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Dominant height growth and site index curves for Calabrian pine (*Pinus brutia* Ten.) in central Cyprus

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ABSTRACT

A dominant height growth model and a site index model were developed for Calabrian pine (*Pinus brutia* Ten.) in central Cyprus. Data from 64 stem analysis in 32 temporary plots, where Calabrian pine was the only tree species, were used for modeling. The plots were selected randomly in proportion to two site types. Four difference equations were tested. The evaluation criteria included qualitative and quantitative examinations and a testing with split data. The difference equation of Korf showed the best results for all data. An analysis of the height growth patterns among sites - as these were defined from the selected equation - was made in order to study the behavior of different site index curves. Results indicated the validity of a common height growth model for the two sites. In spite of the irregular height growth pattern observed in Calabrian pine, the model obtained allows us to classify and compare correctly Calabrian pine stands growing at different sites.

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1. Introduction

The species *Pinus brutia* Ten. (Calabrian pine) is a characteristic species of the eastern Mediterranean [12,26,27,34,64,83]. *P. brutia* is widely extended in Turkey and far Eastern Greece, secondarily in the Crimea, Caucasus coast, Azerbaijan, Iraq, Syria, Lebanon, Crete and Cyprus [54].

It is an important species for multi-purpose forestry; construction, industry, carpentry, firewood and pulp [7,10,61]. Additionally, its post-fire regeneration ability makes it a unique forest species within the fragile Mediterranean ecosystems [68].

P. brutia generally occurs in the Mediterranean-type climate of hot and dry summers and mild and rainy winters. This species occurs most abundantly in the semi-arid and sub-humid zones [64]. The species has strict rainfall requirements, being absent from the arid bioclimatic zone and rare in the lower semi-arid zone, but widespread in the humid zone [63]. We find Calabrian pine in zones with a mean annual precipitation between 400 and 2000 mm [36,45]. *P. brutia* is well adapted to the Mediterranean-type climate in several physiological and morphological characteristics and is a drought resistant species [17,19,33,44,45,53]. The adaptabilities of its provenances to drought vary [32], but *P. brutia*

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generally achieves its optimum growth in rainy regions of more than 900–1000 mm mean annual precipitation. Its typical elevation range is between 0 and 1500 m above sea level [45]. The geographical isolation among populations implies the existence of several races, with different ecological characteristics and behavior [54].

Calabrian pine is a fast growing tree species; its mean annual increment in plantations can be over 10 m^3/ha (at a spacing of 4.5 m^2; 2222 trees per hectare, site class I, site index 20 m) between the ages of 25 and 35 years [35]. New stands of *P. brutia* generally begin after fires, although it can also naturally regenerate without fire [26,27,46,47,48,76,77]. Several adaptations greatly contribute to its post-fire regeneration [20,46]. Seedlings develop rapidly growing tap roots while the stems grow comparatively slowly in height, so that seedlings can have 65 cm tap roots within five to six months after germination [26,27,46]. Early stem growth is greater at higher elevations, while average root growth is the opposite [77]. The early rapid growth of *P. brutia* continues during the following years; the mean annual increment can be over 10 m^3/ha in appropriately spaced plantations between the ages of 25 and 35 years, as described earlier (site class I, site index 20 m [35].

Calabrian pine is the main forest species in Cyprus growing from sea level up to the 1600 m altitude [79]. Its forests represent about 90% of the Island's forest area, which totals at 173,182 ha [5]. Most of these forests were classified currently unexploitable after a recently carried out inventory while 41,399 ha were classified as currently exploitable [5]. Fellings are confined in the latter. The annual wood output for the periods 1988–1992, 1998–2002 and 2003–2007 was 56,100 m^3, 27,633 m^3 and 14,384 m^3, respectively [5]. This wood is utilized locally for the production of sawn timber, chipboard, box-shooks, fuelwood, charcoal and other minor wood products [79]. Sixteen thousand eight hundred thirty five hectares of the *P. brutia* forests have been selected and preliminarily classified either as National Forests Parks to provide amenities to the public, or as Nature Reserves for nature conservation [5].

The past management (silvicultural system) of pine forests in Cyprus proved to be unsuitable, resulting in serious ecological, economic and social constraints [79]. This may put in danger the survival of these stands in the long term [43]. The degradation of pine forests in Cyprus has resulted in drastic reduction of annual wood output from 56,100 m^3 (for the period 1988–1992) to 14,384 m^3 (for the period 2003–2007) [5]. The recognition of this situation and the increasing interest in using these stands for either direct production, or indirect production (environmental preservation) justifies the need for a sustainable management of Calabrian pine stands. Considering the high environmental and silvicultural variability of *P. brutia* stands [43], it is necessary to typify and characterize them in order to optimize their management.

Estimating forest productivity is both necessary for effective forest management and useful for evaluating basic site conditions for ecological field studies. Site quality is therefore influenced by factors such as available light, heat, moisture, and nutrients, along with other soil characteristics such as soil depth and aeration [29]. Although it would be best to directly measure and predict these factors, they require precise measurements that may be difficult to extrapolate across scales. Therefore, indirect methods for evaluating site quality are more frequently used in forest management [56,67,72].

Site index, defined as dominant height at some fixed base age, is one of the most commonly used indicators of site productivity because there is a close correlation between volume and dominant height growth [72]. Many mathematical functions are available to model dominant height growth. Desirable characteristics for growth functions are: polymorphism, existence of inflection point and horizontal asymptote, logical behavior, right theoretical basis, base-age invariance, and parsimony [9,14,65]. These requirements depend on both the construction method and the mathematical function used to develop the curves [65]. Among other methods for site index curve construction [38], the algebraic difference approach presents certain advantages: short observation periods can be effectively used, and the structure of equations is base-age invariant [9,14,15,42].

Modeling dominant height growth for *Pinus* sp. in the Mediterranean region has received some attention. Río and Montero [58] developed site index curves for *Pinus sylvestris* in Spain, Calama et al. [67] for *Pinus pinea* in Spain, Bravo-Oviedo et al. [2] for *Pinus pinaster* in Spain, Hatzistathis et al. [4] and Kitikidou et al. [41] for *P. brutia* in Greece.

Shater et al. [85] developed dominant height, individual-tree diameter increment, tree height, and self-thinning site curve models for *P. brutia* stands in Syria. In this work, the Chapman-Richards line was selected to show the development of dominant height on average site. Palahí et al. [57] developed and compared two sets of models (site index models for even-aged and uneven-aged stands) which enable tree-level simulation of the development of pure and mixed stands of *P. brutia* in North-eastern Greece. Adamopoulos et al. [73] examined the impact of site qualities on *P. brutia* wood characteristics in North-eastern Greece, while Kavgacı et al. [6] studied the post-fire long-term regeneration of the species in South-western Turkey through a floristic survey. Aertsen et al. [80] compared and evaluated five different modeling techniques (multiple linear regression, classification and regression trees, boosted regression trees, generalized additive models and artificial neural networks) to model site index of homogeneous stands of important tree species of Turkey (*P. brutia* among others) by using environmental variables (soil, vegetation and topographical variables) as predictors. In another study, Aertsen et al. [81] compared the performance of the same five modeling techniques for the prediction of forest site index (*P. brutia* stands among others) in two contrasting ecoregions (lowlands in Belgium and Mediterranean mountains in Turkey). Artificial neural network models have been developed to estimate volume of dominant Calabrian pine trees [49,51]. Finally, Diamantopoulou et al. [50] applied Principal Components Analysis and Hierarchical Cluster Analysis in order to interpret the behavior of several quantitative variables of reforestation Calabrian pine trees (dominant height among others).

The main goal of this study was to develop a dominant height growth model for *P. brutia* growing in two different site types in central Cyprus, from which a site quality model would be created. To achieve this objective, the variability in dominant height growth patterns and the differences among the sites were analyzed.

2. Materials and methods

2.1. Data set

The study was conducted in central Cyprus (34°56N, 33°17E), in middle elevation (300–750 m a.s.l.) forest areas. This area covers about 14,000 ha. The annual rainfall and the mean yearly temperature (for 1991–2000), according to the closest meteorological station (Kornos, 34°55N, 33°24E, 370 m a.s.l.), are 477.1 mm and 18.4 °C respectively. The geological substrate of the study area, belongs to volcanic sequence diabase dykes with pillow lava screens [30]. The soil texture is mainly sandy loam to sandy clay loam (Petrou and Milios [62], data from Forest Department of Cyprus).

The study area was formerly consisting mainly of vine and olive yards. The majority of those fields were abandoned during the last century and nowadays they have been recolonized mainly by *P. brutia* trees which is the dominant species in the area. A few olive yards are still cultivated. Moreover three built up areas are located