* (pour les *Mahi*), soit pour une autre divinité (chez les *Kotafon*). Au sein du groupe ethnolinguistique *Nagot*, les adeptes du culte *Oro* ont plus de connaissances sur l'usage de *T. scleroxylon* que ceux des autres divinités ($p < 0,001$) avec un nombre d'usages moyen de $17,90 \pm 3,7$ et un nombre d'usages médian de 18 contre $7,9 \pm 3,0$ usages moyens pour 7 usages médians.

Valeur d'usage des organes de *Triplochiton scleroxylon*

Plusieurs parties de *T. scleroxylon* sont sollicitées quotidiennement pour divers usages : feuilles, fleurs, fruits/grains, racines, écorce, tige et bois. Les valeurs d'usage varient entre les organes de l'espèce. La feuille est l'organe le plus utilisé, suivie du bois, de la tige et des racines (figure 3).

La figure 4 présente les valeurs d'usage moyennes des différentes parties de *T. scleroxylon* suivant les groupes ethnolinguistiques (figure 4). Les groupes qui utilisent le plus les organes de *T. scleroxylon* sont les *Nagot* et les *Mahi* (figure 4). Cependant, il faut noter que l'usage de toutes les parties de l'espèce est beaucoup plus prononcé parmi les *Nagot* que chez les autres groupes ethnolinguistiques (figure 4).

Importance culturelle de *Triplochiton scleroxylon*

La figure 5 présente la variation de l'importance culturelle de *T. scleroxylon* suivant les groupes ethnolinguistiques au Bénin. Les *Nagot* accordent une importance relativement plus marquée à l'ensemble des usages de l'espèce que les autres groupes ethnolinguistiques (figure 5). Cependant, il faut noter que les usages culturels, cultuels et ceux comme le bois d'œuvre de *T. scleroxylon* sont beaucoup plus marqués pour cette communauté. La plupart des groupes ethnolinguistiques accordent davantage d'importance à l'usage médicinal qu'à celui du bois d'œuvre de l'espèce. Les usages de l'espèce comme le bois énergie et l'agropastoralisme sont quasiment sans importance pour les enquêtés (figure 5).

L'importance culturelle des organes de *T. scleroxylon* diffère suivant les groupes ethnolinguistiques (figure 5). La plupart des parties de l'espèce ont de l'importance pour les groupes ethnolinguistiques *Nagot* et *Mahi*. Les feuilles, les racines et le bois de *T. scleroxylon* sont culturellement plus importants que toutes les autres parties de la plante pour cette communauté. Le bois de l'espèce a de l'importance pour tous les groupes ethnolinguistiques rencontrés.

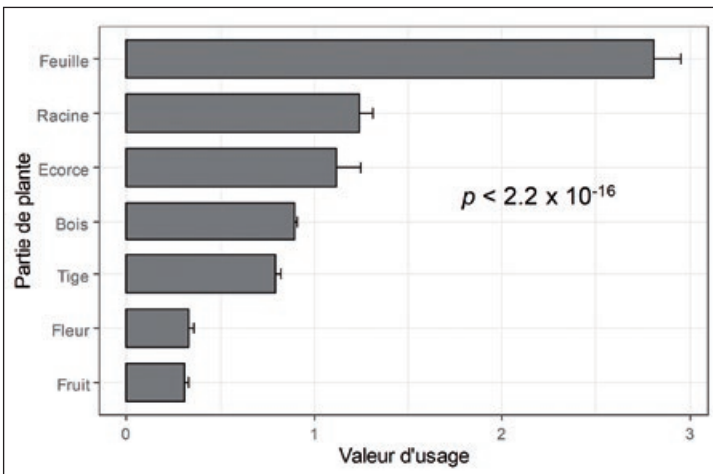
Tableau V.
 Sélection du modèle parcimonieux.
Selection of the parsimonious model.

Modèles candidats	AIC	Δ AIC
GSC + CA + GSC : CA	2 123,6	0
CA + Âge + CA : Âge	2 226,8	103,2
CA + DomAct + CA : DomAct	2 228	104,4
CA	2 238,1	114,5
GSC + DomAct + GSC : DomAct	2 351	227,4
GSC + Âge + GSC : Âge	2 407,8	284,2
GSC	2 415	291,4
DomAct + Âge + DomAct : Âge	2 520,1	396,5
DomAct	2 522,5	398,9
Âge	2 570,5	446,9

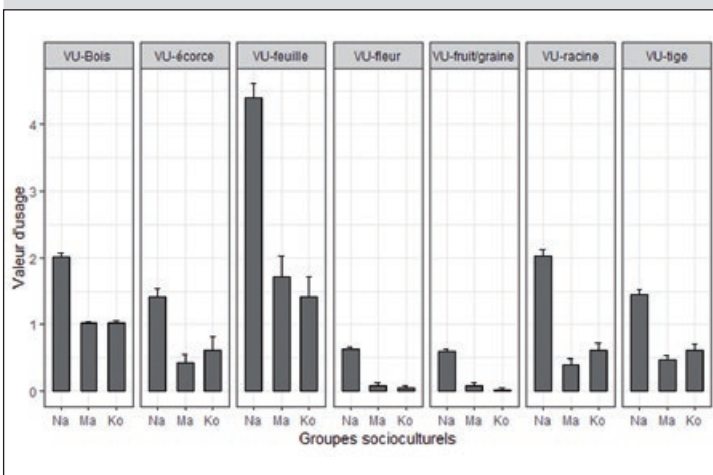
Tableau VI.

Résultats de la régression binomiale négative sur les valeurs d'usage.
Results of the negative binomial regression on use values.

	Estimation	Erreur type	Valeur de Z	Probabilité (> z)
Intercept	1,23547	0,07795	15,85	< 0,001***
Mahi	0,80825	0,09262	8,727	< 0,001***
Nagot	0,83814	0,08296	10,103	< 0,001***
Adeptes du culte Oro	0,81141	0,03686	22,015	< 0,001***

**Figure 3.**

Importance d'usage des parties de plante de *Triplochiton scleroxylon*.
Importance of using the plant parts of *Triplochiton scleroxylon*.

**Figure 4.**

Valeur d'usage des organes ou parties de *Triplochiton scleroxylon* suivant les groupes ethnolinguistiques.
Use value of organs or parts of *Triplochiton scleroxylon* according to ethnolinguistic groups.
Na = Nagot ; Ma = Mahi ; Ko = Kotafon

Discussion

Les perceptions sur l'appellation de l'espèce varient suivant les groupes ethnolinguistiques rencontrés. Par exemple, les Nagot désignent *T. scleroxylon* sous le nom de « Aréré » comme étant l'arbre de l'étage dominant de la forêt, « Egui Oro » l'arbre qui symbolise le fétiche Oro et « Egui ogù » pour son statut d'arbre sacré. Le nom vernaculaire d'une espèce est donc la révélation d'une tradition donnée (Assogba *et al.*, 2017) ou du trait morphologique de l'espèce (Achigan-Dako *et al.*, 2010 ; Fandohan *et al.*, 2017 ; Assogba *et al.*, 2017). L'appellation « Egui Oro » ou « Egui ogù » en milieu Nagot suggère qu'il s'agit d'une espèce ayant un fort degré de signification culturelle au sein de ce groupe ethnolinguistique.

Les usages les plus connus par les enquêtés, qui sont les traitements des affections gynécologiques (accouchement difficile, irrégularité des menstrues et menstrues intermittentes, pertes blanches, fibrome ou kyste et myomes) et de l'épilepsie, étaient absents de la littérature. Ces usages pourraient offrir des perspectives de recherche intéressantes en phytochimie.

Le résultat montrant que les acteurs du culte Oro ont plus de connaissances sur *T. scleroxylon* que les acteurs d'autres divinités pourrait être lié au contact régulier avec l'espèce à travers les cérémonies rituelles du culte Oro, et cela confirme l'hypothèse selon laquelle les savoirs et le degré de connaissance sur les plantes dépendent des cultures et des us et coutumes des peuples (Sundriyal *et al.*, 2004). Cette hypothèse est d'autant plus vérifiée que, en plus d'être du même groupe ethnolinguistique, les adeptes du culte Oro ont plus de connaissances sur l'usage de *T. scleroxylon* que les Nagot, acteurs d'autres divinités des écosystèmes sacrés abritant l'espèce.

Les connaissances traditionnelles sur *T. scleroxylon* n'ont pas varié suivant les catégories d'âge (figure 2). Bien que les vieux aient plus recours à l'espèce que les adultes, la variation des connaissances n'est pas significative. L'hypothèse de Souto et Ticktin (2012), qui prédit que la connaissance traditionnelle dépend de l'âge (Gaoué *et al.*, 2017), est ainsi mise en défaut. Les résultats obtenus pourraient se justifier par la position qu'occupent les adultes au sein de la tradition du culte Oro, qui influence significativement la connaissance et l'usage de *T. scleroxylon*. En effet, le trône de Adjana (responsable de la tradition Oro) est spécialement destiné à certaines familles. Ainsi, à partir de 18 ans, tout membre de la famille peut être choisi par les dieux après consultation pour occuper le poste de Adjana. Les secrets et les connaissances liés à ce rang devront lui être transmis par ses pairs. Il découle alors des résultats obtenus une hypothèse selon laquelle le degré des connaissances endogènes sur les espèces sacrées est fonction du niveau de responsabilité de l'informateur dans la tradition considérée. Elle se justifie d'autant plus que, en considérant les trois catégories d'âge, la valeur d'usage moyenne

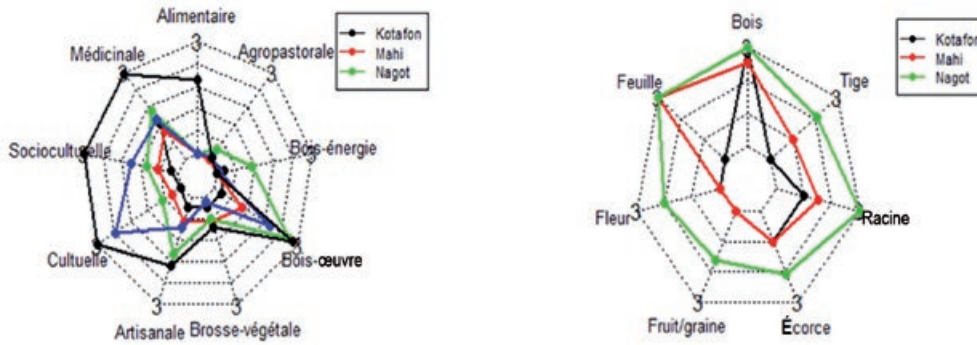


Figure 5.
 Importance culturelle des catégories d'usage et des organes de *Triplochiton scleroxylon* en fonction des groupes ethnolinguistiques.
 Cultural significance of use categories and organs of *Triplochiton scleroxylon* according to ethnolinguistic groups.

des sept enquêtés ayant moins de 30 ans (jeunes) est supérieure à celle des adultes (âge supérieur à 30 ans) et à celle des vieux. Cette hypothèse pourrait cependant être approfondie par des travaux complémentaires en ethnobiologie sur d'autres espèces rituelles.

La singularité des connaissances et usages de *T. scleroxylon* par les acteurs du culte *Oro* serait en lien avec l'unicité des places qu'occupe chaque organe de la plante dans l'identité et la stabilité du culte *Oro*. *Oro* est un culte qui caractérise potentiellement l'identité du grand groupe des Yoruboides du Bénin et du Nigeria. Les Yoruboides regroupent les *Yoruba*, *Nagot*, *Idatcha* et apparentés. Il est donc important d'explorer les impacts du déclin de *T. scleroxylon* sur l'identité et la stabilité culturelle des peuples qui en dépendent, en relation avec les implications écologiques pour la conservation des écosystèmes sacrés. L'identification et l'appréciation du réseau complexe de connexions entre la diversité biologique et culturelle/culturelle, l'importance de la résilience et la réponse adaptative dans les communautés socio-écologiques sont très prisées dans les efforts de conservation et de restauration (Garibaldi et Turner, 2004). La multiplicité des usages de l'espèce pourrait avoir aussi des impacts sur son écologie puisqu'il est montré que les effets de l'anthropisation peuvent impacter la structure et la stabilité des populations de plantes préférées (Gaoué et Ticktin, 2007). La conséquence écologique la plus immédiate de la pression humaine sur les essences prisées est l'altération du taux de survie, de la croissance et de la reproduction de ces individus. Cependant, l'existence des tabous relatifs à l'espèce, liés à son statut d'arbre sacré et vénéré, pourrait aussi contribuer à sa conservation. En effet, selon l'hypothèse des tabous comme stratégie de conservation, les espèces sont rendues taboues pour les protéger de la surexploitation et de l'extinction (Colding et Folke, 1997). Les cultes étant les seuls producteurs de tabous, leur implication dans la préservation des ressources naturelles constitue une perspective à ne pas négliger dans les

stratégies de conservation de la biodiversité. Compte tenu de l'importance de l'espèce et de son usage dans les cérémonies et rituels, des études sur l'impact de la prévalence de ces cérémonies et des tabous sur la structure démographique et spatiale des peuplements de *T. scleroxylon* pourraient améliorer l'état des connaissances sur l'espèce.

Conclusion

Cette étude a porté sur l'importance des cultes dans la préservation des espèces d'arbre et a été conduite auprès des sages, dignitaires et autres informateurs clés des écosystèmes sacrés abritant *Triplochiton scleroxylon* au Bénin. Elle a permis de construire une base de données sur les connaissances et les usages traditionnels de l'espèce dans ce pays. Les résultats obtenus témoignent de la nécessité d'investir dans la sylviculture des espèces forestières qui occupent une place de choix dans l'ethnosphère africaine pour le renforcement de système socio-écologique. En effet, l'usage de *T. scleroxylon* est connu de plusieurs groupes ethnolinguistiques, son importance variant suivant ces différents groupes, avec une particularité liée aux acteurs du culte *Oro* qui détiennent plus de connaissances sur l'usage de l'espèce et de ses différentes composantes. Une étude de l'impact de la disparition de *T. scleroxylon* sur la diversité bioculturelle est donc nécessaire. Compte tenu de la place de *T. scleroxylon* dans la tradition, il est aussi important d'évaluer l'impact de la prévalence des cérémonies rituelles et des tabous liés à l'espèce sur la structure démographique et spatiale de *T. scleroxylon*. Les usages de l'espèce en médecine traditionnelle pour le traitement des affections gynécologiques et de l'asthme suggèrent aussi des études de « screening » phytochimique des feuilles, des racines et des écorces de *T. scleroxylon* pour plus d'informations sur les propriétés pharmacologiques de l'espèce.

Références

- Achigan-Dako E. G., Pasquini M. W., Assogba-Komlan F., N'Dani-kou S., Yédomonhan H., Dansi A., *et al.*, 2010. Traditional vegetables in Benin. Cotonou, Institut national des recherches agricoles du Bénin, CENAP, 282 p.
- Adomou A. C., 2005. Vegetation patterns and environmental gradients in Benin. Implications for biogeography and conservation. PhD thesis, Wageningen University, Wageningen, The Netherlands, 136 p. <https://library.wur.nl/WebQuery/wurpubs/fulltext/121707>
- Adomou C. A., Agbani O. P., Sinsin B., 2011. Plants. In: Neuenschwander P., Sinsin B., Goergen G. (eds). Nature Conservation in West Africa: Red List for Benin. Ibadan, Nigeria, International Institute of Tropical Agriculture, 21-46.
- Akaike H., 1973. Information theory as an extension of the maximum likelihood principle. In: Petrov B. N., Csaki F. (eds). Second International Symposium on Information Theory. Budapest, Hungary, Akademiai Kiado, 267-281.
- Akoegninou A., Van der Burg W. J., Van der Maesen L. J. G., Adjakidjè V., Essou J. P., Sinsin B., *et al.* (éds), 2006. Flore analytique du Bénin. Leiden, Pays-Bas, Backhuys Publishers, 1 034 p. <https://library.wur.nl/WebQuery/wurpubs/fulltext/281595>
- Assogba G. A., Fandohan A. B., Salako V. K., Assogbadjo A. E., 2017. Usages de *Bombax costatum* (Malvaceae) dans les terroirs riverains de la Réserve de biosphère de la Pendjari, République du Bénin. Bois et Forêts des Tropiques, 333 (3) : 17-29. <https://doi.org/10.19182/bft2017.333.a31465>
- Bayol N., Demarquez B., De Wasseige C., Ebaa A. R., Fisher J. F., Nasi R., *et al.*, 2012. Forest management and the timber sector in Central Africa. Luxembourg, Publications Office of the European Union, 19 p. https://www.researchgate.net/profile/Robert_Nasi/publication/232660071_Forest_Management_and_the_Timber_sector_in_Central_Africa/links/0046352c201965d00a000000.pdf
- Cavendish W., 2000. Empirical regularities in the poverty-environment relationship of rural household: evidence from Zimbabwe. World Development, 28 (11): 1979-2003. [https://doi.org/10.1016/S0305-750X\(00\)00066-8](https://doi.org/10.1016/S0305-750X(00)00066-8)
- Cochran W. G., 1977. Sampling techniques. 3rd edition. New York, USA, Wiley, 448 p.
- Colding J., Folke C., 1997. The relations among threatened species, their protection, and taboos. Ecology and Society, 1 (1): 6. <https://www.ecologyandsociety.org/vol1/iss1/art6/>
- de Albuquerque U. P., Soldati G. T., Sieber S. S., Ramos M. A., De Sã J. C., De Souza L. C., 2011. The use of plants in the medical system of the Fulni-ô people (NE Brazil): A perspective on age and gender. Journal of Ethnopharmacology, 133: 866-873. <https://doi.org/10.1016/j.jep.2010.11.021>
- Fandohan A. B., Chadare F. J., Gouwakinnou G. N., Tovissode C. F., Bonou A., Djonlonkou S. F. B., *et al.*, 2017. Usages traditionnels et valeur économique de *Syncepalum dulcificum* au Sud-Bénin. Bois et Forêts des Tropiques, 332 (2) : 18-30. <https://doi.org/10.19182/bft2017.332.a31330>
- FAO, 2018. La situation des forêts du monde 2018. Les forêts au service du développement durable. Rome, Italie, FAO, 158 p. <https://www.fao.org/documents/card/fr/c/I9535FR/>
- Fayolle A., Engelbrecht B., Freycon V., Mortier F., Swaine M., Réjou-Méchain M., *et al.*, 2012. Geological substrates shape tree species and trait distributions in African moist forests. PLoS ONE 7, e42381. <https://doi.org/10.1371/journal.pone.0042381>
- Friedman J., Yaniv Z., Dafni A., Palewith D., 1986. A preliminary classification of the healing potential of medicinal plants, based on a rational analysis of an ethnopharmacological field survey among Bedouins in the Negev Desert, Israel. Journal of Ethnopharmacology, 16 (2-3): 275-287. [https://doi.org/10.1016/0378-8741\(86\)90094-2](https://doi.org/10.1016/0378-8741(86)90094-2)
- Gaoué O. G., Ticktin T., 2007. Patterns of harvesting foliage and bark from the multipurpose tree *Khaya senegalensis* in Benin: variation across ecological regions and its impacts on population structure. Biological Conservation, 137 (3): 424-436. <https://doi.org/10.1016/j.BIOCON.2007.02.020>
- Gaoué O. G., Coe M. A., Bond M., Hart G., Seyler B. C., McMillen H., 2017. Theories and major hypotheses in ethnobotany. Economic Botany, 71 (3): 269-287. https://www.fs.fed.us/nrs/pubs/jrnl/2017/nrs_2017_gaoue_001.pdf
- Garibaldi A., Turner N., 2004. Cultural keystone species: Implications for ecological conservation and restoration. Ecology and Society, 9 (3): 1. <https://www.ecologyandsociety.org/vol9/iss3/art1>
- Gomez-Beloz A., 2002. Plant use knowledge of the Winikina Warao: The case for questionnaires in ethnobotany. Economic Botany, 56 (3): 231-241. <https://www.jstor.org/stable/4256576>
- Gouwakinnou G. N., Lykke A. M., Assogbadjo A. E., Sinsin B., 2011. Local knowledge, pattern and diversity of use of *Sclerocarya birrea*. Journal of Ethnobiology and Ethnomedicine, 7: 8. <https://doi.org/10.1186/1746-4269-7-8>
- Hall J. B., Bada S. O., 1979. The distribution and ecology of Obeche (*Triplochiton Scleroxylon*). Journal of Ecology, 67: 543-564. <https://www.jstor.org/stable/2259111>
- Hanazaki N., Herbst D. F., Marques M. S., Vandebroek I., 2013. Evidence of the shifting baseline syndrome in ethnobotanical research. Journal of Ethnobiology and Ethnomedicine, 9: 75. <https://doi.org/10.1186/1746-4269-9-75>
- Houehanou T. D., Assogbadjo A. E., Glèlè Kakaï R., Houinato M., Sinsin B., 2011. Valuation of local preferred uses and traditional ecological knowledge in relation to tree multipurpose tree species in Benin (West Africa). Forest Policy and Economics, 13 (7): 554-562. <https://bec.uac.bj/uploads/publication/3335705f39c976b9c5c7e9f2e91a1d49.pdf>
- International Society of Ethnobiology, 2006. ISE Code of Ethics (With 2008 additions). ISE, 12 p. <https://www.ethnobiology.net/what-we-do/core-programs/ise-ethics-program/code-of-ethics/>
- Johns T., Mohoro E. B., Sanaya P., 1996. Food plants and mastics of the Batemi of Ngorongoro District, Tanzania. Economic Botany. 50: 115-121.
- Johnson J. B., Omland K. S., 2004. Model selection in ecology and evolution. Trends in Ecology and Evolution, 19 (2): 101-108. <http://faculty.washington.edu/skalski/classes/QERM597/papers/Johnson%20and%20Omland.pdf>

Kalinganire A., Weber J. C., Uwamariya A., Kone B., 2008. Improving rural livelihoods through domestication of indigenous fruit trees in the parklands of the Sahel. In: Akinnifesi F. K., Leakey R. R. B., Ajayi O., Silési G., Tchoundjeu Z., Matakala P., et al. (eds). Indigenous fruit trees in the tropics: Domestication, utilization and commercialization. Oxford, United Kingdom, CABI Publishing, 186-203. <https://www.cabi.org/cabebooks/ebook/20083134907>

Kokou K., Sokpon N., 2006. Les forêts sacrées du couloir de Dahomey. Bois et Forêts des Tropiques, 288 (2) : 15-23. <https://revues.cirad.fr/index.php/BFT/article/view/20312>

Maxted N., Scholten M. A., Codd R., Ford-Lloyd B. V., 2007. Creation and use of a national inventory of crop wild relatives. Bio-Conservation, 140 (1-2): 142-159. <https://doi.org/10.1016/j.biocon.2007.08.006>

Nolan J. M., Turner N. J., 2011. Ethnobotany: The study of people-plant relationships. In: Anderson E. N., Pearsall D., Hunn E., Turner N. (eds). Ethnobiology. Hoboken, NJ, USA, Wiley-Blackwell, 133-147. <https://doi.org/10.1002/9781118015872.ch9>

Onoagbe I. O., Attah V., Luther M. M., Esekheigbe A., 1999. Hypoglycemic and anti-diabetic effects of *Morinda lucida* and *Tetracera alnifolia* in normal and streptozotocin-induced diabetic rabbits, West Africa. Journal of Biology Science, 9: 1-8.

Palla F., Louppe D., 2002. Obeché. Cirad, France, 6 p. https://agritrop.cirad.fr/515653/1/document_515653.pdf

Pilgrim S. E., Cullen L. C., Smith D. J., Pretty J., 2008. Ecological knowledge is lost in wealthier communities and countries. Environmental Science & Technology, 42 (4): 1004-1009. <https://doi.org/10.1021/es070837v>

Quiroz D., van Andel T., 2015. Evidence of a link between taboos and sacrifices and resource scarcity of ritual plants. Journal of Ethnobiology and Ethnomedicine, 11: 5. <https://doi.org/10.1186/1746-4269-11-5>

Rajesh B., Nair N., 2018. Ethnobotanical studies of medicinal plants used in traditional (folk) medicines. International Journal of Science and Research, 8 (3): 437-442.

Saynez-Vaquez A., Vibrans H., Vergara-Silva F., Caballero J., 2016. Intracultural differences in local botanical knowledge and knowledge loss among the Mexican Isthmus Zapotecs. PLoS ONE, 11 (3): e0151693. <https://doi.org/10.1371/journal.pone.0151693>

Siepel A., Poorter L., Hawthorne W., 2004. Ecological profiles of large timber species. In: Poorter L., Bongers F., Kouame F. N., Hawthorne W. D. (eds). Biodiversity of West African Forests. An Ecological Atlas of Woody Plant Species. Oxon, United Kingdom, CABI, 391-446.

Souto T., Ticktin T., 2012. Understanding interrelationships among predictors (age, gender, and origin) of local ecological knowledge. Economic Botany, 66 (2): 149-164. <https://doi.org/10.1007/s12231-012-9194-3>

Sundriyal M., Sundriyal R. C., Sharma E., 2004. Dietary use of wild resources in the Sikkim Himalaya, India. Economic Botany, 58 (4): 626-638. <https://www.jstor.org/stable/4256875>

TRAMIL, 1989. Vers une Pharmacopée Caraïbe (TRAMIL4). Tegucigalpa, Honduras, enda-caribe, Université nationale autonome du Honduras (UNAH), 475 p.

Voeks R. A., 2007. Are women reservoirs of traditional plant knowledge? Gender, ethnobotany and globalization in northeast Brazil. Singapore Journal of Tropical Geography, 28: 7-20. <https://lib.icimod.org/record/9107>

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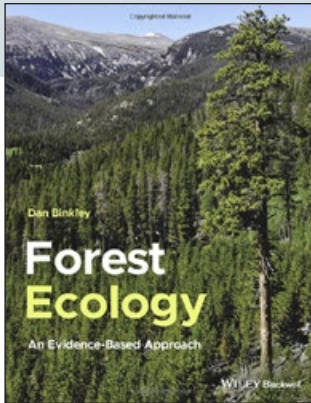
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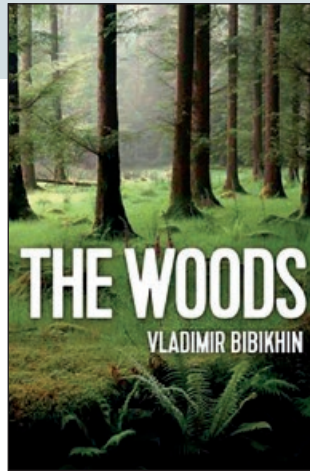


BINKLEY D., 2021. **FOREST ECOLOGY: AN EVIDENCE-BASED APPROACH.** UNITED STATES, WILEY BLACKWELL PUBLISHING, 288 P.

Forest ecology is the science that deals with everything in forests, including plants and animals (and their interactions), the features of the environment that affect plants and animals, and the interactions of humans and forests. All of these components of forests interact across scales of space and time. Some interactions are constrained, deterministic, and predictable; but most are indeterminant, contingent, and only broadly predictable. Forest Ecology: An Evidence-Based Approach examines the features common to all forests, and those unique cases that illustrate the importance of site-specific factors in determining the structure, function, and future of a forest. The author emphasizes the role of evidence in forest ecology, because appealing, simple stories often lead to misunderstandings about how forests work. A reliance on evidence is central to distinguishing between appealing stories and stories that actually fit real forests. The evidence-based approach emphasizes the importance of real-world, observable science in forests. Classical approaches to ecology in the twentieth century often over-emphasized appealing concepts that were not sufficiently based on real forests. The vast amount of information now available on forests allows a more complete coverage of forest ecology that relies on a strong, empirical foundation. Forest Ecology: An Evidence-Based Approach is the ideal companion text for the teaching of upper-level undergraduate and graduate courses in forest ecology.

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BIBIKHIN V., TAIT A. (TRANS.), 2021. **THE WOODS.** UNITED STATES, WILEY BLACKWELL PUBLISHING, 416 P.

In our modern, urbanized societies, our engagement with the natural world often seems distant and superficial. Human life is now far removed from its prehistoric origins, when humans dwelt deep within the forests and depended on them for their survival. In this important book, Vladimir Bibikhin, one of Russia's most influential twentieth-century philosophers, argues that, although most humans now live far from woods and forests, our existence remains profoundly linked to them. It was Aristotle who first appreciated their primal role, even deriving his notion of 'matter' from the Greek words for wood and forest. As timber, the woods may be seen as inanimate material, but at the same time they also constitute a living ecosystem and the source of energy and life. By opening up this duality, the woods are transformed from simple matter to a living environment, serving as a reminder that we belong to the world of biological life to a far greater extent than we usually think. The Woods will be of interest to students and scholars in philosophy and the humanities generally and to anyone concerned with the environment and our relationship to the natural world.

Adapted from the publisher's summary.

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ASNAWI I., 2019. **L'ESPRIT DE LA JUNGLE.** FRANCE, PRESSES UNIVERSITAIRES DE FRANCE (PUF), 128 P.

« Que restera-t-il de l'humanité lorsque toutes nos forêts auront été brûlées, nos rivières asséchées, nos ressources naturelles épuisées ? » Iwan Asnawi est guérisseur. Il a grandi au cœur de la prodigieuse jungle indonésienne, sur un territoire aujourd'hui dévasté par les plantations de palmiers à huile, et devenu socialement le plus dangereux du pays. Par son histoire, il est le témoin des conséquences écologiques, culturelles et sociales désastreuses de la déforestation massive imposée par la dictature militaire. Au fil de ce récit, Iwan Asnawi rend hommage au peuple indonésien, à ses traditions, ses clans, ses souffrances, et à son syncrétisme spirituel parfois si déroutant pour les Européens. Humaniste, militante, sa parole est un plaidoyer pour tous ceux qui se battent pour protéger leurs forêts, leurs savoirs et notre avenir.

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Détermination des paramètres d'évaluation du stock de carbone dans les écosystèmes forestiers (*Cedrus atlantica* Manetti, cèdre de l'Atlas au Maroc) : méthodes spécifiques et génériques

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Photo 1.
Peuplement du cèdre de l'Atlas (*Cedrus atlantica*) de la forêt d'Azrou.
Stand of Atlas Cedar (*Cedrus atlantica*) in the Azrou forest.
Photo M. El Mderssa.

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RÉSUMÉ

Détermination des paramètres d'évaluation du stock de carbone dans les écosystèmes forestiers (*Cedrus atlantica* Manetti, cèdre de l'Atlas au Maroc) : méthodes spécifiques et génériques

La quantification du carbone emmagasiné dans les écosystèmes forestiers et de son équivalent en CO₂ constitue un impératif pour une estimation fiable de la contribution de ce puits de carbone dans la limitation des émissions de gaz à effet de serre. La présente étude vise dans un premier temps, par une étude de terrain, à évaluer le volume de bois sur pied et à estimer la quantité de carbone contenue dans les parties aériennes et racinaires, tout en déterminant le facteur d'expansion et de conversion de la biomasse (FECB) spécifique du cèdre de l'Atlas (*Cedrus atlantica* Manetti) situé dans la zone du Moyen Atlas central. D'autre part, les résultats obtenus ont été comparés à ceux provenant de l'utilisation des paramètres génériques du Groupe d'experts Intergouvernemental sur l'évolution du climat (GIEC) en 2006. Le volume de bois sur pied et la biomasse aérienne ont été déterminés en utilisant des tarifs de cubage et des modèles de biomasse développés à partir des mesures directes du poids sec et du volume sur 30 arbres échantillonnés et prélevés dans chaque forêt de la zone d'étude. Le volume et la biomasse aérienne ont été évalués respectivement à 3 321 284 m³ et à 1 179 188 t de matière sèche. Le FECB, déterminé par le rapport entre le volume et la biomasse, est de 0,36 tMS/m³, valeur inférieure à celle estimée par le GIEC (0,55 tMS/m³). La fraction de carbone (FC), issue de la calcination des échantillons de bois prélevés, est de l'ordre de 0,5643 tC/tMS. Elle est supérieure à la valeur donnée par le GIEC (0,51 tC/tMS). Au final, la quantité de carbone contenue dans l'écosystème étudié est de 858 387 t de matière sèche contre 1 201 789 t estimées à partir des paramètres du GIEC.

Mots-clés : carbone, GES, FECB, biomasse, fraction de carbone, GIEC, changements globaux, Maroc.

ABSTRACT

Determining parameters to assess carbon stocks in forest ecosystems with *Cedrus atlantica* Manetti (Atlas Cedar) in Morocco: specific and generic methods

Quantifying the amounts of carbon stored in forest ecosystems and their CO₂ equivalent is essential to make reliable estimations of the contribution of this carbon sink in limiting greenhouse gas emissions. With this study, we aimed, firstly, to evaluate the volume of standing wood through field surveys in the central Middle Atlas zone, and thus to estimate the quantity of carbon contained in the aerial and root parts while determining the specific Biomass Conversion and Expansion Factor (BCEF) of Atlas Cedar (*Cedrus atlantica* Manetti) in this region. Secondly, we compared our results with those obtained using the generic parameters issued by the Intergovernmental Panel on Climate Change (IPCC) in 2006. Standing volume and above-ground biomass were determined using volume tables and biomass models developed from direct measurements of dry weight and volume taken from 30 sample trees in each forest in the study area. Volume and above-ground biomass were estimated, respectively, at 3,321,284 m³ and 1,179,188 t dry matter. The BCEF, determined by the ratio of volume to biomass, was found to be 0.36 tMS/m³, which is lower than the IPCC estimation (0.55 tMS/m³). The carbon fraction (CF), resulting from calcination of the wood samples taken, is around 0.5643 tC/tMS, which is higher than the IPCC figure (0.51 tC/tMS). Finally, the quantity of carbon contained in the ecosystem studied is 858,387 t of dry matter compared to 1,201,789 t estimated with the IPCC parameters.

Keywords: carbon, GHG, BCEF, biomass, carbon fraction, IPCC, global change, Morocco.

RESUMEN

Determinación de los parámetros de evaluación de las reservas de carbono en los ecosistemas forestales de *Cedrus atlantica* Manetti (cedro del Atlas) en Marruecos: métodos específicos y genéricos

Es necesario cuantificar el carbono almacenado en los ecosistemas forestales y su equivalente en CO₂ para estimar de forma fiable la contribución de este sumidero de carbono en la limitación de las emisiones de gases de efecto invernadero. El presente estudio pretende, en primer lugar mediante un estudio de campo, evaluar el volumen de madera en pie y estimar la cantidad de carbono contenida en las partes aéreas y radiculares, determinando al mismo tiempo el factor de expansión y conversión en biomasa (FECB) específico del cedro del Atlas (*Cedrus atlantica* Manetti) situado en la zona central del Atlas Medio. Los resultados obtenidos se compararon con los provenientes de la utilización de los parámetros genéricos del Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC) de 2006. Los volúmenes de madera en pie y en biomasa aérea se determinaron utilizando tasas de cubicación y modelos de biomasa desarrollados a partir de mediciones directas del peso seco y del volumen de 30 árboles muestreados en cada bosque de la zona de estudio. El volumen y la biomasa aérea se evaluaron en 3 321 284 m³ y 1 179 188 t de materia seca, respectivamente. El FECB, determinado por la relación entre el volumen y la biomasa, es de 0,36 tMS/m³, que es inferior al valor estimado por el IPCC (0,55 tMS/m³). La fracción de carbono (FC), resultante de la calcinación de las muestras de madera recogidas, es del orden de 0,5643 tC/tMS. Es superior al valor dado por el IPCC (0,51 tC/tMS). Finalmente, la cantidad de carbono contenida en el ecosistema estudiado es de 858 387 t de materia seca frente a 1 201 789 t estimadas a partir de los parámetros del IPCC.

Palabras clave: carbono, GES, FECB, biomasa, fracción de carbono, IPCC, cambios globales, Marruecos.

Introduction

Il est devenu évident que l'augmentation des gaz à effet de serre (GES) émis dans l'atmosphère, notamment le dioxyde de carbone (CO₂), engendre de sérieux effets néfastes sur l'environnement ainsi que des dérèglements climatiques. Ce phénomène inquiète fortement les communautés scientifiques et civiles, qui reconnaissent que le système climatique est une ressource commune et partagée dont la stabilité peut être affectée. Dans ce sens, les scientifiques ont commencé à mettre en place des instances et des mécanismes, basés sur la connaissance et l'adoption de méthodologies de quantification du phénomène et sur la proposition de mesures d'atténuation et ou d'adaptation, pour y faire face.

Pour une bonne maîtrise de l'impact de ce phénomène des changements climatiques, l'identification des sources et des quantités des GES émis, ainsi que la détermination des puits de carbone qui contribuent à la séquestration de ces derniers dont les forêts, qui en constituent un réservoir clef, semblent indispensables. En effet, toutes les plantes forestières utilisent la photosynthèse pour absorber le CO₂ atmosphérique et le transformer en différents composés organiques qui constituent leur matériel végétal comme le bois, l'écorce ou les feuilles (ILWAC, 2013). Le stockage de carbone, sous forme de biomasse végétale, constitue à cet effet une solution efficace, peu coûteuse et très prometteuse pour la diminution et la régulation du niveau du CO₂ dans l'atmosphère.

En raison de la longue durée de vie de la plupart des arbres forestiers et de leurs dimensions relativement importantes, les forêts sont considérées comme le réservoir terrestre de carbone le plus important. En effet, le Groupe d'experts Intergouvernemental sur l'évolution du climat (GIEC) et d'autres comités scientifiques (FAO, Cirad) estiment que jusqu'à 25 % de l'absorption du CO₂ atmosphérique se fait au sein des forêts (ILWAC, 2013). Elles séquestrent 9,2 Gt/an d'émissions nettes de CO₂, soit l'équivalent de 33 % des émissions de GES mondiales (GIEC, 2014).

Au Maroc, les ressources forestières qui s'étendent sur une superficie de plus de 9 millions d'hectares, dont environ 6 millions d'hectares sont boisés (Global Forest Resources Assessment, 2020), constituent un support essentiel et incontournable pour la vie humaine. Elles remplissent de multiples fonctions capitales en termes d'atténuation des changements climatiques et d'adaptation à leurs effets en raison de la diversité des écosystèmes. Elles contribuent, selon les données de la Troisième Communication nationale (2016), à l'absorption annuelle de 4 018 Gt de CO₂, soit l'équivalent de 1 096 Gt de C par an en termes de séquestration de carbone (Ministère de l'Énergie, des Mines, de l'Eau et de l'Environnement, 2016). L'estimation de ces données d'absorption de CO₂ s'est basée sur des facteurs génériques et des hypothèses proposées par le GIEC, et ce en l'absence d'études au niveau national pour la production de ces facteurs (GIEC, 2007).

Dans ce sens, et pour la définition de stratégies nationales adaptées et acceptables vis-à-vis des engagements internationaux en matière de marché de carbone, l'adoption et l'utilisation de méthodes fiables pour la connaissance et la quantification nationale du potentiel de volume et de carbone du bois sur pied s'imposent.

Le cèdre de l'Atlas (*Cedrus atlantica* Manetti) est une espèce qui est présente principalement dans les zones montagneuses du Maroc situées entre 1 500 et 2 500 m d'altitude (Emberger, 1939 ; Lepoutre et Pujos, 1964). C'est un arbre d'allure beaucoup plus majestueuse et imposante que les autres espèces (Lepoutre et Pujos, 1964 ; M'Hirit et al., 1994 ; M'Hirit, 1994). Sa hauteur atteint facilement les 40 m, pour une circonférence comprise entre 2 et 3 m. Il s'étend sur plus de 116 000 ha dans le Moyen et le Haut Atlas, et sur 15 000 ha dans le Rif (Inventaire forestier national, 1996). Il couvre un large éventail de climats, s'étendant du subhumide à l'étage montagnard méditerranéen, en passant par le climat humide.

Élément traditionnel de la culture et du paysage marocains, il constitue également une ressource économique importante pour le Maroc, puisqu'il représente 90 % des ressources en bois d'œuvre et fournit environ 90 000 m³ de bois de feu chaque année dans ce pays (El Abid, 1993).



Photo 2.

Peuplement du cèdre de l'Atlas (*Cedrus atlantica*) de la forêt de Jbel Aoua Sud.

Stand of Atlas Cedar (*Cedrus atlantica*) in the forest of Jbel Aoua Sud.

Photo M. El Mderssa.

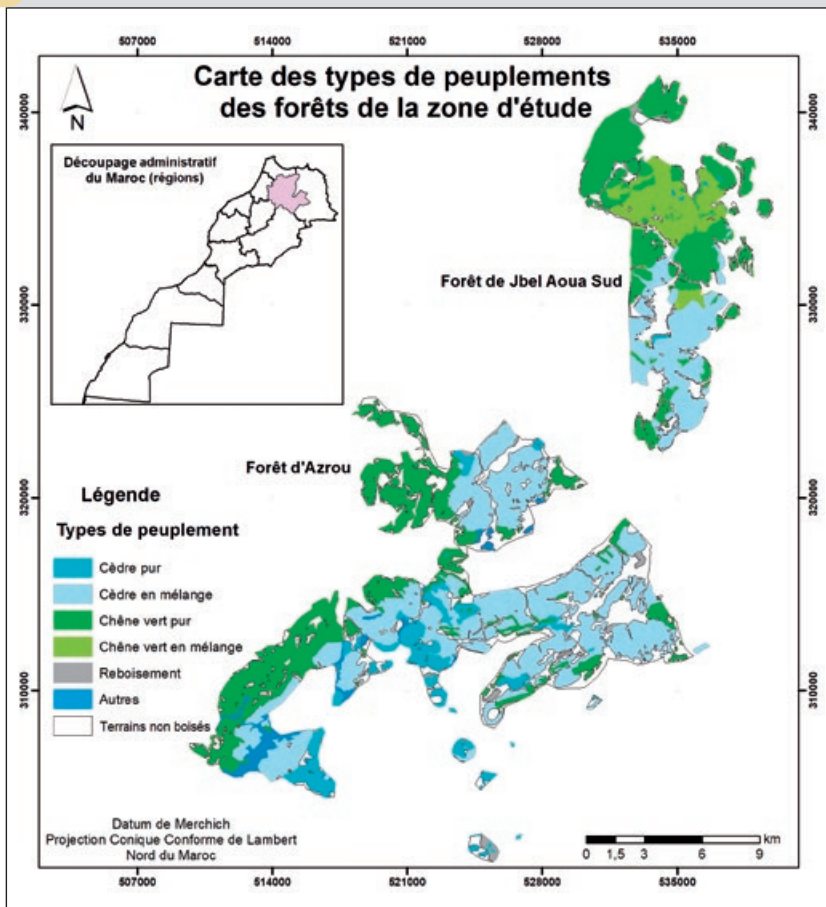


Figure 1.
Carte des types de peuplements dans les forêts d'Azrou et de Jbel Aoua Sud au Maroc.
Map of stand types in the forests of Azrou and Jbel Aoua Sud in Morocco.

De par l'importance de cette ressource à l'échelle locale et régionale, cette étude aborde les différentes étapes mises en œuvre pour la quantification du volume de bois sur pied et de la biomasse aérienne du cèdre de l'Atlas, nécessaires à la détermination du facteur d'expansion et de conversion de la biomasse (FECB) spécifique à cette espèce dans les forêts d'Azrou et de Jbel Aoua Sud du Moyen Atlas central, et par la suite la détermination de la fraction de carbone (FC) contenue dans la biomasse ligneuse aérienne et souterraine, pour enfin en déduire la quantité de carbone stockée. Les valeurs du FECB, de la FC et de la quantité de carbone issues des mesures réalisées sur la zone étudiée sont ensuite comparées à celles provenant des méthodes génériques proposées par le GIEC, permettant par conséquent d'améliorer la qualité et la précision des estimations du potentiel forestier (biomasse, quantité des GES...) à travers l'utilisation de ces valeurs spécifiques et nationales.

Matériels et méthodes

Présentation de la zone d'étude

L'étude s'est portée sur les peuplements de cèdre de l'Atlas composant les forêts du Moyen Atlas central, plus particulièrement les forêts d'Azrou et de Jbel Aoua Sud (figure 1).

La forêt d'Azrou est située sur la bordure nord du plateau du Moyen Atlas et s'étend sur une superficie de 17 806,7 ha. Elle est caractérisée par un relief contrasté avec des altitudes très variables allant de 1 250 m à 2 103 m. Les précipitations sont relativement élevées, atteignant en moyenne 982 mm/an, et se produisent sous forme de pluie ou de neige (Achehboune, 2006 ; Laariby et Belghazi, 2016). Au sein de cette forêt, le coefficient pluviométrique d'Emberger varie entre 101 et 114, définissant ainsi un bioclimat méditerranéen humide à variante froide et subhumide à variante tempérée. Le climat se caractérise aussi par des orages importants, particulièrement en été, rendant plus favorables l'installation et le développement de la cédraie.

Quant à la forêt de Jbel Aoua Sud, elle couvre une superficie de 7 865,4 ha. Sa structure géologique est très compliquée avec de nombreux redoublements des couches du Lias moyen, calcaire et dolomitique. Les précipitations moyennes annuelles varient entre 537 mm et 1 122 mm, les températures moyennes minimales de $-4,9\text{ }^{\circ}\text{C}$ à $-1,3\text{ }^{\circ}\text{C}$, et celles maximales entre $29,5\text{ }^{\circ}\text{C}$ et $32,5\text{ }^{\circ}\text{C}$. L'analyse bioclimatique de cette forêt montre que la période de sécheresse dure 5,5 mois et que l'ambiance bioclimatique est subhumide à variante froide (HCEFLCD, 2007). En ce qui concerne la neige, la zone étudiée enregistre annuellement 20 jours de neige en moyenne et 50 à 100 jours de gelée, à titre indicatif (Alami, 2010).

La composition des formations végétales des deux massifs forestiers est représentée dans le tableau I et la figure 1. Elle comprend des peuplements purs de cèdre, le cèdre en mélange essentiellement avec le chêne vert (*Quercus ilex*), des peuplements purs de chêne vert et des reboisements à base de cèdre, de cyprès de l'Arizona et de peuplier, ainsi que des espaces non boisés (HCEFLCD, 2007).

Approche méthodologique

L'estimation du stock de carbone des arbres de cèdre de la zone étudiée, qu'il soit aérien ou souterrain (racines), nécessite une évaluation de leur volume et leur biomasse disponible. Pour ce faire et dans le but de connaître la structure des peuplements de cèdre et d'étendre l'estimation du stock de carbone des différentes placettes échantillons à l'ensemble des peuplements des deux forêts, un inventaire exhaustif des circonférences à 1,30 m du sol de

Tableau I.Composition forestière dans les forêts d'Azrou et de Jbel Aoua Sud.
Forest composition in the forests of Azrou and Jbel Aoua Sud.

Type de peuplement	Forêt d'Azrou		Forêt de Jbel Aoua Sud	
	Superficie (ha)	Pourcentage dans l'ensemble de la forêt (%)	Superficie (ha)	Pourcentage dans l'ensemble de la forêt (%)
Cèdre de l'Atlas pur (<i>Cedrus atlantica</i>)	1 497,4	8,41	16,7	0,21
Chêne vert pur (<i>Quercus ilex</i>)	4 419,8	24,82	3 384,6	43,50
Cèdre de l'Atlas (<i>Cedrus atlantica</i>) + chêne vert (<i>Quercus ilex</i>)	7 182,0	40,33	2 008,5	26,28
Chêne vert (<i>Quercus rotundifolia</i>) + pin maritime (<i>Pinus pinaster</i>)			1 509,2	19,24
Cèdre de l'Atlas (<i>Cedrus atlantica</i>) + chêne vert (<i>Quercus ilex</i>) + pin maritime (<i>Pinus pinaster</i>)			196,2	2,50
Reboisement : cèdre de l'Atlas (<i>Cedrus atlantica</i>) + cyprès (<i>Cupressus</i> sp.) + peuplier (<i>Populus</i> sp.)	315,1	1,78		
Reboisement			51,0	0,64
Autres : vides asylvatiques + essences secondaires	4 392,4	24,67		
Vides asylvatiques			600,2	7,63
Total	17 806,7	100	7 865,4	100

Source : HCEFLCD, 2007.

tous les arbres à l'intérieur des placettes d'échantillonnage circulaires, d'une superficie de 5 ares chacune dans la zone d'étude, a été réalisé. Le nombre total des placettes est de 56. Ces placettes ont été réparties suivant un échantillonnage stratifié systématique.

La quantification du volume de matière ligneuse sur pied est une opération primordiale et indispensable pour la définition des facteurs de production. L'estimation des volumes a nécessité l'ajustement des modèles mathématiques des tarifs de cubage spécifiques pour le cèdre. Le tarif a été élaboré à partir d'observations comprenant la variable expliquée (volume en m³) et les variables explicatives (circonférence du tronc à 1,30 m en cm et hauteur en m). Situés dans les deux forêts, les arbres abattus dans le cadre des lots d'exploitation régulière des peuplements de cèdre ont été utilisés. Un échantillonnage de 30 arbres par forêt, pondérés par classes de circonférence selon les résultats de l'inventaire réalisé, a été choisi afin d'effectuer les mesures suivantes :

- mesure de la circonférence à 1,30 m du sol de l'arbre sur pied à l'aide d'un compas électronique ;
- mesure des circonférences gros bout et petit bout des billons de 2 m de longueur chacun, à partir de la base de l'arbre jusqu'à la découpe du bois fort (20 cm de circonférence) de l'arbre abattu, à l'aide d'un mètre ruban ;
- mesure de la longueur totale de l'arbre abattu à l'aide d'un mètre ruban.

Le volume des billons successifs des tiges a été estimé par la formule de Smalian :

$$V = [(B^2 + b^2)/2]L \times \pi/4$$

où B est le diamètre de gros bout, b le diamètre de petit bout et L la longueur de billon (2 m).

Le volume total de l'arbre est la somme des volumes des différents billons du même arbre.

De même, et pour déterminer la biomasse individuelle, le même échantillonnage de 30 arbres pondérés par classes de circonférence a été utilisé, pour lequel, en plus des mesures déjà décrites pour l'estimation des volumes, la séparation des différentes parties de chaque arbre échantillon et puis la pesée des paramètres en dessous a été effectuée :

- masse totale des branches (en kg) à l'aide d'une balance à ressort (*pocket balance*) avec une précision d'un kilogramme ;
- masse totale des aiguilles à l'aide d'une balance électronique avec une précision d'un gramme ;
- masse totale du tronc estimée en multipliant le volume de bois par la densité du bois de cèdre.

À la fin de ces pesées, il a été prélevé :

- au niveau du tronc, trois rondelles de 5 cm d'épaisseur, une à la base, une à mi-longueur et une à la découpe 5 cm de diamètre ;
- au niveau de la branche moyenne de chaque arbre, une rondelle de 3 cm d'épaisseur à mi-longueur ;
- au niveau des aiguilles, un échantillon d'environ 100 g de chaque arbre.

Tableau II.

Modèles d'équations testées pour l'estimation du bois et de la biomasse.
Tested equation models for wood and biomass estimation.

Type de tarif	Équations testées
Tarif de cubage bois	$V = b + aC$
	$V = b + aC^2$
	$V = b + aC + dC^2$
	$V = aC^b$
Tarif de cubage biomasse	$PST = a(C^2H)^b$
	$PST = aC^b H^d$

V : volume (m³) ; PST: poids sec total (t) ; C : circonférence de l'arbre à 1,30 cm (m) ; H : hauteur totale de l'arbre (m) ; a, b et d : coefficients de régression à estimer.

Les rondelles et l'échantillon d'aiguilles ont été mis dans des sachets de polyéthylène pour étuvage au laboratoire pendant 24 h aux températures respectives de 105 °C pour le bois et 65 °C pour les aiguilles (Riedacker, 1978 in Belghazi, 2001) afin de déterminer leur poids sec.

Aussi et afin de définir la teneur en carbone organique dans chaque compartiment de l'arbre (fraction carbone), des aliquotes de bois et des aiguilles ont été prélevés à partir de chaque arbre échantillonné. Ces aliquotes ont été mis par la suite dans un four à moufle pour calcination à 600 °C pendant 24 h.

Ainsi, le facteur d'expansion et de conversion de la biomasse (FECB) a été déduit à partir de la formule suivante, dite formule générale de calcul de la biomasse aérienne :

$$BA = V * FECB$$

avec BA la biomasse aérienne en t/ha, V le volume en m³.

En matière d'analyse statistique, les tarifs de cubage du volume et de la biomasse ont été élaborés sous forme de relations de régression mathématique entre deux catégories de variables : une variable dépendante qui est le volume ou la biomasse de l'arbre et une ou plusieurs variables indépendantes qui sont les entrées du tarif, lesquelles sont dans notre cas la circonférence à 1,30 m et la hauteur totale de l'arbre.

Aussi, un modèle carbo-masse permettant l'estimation directe du stock de carbone à partir de la circonférence à 1,30 m du sol et la hauteur totale a été établi et il est largement utilisé dans les études de biomasses forestières (Boulmane *et al.*, 2013 ; Picard *et al.*, 2012 ; McGhee *et al.*, 2016 ; Huaijiang *et al.*, 2018). L'ajustement des modèles par les techniques de la régression linéaire a été opéré à l'aide du logiciel R. Les modèles des équations testées sont retranscrits dans le tableau II. Également, un modèle pour l'estimation des hauteurs des arbres en fonction de la circonférence à 1,30 m a été développé.

Le choix du meilleur modèle pour chacune des variables à expliquer a été fondé sur l'analyse d'un certain nombre de paramètres statistiques, à savoir :

**Photo 3.**

Peuplement du cèdre de l'Atlas (*Cedrus atlantica*) de la forêt de Jbel Aoua Sud.
*Stand of Atlas cedar (*Cedrus atlantica*) in the forest of Jbel Aoua Sud.*
Photo M. El Mderssa.

▪ le coefficient de détermination (R²), qui traduit la part de la variation expliquée par le modèle qui doit être élevée ; ce paramètre est calculé comme suit :

$$R^2 = 1 - SRC/SCT$$

avec SCR la somme des carrés des écarts et SCT la somme des carrés totaux ;

▪ le test statistique de Durbin-Watson (D) qui traduit l'indépendance des résidus ; selon la table de Durbin-Watson, une valeur inférieure à 2 indique l'existence d'une corrélation positive entre les résidus successifs, et une valeur supérieure à 2 correspond à une corrélation négative entre ces mêmes aléas ; par contre une valeur voisine de 2 ne permet pas de rejeter l'hypothèse d'indépendance des résidus (Tranchefort, 1974). La formule de calcul de ce paramètre est la suivante :

$$D = \frac{\sum_{i=2}^n (e_i - e_{i-1})^2}{\sum_{i=1}^n e_i^2}$$

avec e la moyenne des écarts ;

▪ le critère d'information d'Akaike (AIC), qui se base sur le principe de la vraisemblance, permet de pénaliser les modèles en fonction du nombre de paramètres afin de satisfaire le critère de parcimonie. Le modèle avec l'AIC le plus faible (Akaike, 1974) est alors choisi. L'AIC se calcule ainsi :

$$AIC = -2 \ln l(\theta) + 2q$$

Tableau III.

Caractéristiques dendrométriques du cèdre de l'Atlas (*Cedrus atlantica*) dans les forêts d'Azrou et de Jbel Aoua Sud.
Dendrometric characteristics of Atlas cedar (Cedrus atlantica) in the Azrou and Jbel Aoua Sud forests.

Superficie totale de la zone d'étude (ha)	Superficie totale du cèdre de l'Atlas (ha)	Pourcentage du cèdre de l'Atlas (%)	Densité moyenne par hectare	Circonférence moyenne par hectare (cm)	Surface terrière moyenne (m ² /ha)
25 672,21	10 900,87	42,46	103	160	25,23

avec $l(\theta)$ la vraisemblance du modèle et q le nombre de paramètres libres estimés ;

▪ l'erreur quadratique moyenne type (RMSE), qui est la racine carrée de la MSE (erreur quadratique moyenne), représentant ainsi la moyenne arithmétique des carrés des écarts entre les prévisions et les observations, valeur à minimiser dans le cadre d'une régression simple ou multiple. La méthode est fondée sur la nullité de la moyenne des résidus. Le meilleur modèle est celui qui présente une RMSE plus faible. Ce paramètre est calculé à partir de la formule suivante :

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\ln Y_i - \widehat{\ln Y_i})^2}{n}}$$

où Y_i et \widehat{Y}_i sont les valeurs observées et prédites du modèle, n est le nombre d'arbres échantillons.

Résultats

Description dendrométrique des peuplements de cèdre

À l'issue de la réalisation de l'opération d'inventaire forestier des différents peuplements de cèdre au sein des forêts étudiées, les principales caractéristiques dendrométriques obtenues sont présentées dans le tableau III.

Établissement de la relation hauteur-circonférence

Compte tenu du fait que l'opération de mesure des hauteurs des arbres d'un peuplement est onéreuse et n'est pas toujours facile à réaliser sur le terrain, le recours à l'établissement d'une relation liant la hauteur de l'arbre à sa circonférence a été jugé indispensable et efficace. Les caractéristiques du modèle retenu sont présentées dans le tableau IV.

Élaboration du tarif de cubage bois et détermination du volume total

Les caractéristiques du modèle retenu pour l'estimation des volumes sur pied des peuplements de cèdre au sein des deux massifs forestiers et les critères de validation sont présentés dans le tableau V.

L'application pondérée dudit tarif retenu aux résultats de l'inventaire des peuplements de cèdre au sein des deux forêts a permis d'estimer le volume total de cette espèce à 3 321 284 m³, soit une moyenne de l'ordre de 305 m³/ha pour les différentes formations à base de cèdre.

Élaboration du tarif biomasse et détermination de la biomasse totale

La détermination de la biomasse des arbres du cèdre a été opérée par la sommation des biomasses de chacun des compartiments des arbres échantillons, tronc, branches et aiguilles, après laquelle un tarif d'estimation de la biomasse aérienne a été ajusté. Les caractéristiques du modèle d'estimation de la biomasse retenu sont consignées dans le tableau VI.

Tableau IV.

Caractéristiques statistiques du modèle hauteur-circonférence retenu.
Statistical characteristics of the selected height-conference model.

Modèle ajusté	R ²	RMSE	D	AIC
$H = -6,809 + 28,356 C - 6,781 C^2$	80,87	7,595	2,011	138,11

R² : coefficient de détermination ; RMSE : erreur quadratique moyenne type ; D : statistique de Durbin-Watson ; AIC : critère d'information d'Akaike ; C : circonférence de l'arbre à 1,30 cm (m) ; H : hauteur totale de l'arbre (m).

Tableau V.

Caractéristiques statistiques du modèle tarif de cubage-volume.
Statistical characteristics of the cubic volume tariff model.

Modèle retenu	R ²	Erreur	D standard	Intervalle d'application
$V = 0,822 C^{2,241}$	98,9	0,22	2,56	50-500 cm

V : volume (m³) ; R² : coefficient de détermination ; D : statistique de Durbin-Watson ; C : circonférence de l'arbre à 1,30 cm (m).

Tableau VI.

Caractéristiques statistiques du modèle biomasse.
Statistical characteristics of the biomass model.

Modèle ajusté	R ²	RMSE	AIC	CF
$\ln(\text{PST}) = 4,5656 + 2,1437 \ln(\text{C}) + 0,4026 \ln(\text{H})$	98,1	1,814	-12,348	1,017

PST : masse sèche totale de l'arbre (t) ; R² : coefficient de détermination ;
RMSE : erreur quadratique moyenne type ; AIC : critère d'information d'Akaïke ;
CF : facteur de correction ; C : circonférence de l'arbre à 1,30 cm (m) ;
H : hauteur totale de l'arbre (m).

L'application du modèle biomasse ci-dessous mentionnée a permis de quantifier la biomasse aérienne pondérée du cèdre dans la zone d'étude à 1 179 189 t dans la partie aérienne, soit l'équivalent de 108 tMS/ha (tMS = tonne de matière sèche).

Pour la quantification de la matière végétale constituant la partie racinaire, les données génériques du GIEC ont été utilisées. De ce fait, et en se référant au tableau 4.4 du GIEC qui présente le taux de la biomasse souterraine par rapport à la biomasse aérienne et en se basant sur le volume aérien moyen dans la zone étudiée, le taux retenu

(Tx) est de 0,29 % par rapport au volume de la partie aérienne. Le Tx retenu dans notre cas est celui proposé pour les forêts tempérées qui sont supposées les plus proches des forêts méditerranéennes, et ce en l'absence de valeurs propres à ces dernières.

De ce fait, en se référant au taux susmentionné, la biomasse totale aérienne et souterraine pondérée du cèdre dans la zone étudiée est estimée à 1 521 153 t de matière sèche, équivalant à 140 tMS/ha.

Détermination et comparaison du FECB pour le cèdre de l'Atlas avec celui du GIEC (2006)

La valeur du FECB pour le cèdre au sein de la zone étudiée est de 0,36 tMS/m³. Quant à la valeur du FECB proposée par le GIEC en 2006 (pour la zone climatique forêts méditerranéenne, tropicale sèche, subtropicale), elle est de 0,55 tMS/m³. Ces différents résultats sont consignés dans le tableau VII.

Tableau VII.

Valeurs des biomasses et des facteurs d'expansion et de conversion de la biomasse (FECB) du cèdre de l'Atlas (*Cedrus atlantica*) dans les forêts d'Azrou et Jbel Aoua Sud et du GIEC (2006).
Biomass values and Biomass Expansion and Conversion Factors (BECF) of Atlas cedar (Cedrus atlantica) in Azrou and Jbel Aoua South forests and IPCC (2006).

Espèce	Volume total des peuplements de cèdre de l'Atlas (m ³)	Biomasse totale mesurée des peuplements de cèdre de l'Atlas (t MS)	Biomasse totale des peuplements de cèdre selon le GIEC (2006) (t MS)	FECB du cèdre de l'Atlas (t)	FECB du GIEC (2006)*
Cèdre de l'Atlas (<i>Cedrus atlantica</i>)	3 321 284	1 179 188	1 826 706	0,36	0,55

* Valeur GIEC 2006 pour la zone climatique forêts méditerranéenne, tropicale sèche, subtropicale issue du tableau 4.5.

Tableau VIII.

Comparaison de la quantité de carbone contenue dans le matériel végétal du cèdre de l'Atlas (*Cedrus atlantica*) dans les forêts d'Azrou et de Jbel Aoua Sud et leur équivalent en CO₂.
Comparison of the amount of carbon contained in the plant material of the Atlas cedar (Cedrus atlantica) in the forests of Azrou and Jbel Aoua Sud and their CO₂ equivalent.

Biomasse totale mesurée (tMS)	Fraction de carbone mesurée (tC/tMS)	Quantité de carbone (t)	Quantité de CO ₂ (t)	Biomasse totale selon les données du GIEC (2006) (tMS)	Fraction de carbone selon le GIEC (2006)	Quantité de carbone selon le GIEC (2006) (t)	Quantité de CO ₂ selon le GIEC (2006) (t)
1 521 153	0,5643	858 387	- 3 147 705	2 356 450	0,51	1 201 789	- 4 406 960



a c
b

Photos 4.

Prises de mesures : a. Mesure du poids frais d'une rondelle de cèdre de l'Atlas (*Cedrus atlantica*) pour déterminer la biomasse ; b. Mesure du diamètre d'un arbre de cèdre de l'Atlas ; c. Travaux d'inventaire forestier dans le peuplement du cèdre de l'Atlas.
 Measurements: a. Measurement of the fresh weight of an Atlas cedar (*Cedrus atlantica*) log to determine the biomass; b. Measurement of the diameter of an Atlas cedar tree; c. Forest inventory work in the Atlas cedar stand.
 Photos M. El Mderssa.

Détermination et comparaison de la fraction de carbone (FC) du cèdre avec celle du GIEC (2006)

Le résultat d'estimation de la FC contenue dans les arbres de cèdre dans la zone étudiée est évalué à 0,5643 tC/tMS.

La valeur de la FC proposée dans le tableau 4.3 du rapport du GIEC (2006) pour les forêts tempérées et boréales est de 0,51 tC/tMS. Le recours à la FC proposée pour ces forêts a été fait en l'absence de valeurs propres aux forêts méditerranéennes.

Comparaison de la quantité de carbone pour le cèdre dans des forêts étudiées par les mesures directes et les facteurs du GIEC (2006)

La quantification du carbone contenu dans les peuplements de cèdre, basée sur la biomasse totale estimée et la base de la FC mesurée, a été évaluée à 858 387 t (C). Quant à l'estimation de la quantité de carbone de ces mêmes peuplements basée sur les données génériques du GIEC de 2006, elle a été quantifiée à 1 201 789 t (C).

Aussi une conversion de la quantité de carbone en quantité de dioxyde de carbone a-t-elle été opérée à travers la multiplication de la première par 3,667 (le rapport des masses moléculaires de CO₂/C qui correspond au rapport 44/12 ou 3,67) (GIEC, 2006 ; McGhee et al., 2016).

Les résultats de cette comparaison apparaissent dans le tableau VIII.

Discussion

L'atténuation des effets du changement climatique est, aujourd'hui, l'une des stratégies envisagées pour faire face au réchauffement global. Cette stratégie vise à atténuer les émissions de gaz à effet de serre en tentant d'en réduire les sources et d'en consolider les puits (Nadhem, 2011).

Du fait du potentiel de séquestration important de carbone dans les forêts et de la richesse quantitative et qualitative des écosystèmes forestiers au Maroc, la maîtrise du capital sur pied et le développement de facteurs nationaux tenant compte des spécificités locales semblent nécessaires pour une estimation fiable de la quantité de carbone qui y est emmagasinée.

Le matériel végétal aérien et souterrain du cèdre de l'Atlas contenu dans la zone d'étude a été ainsi estimé à un volume de l'ordre de 3 321 284 m³, l'équivalent d'une moyenne de l'ordre de 305 m³/ha. Cette moyenne est considérée comme l'une des plus élevées au niveau national où, par exemple, pour les formations naturelles elle est seulement de 28 m³/ha pour le chêne vert, 63 m³/ha pour le chêne-liège et 34 m³/ha pour le thuya au sein de la forêt de Zltchouine (HCEFLCDA, 2014) et de 20,4 m³/ha et 23,8 m³/ha respectivement pour les reboisements d'eucalyptus et de pin au sein de la forêt de la Maâmora (HCEFLCDB, 2014). Ce grand potentiel de production du cèdre tient au fait de la longévité élevée et des caractéristiques dendrométriques de cette espèce et des conditions de son développement.

Aussi, les travaux de terrain ainsi que les analyses en laboratoire d'un échantillon représentatif des peuplements étudiés ont permis de déterminer, avec une grande précision (R² = 98,1 %), la biomasse totale de cette espèce. Elle a été évaluée à 1 521 153 t de matière sèche, soit une moyenne de 140 tMS/ha. Cette moyenne est également comptée parmi les plus élevées au niveau national, pour les mêmes raisons que celles citées pour le volume. Elle est estimée à 89,5 tMS/ha pour la subéraie occidentale de la Maâmora (Oubrahim, 2015).

Pour ce qui est de la valeur du FECB adoptée, elle a été estimée à 0,36 tMS/m³. En l'absence de valeurs spécifiques au niveau national et comparée à la valeur générique du GIEC en 2006, jusqu'ici utilisée pour la quantification du carbone dans le Maroc, qui est de 0,55 tMS/m³, on constate une différence significative entre cette valeur générique du GIEC (2006), retenue pour toute la zone climatique des forêts méditerranéenne, tropicale sèche, subtropicale, et celle spécifique au cèdre du Moyen Atlas (MA). Le rapport entre les deux valeurs des FECB (FECB cèdre-MA/FECB-GIEC) est de 65 %. Ceci peut être expliqué par l'âge moyen élevé des peuplements étudiés qui est de 105 ans et où le FECB a tendance à décroître en fonction de l'âge du peuplement car la densité du stock en croissance augmente (GIEC, 2006).

Quant à la FC, la valeur mesurée dans la zone étudiée est de 0,5643 tC/tMS. Elle est supérieure à celle générique proposée dans les tableaux du GIEC en 2006, qui est de 0,51 tC/tMS.

Pour ce qui est de la quantité de carbone emmagasinée dans la partie aérienne et racinaire de cette cédraie de la zone étudiée, elle est de 858 387 t de carbone (- 3 147 705 t de CO₂) contre 1 201 789 t de carbone (- 4 406 960 t de CO₂) estimées avec les paramètres du GIEC. Cela témoigne d'une légère sous-estimation en matière de séquestration de carbone comparativement aux données génériques.

La moyenne ainsi retenue est de 78,75 tC/ha, qui est parmi les plus élevées au niveau national, confirmant le constat de Le Clec'h *et al.* (2013) qui concluent que les stocks de carbone les plus élevés se situent dans les zones les plus boisées (forêts denses). En effet, le stock de carbone dans les peuplements de chêne-liège de la Maâmora occidentale varie entre 40,84 tC/ha et 77,70 tC/ha (Oubrahim *et al.*, 2015) et celui du chêne vert du Moyen Atlas est évalué à 58 tC/ha dans la forêt de Reggada et 64 tC/ha dans la forêt de Tafchna (Boulmane *et al.*, 2010).

En comparant nos valeurs à celles d'autres écosystèmes méditerranéens, et plus particulièrement en France, les peuplements à plus fort stock par unité de surface sont les sapinières (87 tC/ha) et les hêtraies (84 tC/ha), les plus faibles étant les peuplements de Douglas (45 tC/ha), en raison de leur jeune âge (Institut de France, 2010).

Conclusion

En raison de leur grande étendue sur plus de 9 millions d'hectares et de leur diversité remarquable, les forêts marocaines fournissent de nombreux produits et services écosystémiques et participent de manière considérable à la régulation du climat et à l'emmagasinement du carbone.

La présente étude s'inscrit dans le cadre de l'estimation des paramètres dendrométriques, de la biomasse aérienne et souterraine, du facteur d'expansion et de conversion de la biomasse (FECB) et de la fraction de carbone (FC) contenue dans l'écosystème du cèdre de l'Atlas dans le Moyen Atlas marocain. Elle vise aussi à comparer les valeurs obtenues à celles génériques du GIEC utilisées à l'heure actuelle pour les estimations de carbone au niveau national marocain.

Les résultats obtenus montrent que la biomasse aérienne pondérée du cèdre de l'Atlas dans la zone d'étude s'élève à 108 tMS/ha pour la partie aérienne, et le matériel végétal aérien et souterrain à 305 m³/ha. Ces deux valeurs sont considérées parmi les plus élevées par rapport aux autres espèces marocaines.

La valeur du FECB obtenue est de 0,36 tMS/m³. Elle est inférieure à celle générique proposée dans les tableaux du GIEC en 2006, qui est de 0,55 tMS/m³; le rapport des deux valeurs est de 65 %.

Quant à la fraction de carbone, la valeur mesurée dans la cédraie des forêts étudiées est de 0,5643 tC/tMS. Elle est supérieure à celle générique proposée dans les tableaux du GIEC (2006), qui est de 0,51 tC/tMS.

La résultante en matière de carbone emmagasiné est de 798 499 t dans les parties aériennes et souterraines contre 1 201 789 t estimées par le GIEC en 2006.

De ce fait, au vu des différences constatées par rapport aux données génériques du GIEC en 2006, les différents

résultats susmentionnés seront sans doute d'une grande utilité pour une évaluation plus précise et plus fiable du matériel végétal des peuplements de cèdre au niveau national ainsi que de leur potentiel de séquestration de carbone. Ils devront être complétés pour les autres espèces marocaines, cela permettant de disposer de valeurs nationales pour ces différents paramètres.

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Accès aux données

Les données utilisées et collectées sont disponibles auprès de l'auteur correspondant.

Références

Achehboune J., 2006. État actuel du dépérissement du cèdre de l'Atlas au Moyen Atlas central en relation avec la station et la sylviculture (cas des forêts : Jbel Aoua sud et Ait Youssi d'Amekla). Mémoire de 3^e cycle, ENFI, Salé, Maroc, 78 p. + annexes.

Akaïke H., 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control, 19: 716-723. <https://doi.org/10.1109/TAC.1974.1100705>

Alami M., 2010. Étude dendrométrique et sylvicole des travaux de dépressages du chêne vert (*Quercus rotundifolia* Lamk.) au niveau des forêts du Moyen Atlas central (cas de la province d'Ifrane). Mémoire de 3^e cycle, ENFI, Salé, Maroc, 97 p.

Belghazi B., 2001. Estimation de la biomasse du chêne vert dans le massif forestier d'Ait Hatem (Oulmes). Annales de la Recherche Forestière au Maroc, 34 (1) : 19-16. <https://search.emarefa.net/detail/BIM-393138>

Boulmane M., Makhloufi M., Bouillet J.-P., Saint-André L., Satrani B., Halim M., *et al.*, 2010. Estimation du stock de carbone organique dans la chênaie verte du Moyen Atlas marocain. Acta Botanica Gallica, 157: 451-467. <https://doi.org/10.1080/12538078.2010.10516222>

Boulmane M., Halim M., Khia A., Oubrahim H., Abbassi H., Amrani A., 2013. Biomasse, minéralomasse et éléments nutritifs retournant au sol dans le *Quercus ilex* du Moyen Atlas central marocain. Nature et Technologie, 5 (2), 41-53. <http://193.194.91.150:8080/en/article/43134>

El Abid A., 1993. Bilan des recherches au Maroc en matière d'exploitation et valorisation du cèdre. Annales de la Recherche Forestière au Maroc, 27 : 628-637.

Emberger L., 1939. Aperçu général sur la végétation du Maroc : commentaire de la carte phytogéographique du Maroc 1:1500.000. Mémoire hors-série de la Société des sciences naturelles du Maroc. Berne, Suisse, Hans Huber, 40-157.

GIEC, 2006. Lignes directrices 2006 du GIEC pour les inventaires nationaux de gaz à effet de serre. Volume 4 : Agriculture, foresterie et autres affectations des terres. Chapitre 4 : Terres forestières. GIEC, 93 p. <https://www.ipcc-nggip.iges.or.jp/public/2006gl/french/vol4.html>

GIEC, 2007. Bilan 2007 des changements climatiques. Conséquences, adaptation et vulnérabilité. Résumé à l'intention des décideurs et Résumé technique. GIEC, 64 p. <https://www.ipcc.ch/site/assets/uploads/2020/02/ar4-wg2-sum-vol-fr.pdf>

GIEC, 2014. Changements climatiques 2014 : Rapport de synthèse. Contribution des Groupes de travail I, II et III au cinquième rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat. GIEC, OMM, PNUE, 180 p. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full_fr.pdf

Global Forest Resources Assessment, 2020. Évaluation des ressources forestières mondiales 2020 – Rapport Maroc. Rome, Italie, FAO, 80 p. <http://www.fao.org/3/cb0140fr/cb0140fr.pdf>

HCEFLCD, 2014a. Procès-verbal de la forêt de Zitchoouine. Étude d'aménagement de la forêt de Zitchoouine. Haut-Commissariat des Eaux et Forêts et à la Lutte contre la Désertification, Maroc.
HCEFLCD, 2014b. Procès-verbal de la forêt de la Maâmora. État actuel et résultats d'inventaire. Haut-Commissariat des Eaux et Forêts et à la Lutte contre la Désertification, Maroc.

HCEFLCD, 2007. Projet d'aménagement et de protection des massifs forestiers de la Province d'Ifrane. Plan d'aménagement et de gestion du Parc national d'Ifrane. Haut-Commissariat des Eaux et Forêts et à la Lutte contre la Désertification, BRL Ingénierie, 66 p.

Huajiang H., Chunyu Z., Xiuhai Z., Folega F. Jinsong W., Haijun D., et al., 2018. Allometric biomass equations for 12 tree species in coniferous and broadleaved mixed forests, northeastern China. PLOS One, 13 (1): e0186226. <https://doi.org/10.1371/journal.pone.0186226>

ILWAC, 2013. Guide méthodologique : Estimation du potentiel de séquestration du carbone au Mali. Observatoire du Sahara et du Sahel, 20 p. http://www.oss-online.org/sites/default/files/2_guide_sequstration.pdf

Institut de France, 2010. Le changement climatique. Institut de France, Académie des sciences, 21 p. <https://www.academie-sciences.fr/pdf/rapport/rapport261010.pdf>

Inventaire forestier national, 1996. Synthèse de l'inventaire forestier national marocain. Rabat, Maroc, Direction du développement forestier.

Laariba S., Belghazi B., 2016. Dynamique et accroissement radial du Cèdre de l'Atlas (*Cedrus atlantica*) : Cas de la forêt d'Azrou (Maroc). Nature et Technologie, 8 (1) : 19-32. <https://www.asjp.cerist.dz/en/article/40653>

Le Clec'h S., Oszward J., Jégou N., Dufour S., Cornillon P. A., de Souza Miranda I., et al., 2013. Cartographier le carbone stocké dans la végétation : perspectives pour la spatialisation d'un service écosystémique. Bois et Forêts des Tropiques. 316 : 35-48. <https://doi.org/10.19182/bft2013.316.a20529>

Lepoutre B., Pujos A., 1964. Facteurs climatiques déterminant les conditions de germination des plantules de cèdre. Annales de la Recherche Forestière au Maroc, 7 : 23-54. http://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_5/b_fdi_08-09/11062.pdf

McGhee W., Saigle W., Padonou E., Lykke A. M., 2016. Méthodes de calcul de la biomasse et du carbone des arbres en Afrique de l'Ouest. Annales des Sciences Agronomiques, spécial Projet Undesert-UE, 20 : 59-66.

M'Hirit O., Samih A., Malagnoux M. (éds), 1994. Le cèdre de l'Atlas (*Cedrus atlantica* Manetti). Présentation générale et état des connaissances. Réseau Silva Mediterranea. Annales de la Recherche forestière au Maroc, 45 p. <http://www.fao.org/3/AH002F/AH002F00.pdf>

M'Hirit O., 1994. Croissance et productivité du cèdre : Approche multidimensionnelle de l'étude des liaisons stations productions. Annales de la Recherche Forestière au Maroc. 27 : 295-312.

Ministère de l'Énergie, des Mines, de l'Eau et de l'Environnement, 2016. Rapport de la Troisième Communication nationale du Maroc à la Convention-cadre des Nations unies sur les changements climatiques. Royaume du Maroc, 296 p. <http://unfccc.int/resource/docs/natc/marnc3.pdf>

Nadhem B., 2011. Réchauffement climatique et vulnérabilité des sols méditerranéens : spatialisation et séquestration du carbone en Tunisie. Thèse de doctorat, Université de Tunis El Manar, Tunisie, 300 p.

Oubrahim H., Boulmane M., Bakker M. R., Augusto L., Halim M., 2015. Carbon storage in degraded cork oak (*Quercus suber*) forests on flat lowlands in Morocco. iForest - Biogeosciences and Forestry, 9 (1): 125-137. <https://iforest.sisef.org/abstract/?id=ifor1364-008>

Picard N., Saint-André L., Henry M., 2012. Manuel de construction d'équations allométriques pour l'estimation du volume et la biomasse des arbres : de la mesure de terrain à la prédiction. FAO, Cirad, 210 p. <http://www.fao.org/3/i3058f/i3058f.pdf>

Tranchefort J., 1974. La régression : application à l'agronomie. Paris, France, Institut technique des céréales et des fourrages (ITCF), 178 p.

El Mderssa et al. – Author's contributions

Rôle du contributeur	Noms des auteurs
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Gestion des données	M. El Mderssa, F. Malki
Analyse formelle	M. El Mderssa
Enquête et investigation	M. El Mderssa, F. Malki
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BLASER J., FRIZZO J., NORGROVE L., 2021. **NOT ONLY TIMBER – THE POTENTIAL FOR MANAGING NON-TIMBER FOREST PRODUCTS IN TROPICAL PRODUCTION FORESTS – A COMPREHENSIVE LITERATURE REVIEW.** INTERNATIONAL TROPICAL TIMBER ORGANIZATION (ITTO), PRECIOUS FORESTS FOUNDATION, 84 P.

Tropical forests contain much more value, commercially and for communities, than just timber. For centuries, forest-dependent peoples have known and used numerous edible nuts, fruits and other plant and animal products for food and medicine – what today we call non-timber forest products (NTFPs). This report, which draws on the authors' field experience and a thorough review of the literature, explores multiple-use forest management approaches in which NTFPs help make the economic case for natural forests. It presents three examples of well-established NTFPs in humid tropical forests – Brazil nut, rattan and rubber. For each, it examines the factors and strategies that have enabled the sustainable harvesting of the NTFP, as well as the challenges in maintaining a sustainable NTFP management regime. The report also describes six promising NTFPs that grow in tropical forests – two each from tropical Africa, Southeast Asia and the Amazon – for which the potential is yet to be fully realized. And it uses a five-star system to rate the potential of 28 individual NTFPs to yield positive economic, social and environmental outcomes. The report concludes that integrating NTFP management in timber production forests could be a decisive step in ensuring economic viability, bearing in mind the imperative to use natural tropical forests wisely and sustainably, or risk losing them forever.

Adapted from the publisher's summary.

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International Tropical Timber Organization (ITTO), International Organizations Center, 5th Floor, Pacifico Yokohama, 1-1-1 Minato-Mirai, Nishi-ku, Yokohama, 220-0012 Japan.



HELD C., MEIER-LANDSBERG E., ALONSO V., 2021. **TROPICAL TIMBER 2050 – AN ANALYSIS OF THE FUTURE SUPPLY AND DEMAND FOR TROPICAL TIMBER AND ITS CONTRIBUTIONS TO A SUSTAINABLE ECONOMY.** INTERNATIONAL TROPICAL TIMBER ORGANIZATION (ITTO), 78 P.

ITTO undertakes a wide range of work on incentives to promote sustainable forestry in tropical countries, including the development of models for forecasting trends in tropical timber supply and demand. Such models can assist in planning policies at the national and international levels, and they can be used to forecast likely recovery times from shocks to the sector – such as that caused by the COVID-19 pandemic. This report describes a model developed to forecast trends in tropical timber supply and trade to 2050. It analyzes potential scenarios and examines previous economic and non-economic shocks to estimate the likely time required for the sector to recover to pre-pandemic levels. The report also considers longer-term factors. With global resource use set to more than double by 2050, it is essential to strive for carbon-neutral production based on renewable and sustainably produced materials such as wood. Sustainably produced tropical timber could take a leading role in this quest as a substitute for non-environmentally friendly materials; the report sets out five complementary strategies that could help drive sustainable growth in the sector. This report is part of an ongoing effort by ITTO to provide knowledge and learning experiences on incentivizing investments in natural tropical forests and the sustainable production of the wood and non-wood products arising from them. Among other things, the wealth of information herein highlights the crucial role that sustainably managed tropical forests can play in climate-change mitigation and adaptation by encouraging the greater engagement of governments and private-sector players in this sphere.

Adapted from the publisher's summary.

Download the report:

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International Tropical Timber Organization (ITTO), International Organizations Center, 5th Floor, Pacifico Yokohama, 1-1-1 Minato-Mirai, Nishi-ku, Yokohama, 220-0012 Japan.



QUENTIN GRAFTON R., LONG CHU H., NELSON H., BONNIS G., 2021. **A GLOBAL ANALYSIS OF THE COST-EFFICIENCY OF FOREST CARBON SEQUESTRATION** OECD ENVIRONMENT WORKING PAPERS 185, 67 P.

The paper proposes a ranking of the countries where forest carbon sequestration is the most cost-efficient among 166 countries for which data are available. Taking into account the main cost factors leads to a more nuanced ranking of the countries to be favoured for cost-efficient forest carbon sequestration compared to the assumption that these would always be in tropical areas with high rainfall. The ranking reflects the differences in the opportunity cost of land use and labour cost (production costs), the quality of the business environment (transaction costs), natural conditions (forest productivity), wildfire risk and the avoided GHG emissions from alternative land use. Cost-efficiency also depends on the type of forest project (afforestation, reforestation or forest conservation) and how private (wood harvest) and non-private (environmental and social) co-benefits are counted. A sensitivity analysis is undertaken to examine the robustness of the results with respect to uncertainties in values of the cost and quantity factors of forest carbon sequestration. The results support the view that forests can be a cost-efficient way to offset GHG emissions and that significant cost reductions are possible by targeting the country and sub-national regions in which to locate forest carbon sequestration projects. The report also reviews the literature on the significance and cost of forest carbon sequestration and provides an overview of forest carbon offset schemes.

Adapted from the publisher's summary.

Download the report:

<https://dx.doi.org/10.1787/e4d45973-en>

Osanga – *Pteleopsis hylodendron* Mildbr.

Extrait de l'Atlas des bois tropicaux – Caractéristiques technologiques et utilisations
 J. Gérard (coord.), D. Guibal (au.), J.-C. Cerre (au.), S. Paradis (au.), et 40 auteurs, 2016.
 Éditions Quæ, 1 000 p.

<https://www.quae.com/produit/1408/9782759225521/atlas-des-bois-tropicaux>

Accès à la notice d'information générale :

<https://doi.org/10.19182/bft2021.347.a36353>

Famille. Combretaceae.

Noms botaniques. *Pteleopsis hylodendron* Mildbr. ; *Pteleopsis myrtifolia* Engl.

Continent. Afrique.

CITES (Convention de Washington, 2016). Pas de restriction commerciale.

Description de la grume

Diamètre. De 80 à 120 cm.

Épaisseur de l'aubier. De 7 à 10 cm.

Flottabilité. Non flottable.

Conservation en forêt. Bonne.

Description du bois

Couleur référence. Brun clair.

Aubier. Peu distinct.

Grain. Fin.

Fil. Droit ou contrefil.

Contrefil. Accusé.

Notes. Bois brun jaune à gris verdâtre. Fil irrégulier.

Propriétés physiques et mécaniques

Propriété	Valeur moyenne
Densité ⁽¹⁾	0,80
Dureté Monnin ⁽¹⁾	6,3
Coefficient de retrait volumique	0,41 % par %
Retrait tangentiel total (Rt)	5,8 %
Retrait radial total (Rr)	3,6 %
Ratio Rt/Rr	1,6
Point de saturation des fibres	34 %
Conductivité thermique (λ)	0,26 W/(m.K)
Pouvoir calorifique inférieur	-
Contrainte de rupture en compression ⁽¹⁾	70 MPa
Contrainte de rupture en flexion statique ⁽¹⁾	110 MPa
Module d'élasticité longitudinal ⁽¹⁾	14 100 MPa

(1) À 12 % d'humidité, avec 1 MPa = 1 N/mm².

Durabilité naturelle et imprégnabilité du bois

Résistance aux champignons. Classe 2 – durable.

Résistance aux insectes de bois sec. Classe D – durable (duramen durable mais aubier peu distinct).

Résistance aux termites. Classe D – durable.

Imprégnabilité. Classe 2-3 – peu à moyennement imprégnable.

Classe d'emploi couverte par la durabilité naturelle. Classe 4 – en contact avec le sol ou l'eau douce.

Notes. Cette essence est mentionnée dans la norme NF EN 350. La durée de performance peut être modifiée par les conditions d'utilisation (telles que décrites par la norme NF EN 335 de mai 2013). Ce bois est considéré comme peu sensible aux foreurs marins.



Dosse.
Photo D. Guibal, Cirad.



Quartier.
Photo D. Guibal, Cirad.

Traitement de préservation

Contre les attaques d'insectes de bois sec. Ce bois ne nécessite pas de traitement de préservation.

En cas d'humidification temporaire. Ce bois ne nécessite pas de traitement de préservation.

En cas d'humidification permanente. Ce bois ne nécessite pas de traitement de préservation.

Séchage

Vitesse de séchage. Lente.

Risque de déformation. Élevé.

Risque de cémentation. Pas de risque particulier connu.

Risque de fentes. Peu élevé.

Risque de collapsé. Pas de risque particulier connu.

Programme de séchage proposé. Programme n° 6 (voir note explicative).

Sciage et usinage

Effet désaffûtant. Normal.

Denture pour le sciage. Denture stellitée.

Outils d'usinage. Au carbure de tungstène.

Aptitude au déroulage. Non recommandé ou sans intérêt.

Aptitude au tranchage. Bonne.

Assemblage

Clouage/vissage. Bonne tenue, avant-trous nécessaires.

Notes. Bois dense : la mise en œuvre du collage doit particulièrement respecter les règles de l'art et les préconisations indiquées pour la colle utilisée.

Classements commerciaux

Classement d'aspect des produits sciés

Selon les règles de classement SATA (1996).

Pour le « Marché général »

Classements possibles avivés : choix i, choix ii, choix iii, choix iv.

Classements possibles coursons : choix i, choix ii.

Classements possibles coursons de chevrons : choix i, choix ii, choix iii.

Pour les « Marchés particuliers »

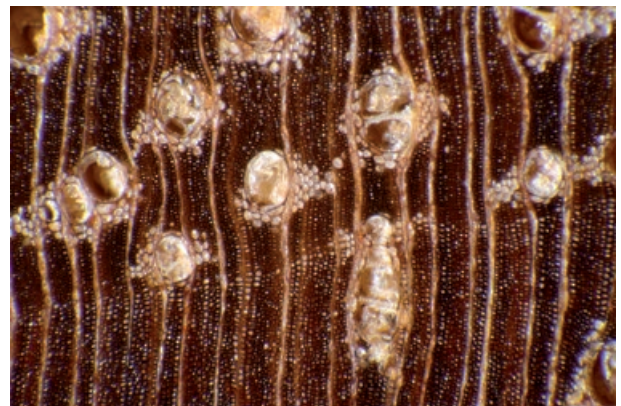
Classements possibles frises et planchettes : choix i, choix ii, choix iii.

Classements possibles chevrons : choix i, choix ii, choix iii.

Sections transversales de *Pteleopsis hylodendron*.
 Photo J.-C. Cerre.



2 mm



0,5 mm

Réaction au feu

Classement conventionnel français

Épaisseur > 14 mm : M3 (moyennement inflammable).

Épaisseur < 14 mm : M4 (facilement inflammable).

Classement selon euroclasses. D-s2, d0.

Ce classement par défaut concerne les bois massifs répondant aux exigences de la norme NF EN 14081-1 (avril 2016) : bois de structure utilisés en parois verticales et plafonds, classés, de densité moyenne minimale 0,35 et d'épaisseur minimale 22 mm.

Principales utilisations

Charpente lourde.

Escalier d'intérieur.

Fond de véhicule ou de conteneur.

Menuiserie extérieure.

Menuiserie intérieure.

Ossature.

Parquet.

Platelage, *decking*.

Pont (en contact avec le sol ou l'eau).

Poteau.

Revêtement extérieur.

Traverse.

Principales appellations vernaculaires

Pays	Appellation
Cameroun	Sikon
Côte d'Ivoire	Koframiré
République démocratique du Congo	Osanga

Doi: <https://doi.org/10.19182/bft2022.350.a36871>

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Date de publication : 1^{er} février 2022



Terrasse bordant une piscine à débordement
– Fournitures, Fibres Industries Bois ;
Réalisation, Agencement Tiby,
La Réunion (France).
Photo David Bodelu, Fibres Industries Bois.

Osanga – *Pteleopsis hylo dendron* Mildbr.

From Tropical timber atlas – Technological characteristics and uses.

J. Gérard (coord.), D. Guibal (au.), J.-C. Cerre (au.), S. Paradis (au.), and 40 authors, 2016.
 Publisher Éditions Quæ, 1000 p.

<https://www.quae.com/produit/1477/9782759227716/tropical-timber-atlas>

Access to the general information leaflet:

<https://doi.org/10.19182/bft2021.347.a36353>

Family. Combretaceae.

Botanical names. *Pteleopsis hylo dendron* Mildbr.; *Pteleopsis myrtifolia* Engl.

Continent. Africa.

CITES (Washington Convention of 2017). No trade restrictions.

Log description

Diameter. 80 to 120 cm.

Thickness of sapwood. 7 to 10 cm.

Buoyancy. Does not float.

Log conservation. Good.

Wood description

Reference colour. Light brown.

Sapwood. Not clearly demarcated.

Texture. Fine.

Grain. Straight or interlocked.

Interlocked grain. Marked.

Notes. Yellow brown to greenish grey. Irregular grain.

Physical and mechanical properties

Property	Mean value
Density ⁽¹⁾	0.80
Monnin hardness ⁽¹⁾	6,3
Coefficient of volumetric shrinkage	0.41% per %
Total tangential shrinkage (Ts)	5.8%
Total radial shrinkage (Rs)	3.6%
T/R anisotropy ratio	1.6
Fibre saturation point	34%
Thermal conductivity (λ)	0.26 W/(m.K)
Lower heating value	-
Crushing strength ⁽¹⁾	70 MPa
Static bending strength ⁽¹⁾	110 MPa
Longitudinal modulus of elasticity ⁽¹⁾	14,100 MPa

(1) At 12% moisture content, with 1 MPa = 1 N/mm².

Natural durability and treatability

Resistance to decay. Class 1 – durable.

Resistance to dry wood borers. Class D – durable (heartwood durable but sapwood not clearly demarcated).

Resistance to termites. Class D – durable.

Treatability. Class 2-3 – poorly to moderately permeable.

Use class covered by natural durability. Class 4 – in ground or fresh water contact.

Notes. This species is listed in the NF EN 350 standard. According to the European standard NF EN 335 of May 2013, performance length might be modified by conditions in which it is used. This wood is given as not very sensitive to marine borers.



Flat sawn.
 Photo D. Guibal, Cirad.



Quarter sawn.
 Photo D. Guibal, Cirad.

Preservation treatment

Against dry wood borer attacks. This wood does not require any preservation treatment. In case of temporary humidification. This wood does not require any preservation treatment.

In case of permanent humidification. This wood does not require any preservation treatment.

Drying

Drying rate. Slow.

Risk of distortion. High risk.

Risk of case hardening. No known specific risk.

Risk of checking. Slight risk.

Risk of collapse. No known specific risk.

Suggested drying schedule. Schedule #6 (see explanatory note).

Sawing and machining

Blunting effect. Normal.

Sawteeth recommended. Stellite-tipped.

Machining tools. Tungsten carbide.

Suitability for peeling. Not recommended or without interest.

Suitability for slicing. Good.

Assembling

Nailing/screwing. Good but pre-boring necessary.

Notes. High specific gravity: important that gluing be performed in compliance with the code of practice and instructions for the glue used.

Commercial grading

Sawn timber appearance grading.

According to SATA grading rules (1996).

For the "General Purpose Market"

Possible grading for square-edged timbers: choice i, choice ii, choice iii, choice iv.

Possible grading for shortlength lumbers: choice i, choice ii.

Possible grading for shortlength rafters: choice i, choice ii, choice iii.

For the "Special Market"

Possible grading for strips and small boards: choice i, choice ii, choice iii.

Possible grading for rafters: choice i, choice ii, choice iii.

Visual structure grading.

According to European standard EN 1912 (2012) and associated national standards (see explanatory note), strength class D40 can be provided by visual grading.

Cross sections of *Pteleopsis hylodendron*.
Photo J.-C. Cerre.



2 mm



0,5 mm

Fire safety

Conventional French grading

Thickness > 14 mm: M3 (moderately flammable).

Thickness < 14 mm: M4 (readily flammable).

Euroclass grading. D-s2, d0

Default grading for solid wood that meets requirements of European standard NF EN 14081-1 (April 2016): structural graded timber in vertical uses and ceilings with minimal mean density of 0.35 and minimal thickness of 22 mm.

Main end uses

Heavy carpentry.

Stairs (inside).

Vehicle or container flooring.

Exterior joinery.

Interior joinery.

House framing.

Flooring.

Decking.

Bridges (parts in contact with water or ground).

Poles.

Exterior panelling.

Sleepers.

Common names

Country	Local name
Cameroon	Sikon
Côte d'Ivoire	Koframiré
Democratic Republic of Congo	Osanga

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Decking around an infinity pool –
 By Agencement Tiby, supplies from *Fibres
 Industries Bois*, La Réunion, France.
 Photo David Bodelu,
Fibres Industries Bois.

Korean Society of Forest Science Proceedings

International Symposium on Ecosystem Restoration for Green and Peace Asia

18 August 2021, Alpensia, Pyeongchang, Republic of Korea

Asia is Earth's largest and most populous continent, covering an area of 44,579,000 km² (approximately 30% of Earth's total land area and 8.7% of Earth's total surface area). This continent has long been home to the majority of the human population and was the site of many of the first civilizations. Asia is notable not only for its overall large size and population, but also for its large and dense settlements, as well as its vast but barely populated regions. Asia's 4.5 billion people constitute roughly 60% of the world's population.

Asia's economy is growing rapidly, led by a rising middle class, but it faces major policy challenges such as inequality, uncertain land tenure, unsustainable land use, loss of biodiversity, food insecurity, and climate change. In addition, agricultural expansion and unsustainable land use change has made the region one of the world's largest sources of greenhouse gas emissions.

Unsustainable land use can be at the root of a health crisis. Desertification, land degradation, and drought lead to social and environmental challenges such as reduced livelihoods, forced migration, water scarcity, and biodiversity loss. These problems put millions of people at risk.

In particular, deforestation and forest degradation have resulted in both environmental damages – soil erosion, land degradation, and biodiversity loss – and socio-economic damages such as insecure food, water and health, as well as the loss of people's cultural identity and dignity. In order to mitigate and combat these emerging challenges, governments and international organizations among various stakeholders have expended significant effort. Investing in healthy land as part of a green recovery is a forward-looking solution and a smart economic decision. Restoration of land-based ecosystems can help reverse biodiversity loss and protect against future crises.

This year's World Environment Day marks the formal launch of the UN Decade on Ecosystem Restoration (www.decadeonrestoration.org), a global initiative that will promote and support the revival of natural spaces degraded mainly due to human activities. It aims to fight the degradation of ecosystems on every continent. This is an opportunity to help turn the tide and develop a network among forest-related institutions in Asian region.

Language: English.

Download the proceedings:

<https://www.iufro.org/fileadmin/material/publications/proceedings-archive/11000-virtual21-ecosystem-restoration-program-book.pdf>

Conference website:

www.iufro.org

RÉSUMÉ DE THÈSE /
ACADEMIC THESIS ABSTRACT / RESUMEN DE TESIS ACADÉMICAÉtude de l'effet des propriétés
biotiques et abiotiques du sol sur
la croissance et la mycorhization
du cèdre, *Cedrus atlantica* Manetti

Belkacem EL AMRANI

RÉSUMÉ

Cedrus atlantica Manetti est une essence emblématique de grand intérêt écologique, économique et social. La faible architecture racinaire constitue une menace sérieuse pour le boisement et la régénération de cette espèce. Bien que la mycorhization aide le cèdre dans les conditions défavorables, nos connaissances sur la mycorhization des plantules de cèdre sont encore fragmentaires. Compte tenu de ces difficultés, apparaît la nécessité d'étudier les interactions entre les racines et les facteurs biotiques et abiotiques du sol, et de rechercher des solutions pour la mycorhization des plantules. Pour atteindre ces objectifs, on a étudié les réponses des plantules aux facteurs physico-chimiques, texturaux, hydromécaniques et microbiologiques du sol ainsi que la réussite de la mycorhization du cèdre au stade juvénile. En réponse aux propriétés texturales et physico-chimiques des sols de cédraie, les plantules de *C. atlantica* montrent une forte dépendance à la teneur en carbone organique, en azote, en phosphore et à la granulométrie du sol. Ces facteurs stimulent la longueur et le nombre de racines secondaires sur certains sols, et la croissance des plantules sur d'autres sols. Les différentes provenances de *C. atlantica* montrent des besoins élevés en azote, cependant que l'une préfère la forme ammoniacale et l'autre l'azote nitrique. Les variations au niveau des cotylédons révèlent différentes formes d'adaptation vis-à-vis de la nutrition azotée. Les propriétés hydromécaniques du milieu de culture affectent profondément les plantules de *C. atlantica*, dans des conditions extrêmes, et entraînent une surstimulation de l'allongement des racines principales sans ramification, ou empêchent complètement leur allongement, avec de nombreuses racines latérales réduites. À l'échelle anatomique, ces réponses sont plus apparentes au niveau du cortex. Les interactions de la microflore indigène du sol présentent un effet déterminant sur la croissance de *C. atlantica*. De sorte que la composition microbienne du sol peut stimuler la croissance des racines et diminuer la densité racinaire. L'appauvrissement nutritif de six sols a permis le piégeage de 15 champignons ectomycorhiziens des jeunes plantules de *C. atlantica*. D'où l'importance de cette nouvelle gamme de champignons mycorhiziens caractérisés pour la première fois chez les plantules de *C. atlantica*.

Mots-clés : *Cedrus atlantica* Manetti, racines, physico-chimie du sol, texture du sol, hydromécanique, microorganismes, mycorhizes, Maroc.

Effects of soil biotic and abiotic properties
on the growth and mycorrhization of Cedar
(*Cedrus atlantica* manetti)

ABSTRACT

Cedrus atlantica Manetti is an emblematic species of great ecological, economic and social value. However, its weak root architecture seriously compromises (re)afforestation and regeneration of the species. Although it is known that mycorrhization is beneficial to cedars growing in unfavourable conditions, our knowledge on the mycorrhization of cedar seedlings remains patchy. These difficulties show a need to study the interactions between the roots and the soil biotic and abiotic factors and to seek solutions to promote the mycorrhization of cedar seedlings. For this purpose, we studied the responses of cedar seedlings to the physico-chemical, textural, hydromechanical and microbiological factors of the soil and mycorrhization success in juvenile cedars. The response of *C. atlantica* seedlings to the textural and physico-chemical properties of soils in cedar woods shows that they are highly dependent on organic carbon, nitrogen and phosphorus contents and on the soil's granulometry. These factors stimulate the length and number of secondary roots on some soils, and the growth of seedlings on other soils. The provenances of *C. atlantica* show a high nitrogen requirement and different preferences for nitrogen forms. Variations in the cotyledons also reveal different patterns of adaptation to nitrogen nutrition. The hydromechanical properties of the culture medium profoundly affect *C. atlantica* seedlings, so that in extreme cases, they either over-stimulate the elongation of unbranched main roots or completely inhibit their elongation, producing a great many reduced lateral roots. On the anatomical scale, these responses are more apparent at the level of the cortex. Interactions with the native soil microflora have a determining effect on the growth of *C. atlantica* seedlings, since the microbial composition of the soil can stimulate growth and decrease the density of roots. The nutrient depletion of 6 soils allowed the trapping of 15 species of ectomycorrhizal fungi of young *C. atlantica* seedlings. This indicates the crucial importance of this new range of mycorrhizal fungi, characterized for the first time in *C. atlantica* seedlings, especially for work aiming to improve the health status of cedar seedlings.

Keywords: *Cedrus atlantica* Manetti, roots, soil physico-chemistry, soil texture, hydromechanics, micro-organisms, mycorrhizae, Morocco.

Estudio del efecto de las propiedades bióticas
y abióticas del suelo en el crecimiento y
la micorrización del cedro, *Cedrus atlantica*
Manetti

RESUMEN

Cedrus atlantica Manetti es una especie emblemática de gran interés ecológico, económico y social. La débil arquitectura radicular es una grave amenaza para la forestación y la regeneración de esta especie. Aunque la micorrización ayuda al cedro en condiciones desfavorables, nuestros conocimientos sobre la micorrización de plántulas de cedro son todavía fragmentarios. Ante estas dificultades, es necesario estudiar las interacciones entre las raíces y los factores bióticos y abióticos del suelo; también hace falta buscar soluciones para la micorrización de las plántulas. Para alcanzar estos objetivos, se estudiaron las respuestas de las plántulas a los factores fisicoquímico, textural, hidromecánico y microbiológico del suelo, así como la micorrización del cedro en las etapas juveniles. En respuesta a la textura y a la fisicoquímica de los suelos de bosques de cedro, las plántulas de *C. atlantica* muestran una fuerte dependencia del contenido de carbono orgánico, nitrógeno y fósforo, y también del tamaño de las partículas del suelo. Estos factores estimulan la longitud y el número de raíces secundarias en algunos suelos, y el crecimiento de las plántulas en otros. Los *C. atlantica* muestran necesidades de nitrógeno elevadas, aunque los de una procedencia prefieren las formas amoniacales, mientras que los de la otra prefieren las formas nítricas. Por otro lado, las variaciones en los cotiledones desarrollan diferentes formas de adaptación ante la nutrición nitrogenada. Las propiedades hidromecánicas del medio de cultivo afectan enormemente a las plántulas de *C. atlantica*, de modo que las condiciones extremas o bien sobreestiman la elongación de la raíz principal sin ramificación, o bien reducen considerablemente la elongación de esta raíz y generan muchas raíces laterales reducidas. A nivel anatómico, estas respuestas son más evidentes en la zona del córtex. Las interacciones con la microflora autóctona del suelo tienen un efecto decisivo en el crecimiento del *C. atlantica*. Así, la composición microbiana del suelo puede estimular el crecimiento de las raíces y disminuir la densidad radicular. La disminución de nutrientes en seis suelos permitió capturar 15 hongos ectomicorrízicos de las plántulas de *C. atlantica*. De ahí la importancia de esta nueva gama de hongos micorrízicos, caracterizados por primera vez en plántulas de *C. atlantica*.

Palabras clave: *Cedrus atlantica* Manetti, raíces, fisicoquímica del suelo, textura del suelo, hidromecánica, microorganismos, micorrizas, Marruecos.

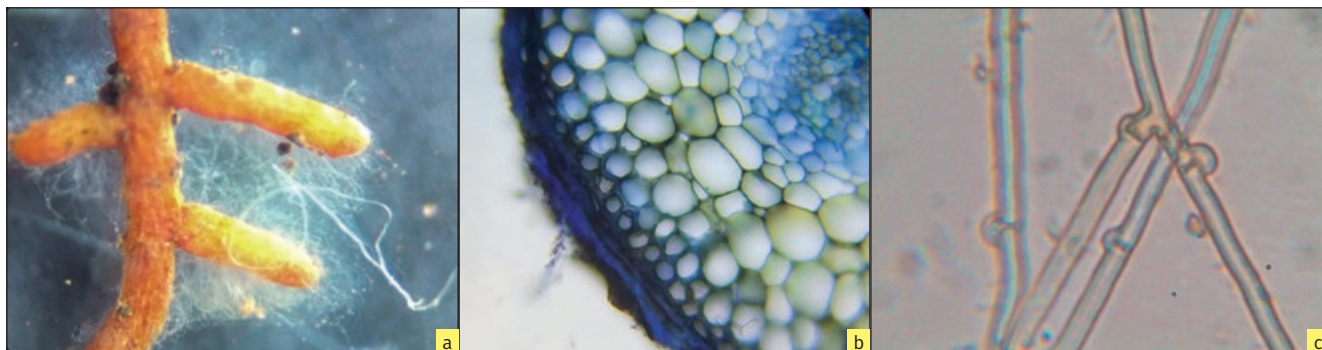


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Photos 1.

a. Aspect morphologique d'une mycorrhize de cèdre sous une loupe binoculaire. b. Coupe transversale d'une racine mycorrhizée de *Cedrus atlantica* Manetti. c. Hyphes émanant d'un champignon mycorrhizien de *C. atlantica*.
 a. Aspecto morfológico de una micorriza de cedro observada con una lupa binocular. b. Corte transversal de una raíz micorrizada de *Cedrus atlantica* Manetti. c. Hifas de un hongo micorrízico de *C. atlantica*.
 Photos B. El Amrani.

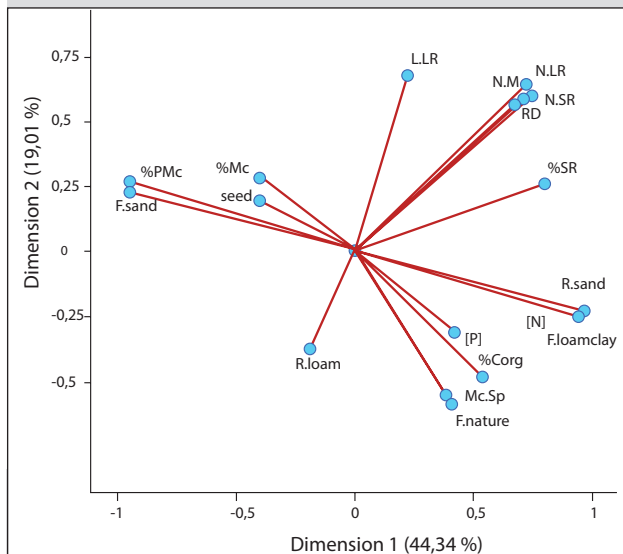


Figure 1.

Résultat de l'analyse des correspondances multiples des principaux facteurs mis en jeu dans la réussite de la mycorrhization des plantules de *Cedrus atlantica* Manetti. Seuls les deux premiers axes d'ordination ont été retenus. F.sand : sable fin ; %PMc : taux de mycorrhization ; %Mc : capacité d'infection ; Seed : présence de jeunes plantules (< 2 ans) sur le site d'origine ; R.loam : limon grossier ; LLR : longueur cumulative des racines latérales ; N.Mc : nombre de pointes mycorrhizées ; N.LR : nombre de racines latérales ; N.SR : nombre de racines courtes ; RD : densité racinaire ; %SR : taux de racines courtes ; R.sand : sable grossier ; [N] : teneur en azote ; F.loamclay : limon fin-argile ; [P] : teneur en phosphore ; %Corg : teneur en carbone organique ; Mc.Sp : espèce de champignon mycorrhizien ; F.nature : nature de la formation forestière.

Figure 1.

Result of the multiple correspondence analysis of the main factors involved in successful mycorrhization of *Cedrus atlantica* Manetti seedlings. Only the first two y-axes are shown. F.sand: fine sand, %PMc: percentage mycorrhization, %Mc: infection capacity, Seed: presence of seedlings (< 2 years) on the original site, R.loam: coarse loam, LLR: cumulative length of lateral roots, N.Mc: number of points with mycorrhization, N.LR: number of lateral roots, N.SR: number of short roots, RD: root density, %SR: percentage of short roots, R.sand: coarse sand, [N]: nitrogen content, F.loamclay: fine loam-clay, [P]: phosphorus content, %Corg: organic carbon content, Mc.Sp: species of mycorrhizal fungus, F.nature: nature of forest stand.

Figura 1.

Resultado del análisis de correspondencias múltiples de los principales factores implicados en conseguir la micorrización de las plántulas de *Cedrus atlantica* Manetti. Solo se han tenido en cuenta las dos primeras ordenadas, que explican mejor la dispersión. F.sand: arena fina, %PMc: tasa de micorrización, %Mc: capacidad de infección, Seed: presencia de plántulas jóvenes (< 2 años) en el lugar original, R.loam: limo grueso, LLR: longitud acumulada de las raíces laterales, N.Mc: número de puntas micorrizadas, N.LR: número de raíces laterales, N.SR: número de raíces cortas, RD: densidad radicular, %SR: tasa de raíces cortas, R.sand: arena gruesa, [N]: contenido de nitrógeno, F.loamclay: limo fino y arcilla, [P]: contenido de fósforo, %Corg: contenido de carbono orgánico, Mc.Sp: especie del hongo micorrízico, F.nature: naturaleza de la formación forestal.

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Liste des articles publiés

El Amrani B., Bendriss Amraoui M., 2020. Biomechanics of Atlas cedar roots in response to the medium hydromechanical characteristics. *Scientifica*, 1-15. <https://doi.org/10.1155/2020/7538698>

El Amrani B., Bendriss Amraoui M., 2018. Effects of some properties of cedar forest soils on secondary roots of *Cedrus atlantica* Manetti. *Journal of Forest Science*, 64: 506-513. <https://doi.org/10.17221/69/2018-JFS>



5th World
Congress on
Agroforestry
.....>
Transitioning to
a Viable World

The 5th World Congress on Agroforestry

July 17-20, 2022, in Québec City, Canada

On July 17-20, 2022, in Québec City, Canada, will be held the Fifth World Congress on Agroforestry: Transitioning to a Viable World. This congress will be an opportunity to stimulate an open and inclusive dialogue between various stakeholders from around the world including farmers, researchers, advisors, policy makers, and representatives from the government, the civil society and the private sector. Considering agroforestry participates in enhancing soil health, protecting water quality, increasing biodiversity, mitigating and adapting to climate change, and providing food security, health and revenues, it is an essential component of the needed ecological, energetic, social and economic transition. This critical transition can and must be achieved through a participatory collaboration process that helps building bridges between research, policy decisions and field work.

The Fifth World Congress on Agroforestry will help creating or strengthening those connections by promoting knowledge sharing for a transition to a unified and healthy world.

Information:

<https://agroforestry2022.org/en>



Master Sciences du Bois

Faculté des sciences

Université de Montpellier

Le Master Sciences du Bois de la faculté des sciences de l'Université de Montpellier forme des cadres, des ingénieur-es et des futur-es chercheur-ses, force de propositions pour le développement et l'innovation dans les entreprises de la filière forêt-bois et les laboratoires de recherche.

Le matériau bois y est abordé depuis sa formation dans l'arbre jusque dans ses usages en tant que matériaux ou molécules. Une attention particulière est portée sur les compétences transversales assurant une vision et une compréhension globale de la filière (amont/aval, ressources, débouchés et valorisation) et permettant ainsi la conception de produits ou services bois innovants dans une logique de développement durable.

« Face aux enjeux climatiques et environnementaux, une transition est nécessaire dans nos modes de production et de consommation. Ce qui est vrai pour l'énergie ou l'alimentation l'est aussi pour les matériaux. Le bois répond clairement à ces grands enjeux et ses usages vont se développer fortement dans les années à venir », souligne Bruno Clair, directeur de recherche au CNRS et à l'origine de la création du Master.

Le master repose sur des pédagogies actives et novatrices telles que l'apprentissage par problèmes (APP), des études de cas d'entreprises et de laboratoires, un projet fil rouge ou encore le développement de l'autonomie et du projet personnel.

Sandrine Bardet, maître de conférence, également initiatrice de cette formation, précise : *« Nous avons pensé ce Master pour qu'il soit interdisciplinaire et s'appuie sur des méthodes d'apprentissage innovantes développant le projet personnel de chacune et chacun dans un esprit de coopération. »*

Le Master est accessible en formation initiale ou par la voie de l'apprentissage. Pour tous les étudiants, la formation débute par une semaine en forêt qui permet une immersion dans le monde du bois pendant des visites en forêts accompagnées d'expertes de l'environnement et de professionnelles de la foresterie et des visites d'entreprises. En première année, les apprentissages se focalisent sur les origines biologiques du bois, sa composition chimique, sa microstructure et ses propriétés physiques et mécaniques. La deuxième année est tournée vers les usages, depuis le bois massif et les composites jusqu'aux valorisations chimique et énergétique. Chaque année, les étudiants effectuent un stage de 4 mois minimum, une année en entreprise, l'autre en recherche académique.

Les candidatures sont ouvertes à partir du mois d'avril. Pour connaître les conditions d'admission, rendez-vous sur le site Internet du Master !

Contact du Master Sciences du Bois

Responsables du Master : Sandrine Bardet et Bruno Clair

<https://master-bois-fds.edu.umontpellier.fr>

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XV WORLD FORESTRY CONGRESS

Building a Green, Healthy and Resilient Future with Forests

2–6 May 2022 | Coex, Seoul, Republic of Korea



SIDE EVENTS

Side events provide an opportunity for sharing expertise, best practices and innovations as well as for increasing opportunities for dialogue and exchange amongst the Congress' participants on the theme and subthemes of the Congress. These events are open to all interested participants who are registered for the Congress.

Organizers of confirmed events are invited to upload their event flyers through the online submission platform no later than 15 February 2022.

Side events currently confirmed

The final list of confirmed events will be posted shortly on the Congress website.

Building data foundations for sustainable forest management: integration, collaboration and experience in reporting at global and regional scales to show progress towards green, healthy and resilient forest.

Contact: Stefanie Linser, Email: stefanie.linser@efi.int

Criteria and Indicators to strengthen sustainable forest management in the Caucasus and Central Asia.

Contact: Stefanie Linser, Email: stefanie.linser@efi.int

NEW DATE! New opportunities for Teak sector in the post-COVID-19 Scenario - TEAKNET.

Contact: P. K. Thulasidas, Email: pktdas@gmail.com

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