Above- and below-ground biomass of *Abies holophylla* under different stand conditions

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Abstract: Effective forestry management requires the selection of appropriate tree species that are able to grow under a range of environmental conditions. Here, we aimed to determine how a single tree species grows under different biotic and abiotic environmental conditions. Specifically, we quantified the total biomass of the above- and below-ground parts of ten 18-year-old Manchurian firs (*Abies holophylla* Max.) located in one stand in Gyeongsan City and one stand in Gyeongju City, Gyeongbuk Province, Korea. The Gyeongsan stand exhibited more growth in diameter, volume, and total biomass. In addition, the roots of this stand grew farther from the stump compared to the Gyeongju stand, resulting in a difference in root growth between the two stands. The S/R rate of the trees was 3.49 and 2.99 in the Gyeongju and Gyeongsan stands, respectively. However the growth pattern of each tree part was similar in both stands. Hence, we demonstrate that planting *A. holophylla* under different biotic and abiotic conditions, such as soil composition, temperature, and humidity, potentially influences initial growth rates; thus, environmental conditions should be considered when deciding which species should be used for afforestation, and appropriate forestry practices should be regulated.
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1. Introduction

In 2011, Korea initiated the fourth basic forest plan, which proposes the construction of sustainable healthy forest resources by afforestation, in addition to species renewal after thinning, clear cutting, and selective timber harvesting (Engelhard 2004; Lester 2006; Korea Forest Service 2010).

The importance of forest management was realized in Korea, following the successful restoration of tracts of devastated forests. Hence, the "afforestation" (or construction) of secondary forests is now required. However, several important factors must be considered before establishing secondary forests, including ecological suitability and biomass. Planting trees that are tolerant to abiotic conditions would help make secondary forests easier to maintain, in parallel to retaining their ecological and cultural significance (Mayer 1984; Burschel and Huss 1987; Donald and Denton 1998; Szymura 2005; Korea Forest Service 2010).

Tree biomass is closely related to tree growth and is influenced by biotic and abiotic factors. Examples of biotic factors include grafting, understory, wildlife, and competition with surrounding trees. Examples of abiotic factors include latitude, longitude, altitude above sea level, temperature, humidity, soil composition, and stand aspect (Stage 1976; Gruber 1992; Gruber 1994; Donald and Denton 1998; Comeau 2002; Kimmins 2003; Green and Hawkins 2005; Gruber and Lee 2005a; Gruber and Lee 2005b).

Studies in the 21st century tend to integrate this information with satellite imagery via geographic information systems (GIS) to estimate landscape-scale forest biomass; however, to extrapolate to this scale, it is necessary to calculate the biomass of individual trees belonging to different age-classes and diameter (Steininger 2000). Lee (2001, 2004) and Seo et al. (2005) estimated the biomass *of Picea abies* and *Pinus densiflora*, respectively, to determine the overall biomass of these forest stands across Korea. In addition, Kim et al. (1996) and Na et al. (2011) studied the biomass of *Larix kaempferi* and *Pinus rigida*, and compared *Pinus densiflora* with the biomass of *Pinus densiflora* for. *erecta*. However, there remains a paucity of studies that compare tree biomass with respect to stand condition, while even fewer studies on the biomass of individual tree parts are available, which could have implications for the adaptability of trees in different regions.

Research on the adaptability and productivity of trees based on growing conditions is required to implement effective conservation and management measures in forests at local and regional scales. In addition, to monitor short- and long-term ecosystem changes and determine effective countermeasures, it is necessary to analyze and infer the current productivity of trees and associated stands under different biotic and abiotic conditions. For instance, it is necessary to estimate tree biomass, including root structure, in forest ecosystems to apply the information to forest management, arboreal growth models, and the study of forest ecosystems (Santantonio 1990; Gruber 1994; Kurz et al. 1996;

Laiho and Finér 1996; Bartelink 1998; Lacointe 2000; Lee 2001; Son et al. 2001; Lee 2004; Gruber and Lee 2005a; Gruber and Lee 2005b).

The biomass of trees belonging to the same species often varies significantly with respect to region, age group, and stand density. In particular, *A. holophylla* exhibits broad differences in above-ground biomass, depending on the biotic and abiotic conditions of the surrounding environment. For instance, one study stated that even a 40- to 49-year-old *A. holophylla* might have a biomass similar to that of an 18-year-old tree of the same species, depending on the growth conditions (Youn 2009).

The Manchurian fir (*Abies holophylla* Max.) grows at altitudes of up to 1600 m, and is evenly distributed throughout South Korea (Wang and Wang 2004). This species reaches a height of 40 m, with a maximum diameter at breast height of 1 m. This species grows on poor podsolic brown soils, in areas with climates of humid-warm summers and dry-cold winters, and annual precipitation rates of between 600 mm and 1340 mm (Wang and Wang 2004; Korea National Arboretum 2009). *A. holophylla* is a versatile and shade tolerant tree that has the ability to adjust to environmental changes and regenerate by proventitious shoots and secondary crown, similar to *Abies alba* (Gruber 1992; Gruber 1994). In the past, *A. holophylla* was the wood used to construct the large crossbeams in Gyeongbok Palace, indicating that this species has high potential as a building material (Choi and Park 2009); therefore, the planting of this tree to establish secondary forests in Korea could potentially generate many economically viable uses.

This study focused on the above- and below-ground growth characteristics of *A. holophylla* planted in two different stands. The responsive ability of *A. holophylla* was investigated in a variety of environmental conditions, such as biotic and abiotic factors and in different stands, in order to detect the species' suitability as a successor of secondary forests. We attempted to show the range of adaptations in relation to the physiology of individual trees and tree-shape under the observed environmental conditions. We anticipate that this information could potentially be used to identify the suitability of this species for use as a successor of secondary forests.

2. Material and Methods

2.1. Study area and site characteristics

This study was initiated in 1994 and was carried out until 2011 in Gyeongbuk Gyeongju-si Nenam-myun Pakdal-ri and Gyeongbuk Gyeongsan-si Dae-dong. The overall conditions of the two study areas are presented in Table 1. Both stands have an open environment without an overstory or canopy layer. The Gyeongju stand contained 3,000 trees per ha, while the Gyeongsan stand contained 2,500 trees per ha.

Table 1. General description of the two study stands

Characters	Stands	
	Gyeongju	Gyeongsan
Location	N 35°43' 24" E 129°6' 7"	N 35°49' 35" E 128°45' 26"
Altitude (m)	16	15.8
Mean temperature (℃)	216	200
Annual precipitation (mm)	6.8	5.6
Stand density (trees/ha)	33	26
Average BD (cm)	3.5	3.7
Average height(cm)	10.6	14.2

Table 2 shows the physical and chemical characteristics of the soil in the two stands. The Gyeongju stand consisted of sand and rock, while the Gyeongsan stand generally consisted of cultivated black soil with a large amount of ash. The cation and anion substitution ability was higher in the Gyeongju stand compared to the Gyeongsan stand. Furthermore, the substitution ability of both stands was similar to the average soil conditions recorded in Korea (Lee 1981).

Table 2. Presentation of the physical and chemical properties of soils in the two study stands

Characters	Stands	
	Gyeongju	Gyeongsan
Moisture content (%)	3.4	4.3
Gravel content (%)	73	53
pH	5.9	5.6
K^+	0.39	0.50
Mg^{2+}	0.61	1.01
Na^+	0.26	0.58
Ca^{2+}	0.98	0.79
PO_4^{3-}	0.31	0.73
SO_4^{2-}	10.71	17.82
NO_3^-	0.17	0.16
Cl^-	14.41	18.51

To determine the physical and chemical characteristics of the two stands, we investigated the percentage water content, gravel content, and level of cation (K^+, Na^+, Ca^{2+}, and Mg^{2+}) and anion (PO_4^{3-}, SO_4^{2-}, NO_3^-, and Cl^-) substitution. One soil sample, representing the forestry characteristics of each stand, was collected without disturbing the surface layer. In addition, two soil samples were collected using sampling machines (400 cc) and cans (100 cc) at a location of 1 m distance from the selected sampling site. The percentage water content was obtained by recording the original can weight and the can weight after drying the contents for 72 h at 104℃. In addition, a 9-mesh-size standard screen was used to determine gravel content, after which the level of cation and anion substitution was analyzed using the method developed by the Korea Rural Development Administration (2000).

2.2. Biomass estimation

After considering various genetic characteristics, we selected five trees (excluding suppressed, overgrowth tree, and dead trees) that were located within 10 m distance of each other in each stand. Each forest stand was homogenous regarding tree age; hence, the selection of just five individuals was considered statistically sufficient to perform the necessary analysis. The selected trees were collected, including the entire root system, so that both the above- and below-ground parts of each tree could be evaluated. Above-ground biomass was estimated using the stems, branches, and needles. The below-ground biomass was estimated using the number of roots, root length, and root weight. To minimize the destruction of roots, when collecting the roots of sampled trees, soil within a radius of 1.50 m horizontally around the stem was retained. Except for the root collar, the diameter through all root parts (such as the number of roots, root length, and root weight) was measured at each 10-cm vertical and each 20-cm horizontal interval. The total biomass was calculated by drying the separated root part categories of each layer per sample to obtain dry weight (Tryon and Chapin Iii 1983). To determine the distribution of the root parts in the different soil layers, we investigated the proportion of vertical and horizontal root growth.

In addition, we estimated the biomass of each internode, by categorizing the internode into "n year" for the stems, branches, and needles that developed in 2010, and "n-1 year" for those that grew in 2009. Biomass estimates were recorded after drying the parts for 3 days at 105℃, and weighing the parts to a unit level of 0.1 g. Finally, we estimated the biomass of the stems by using the sampled trees to estimate yearly growth, diameter growth, and volume growth of the stems. A t-test was performed on the collected data using SPSS 18.0.

3. Results

3.1. Growth characteristics of the above-ground parts

The height increments for each stand are shown in Figure 1. Height growth in the Gyeongju stand averaged 255.3 cm, while that in the Gyeongsan stand averaged 236.3 cm; however, there was no significant difference in the total growth increment between the two stands. Growth increments for diameter and timber volume are shown in Figure 2. The diameter growth and timber volume of trees from 1 to 8 years of age was greater in the Gyeongju stand compared to that of the Gyeongsan stand. A similar result was obtained for diameter growth.

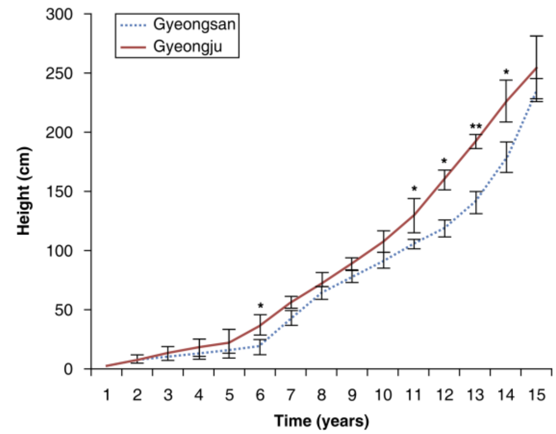

Figure 1. Height growth curves for the two study stands. * and ** indicate significance at the 5% and 1% level, respectively, using the t-test

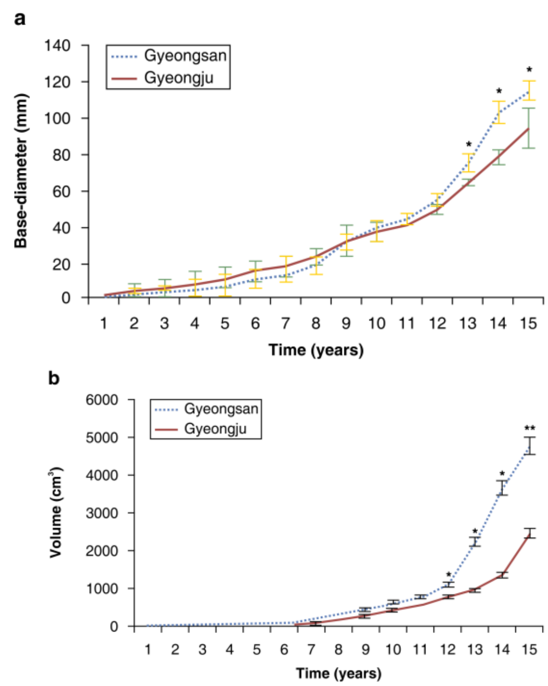

Figure 2. The base diameter growth-curve (a) and the volume growth-curve (b) for the two study stands. * and ** indicate significance at the 5% and 1% level, respectively, using the t-test

The total biomass of the sampled trees in the Gyeongsan and Gyeongju stands is shown in Figure 3 and Figure 4. The stem, branch, and needle standing stock values were higher in the Gyeongsan stand compared to the Gyeongju stand. The stems, needles, roots, and S/R (shoot to root ratio) were similar in the two stands; however, the weight of the branches was significantly different between the two stands. Higher growth increments for the stems, branches, and needles were obtained in the Gyeongsan stand compared to the Gyeongju stand ($p < 0.05$).

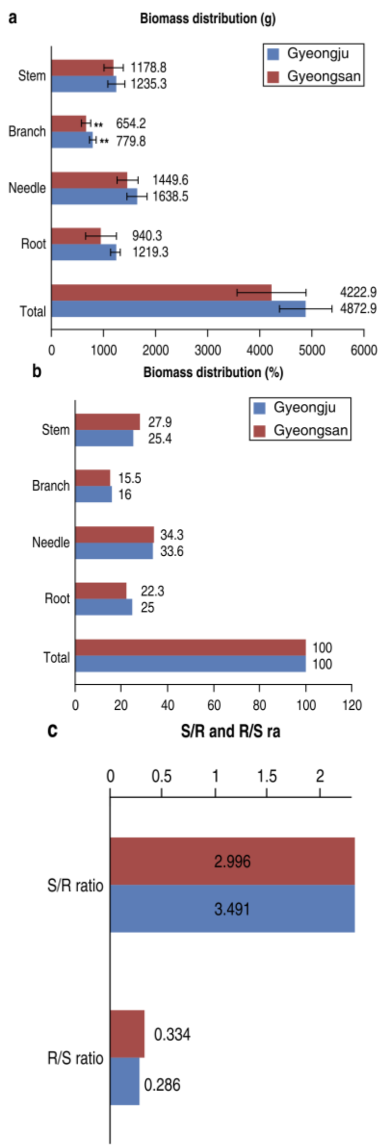

Figure 3. Average biomass distribution (a) and ratio (b) with respect to the total biomass and S/R ratio (c) for the two study stands. ** indicate significance at the 1% levels by t-test

Both stands were located in open environments, without an overstory or canopy cover. In both stands, a large number of needles developed during the early stages of growth; however, this growth rapidly decreased after the tree crown developed, which overshadowed the needles. The annual biomass of the internode is shown in Figure 4, with both stands exhibiting a larger biomass in the current year compared to the previous year.

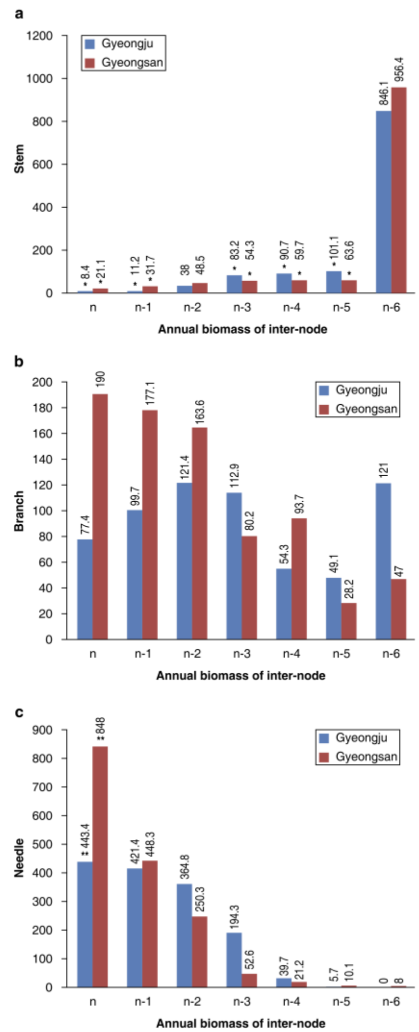

Figure 4. Presentation of stem (a), branch (b), and needle biomass (c) in the two study stands.
* and ** indicate significance at the 5% and 1% level, respectively, using the t-test

3. 2. Growth characteristics of the below-ground parts

The horizontal growth characteristics of each root are shown in Figure 5, including the number of roots, root length, and root weight. The total root length exhibited greater growth in the Gyeongsan stand compared to the Gyeongju stand; however, there was no significant difference. A greater root weight was recorded for the Gyeongju stand compared to the Gyeongsan stand, which was statistically significant ($p < 0.05$).

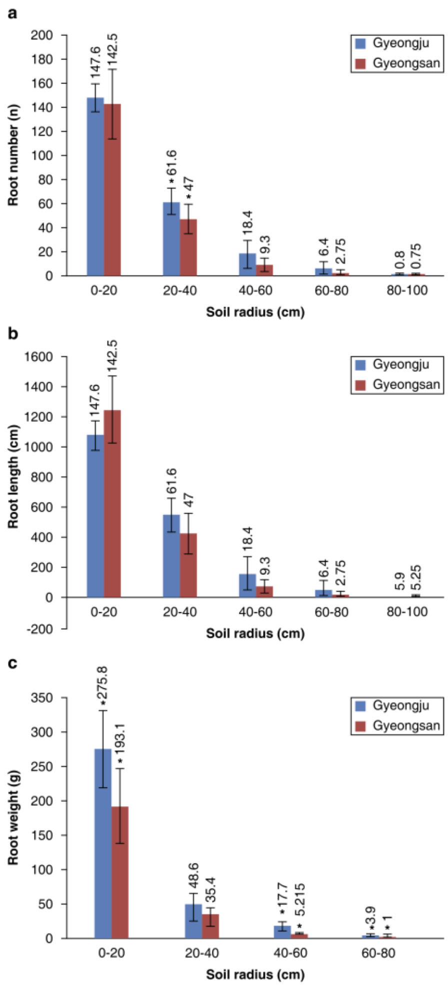

Figure 5. Distribution of the root number (a), length (b), and weight (c) along the horizontal soil radius. * indicate significance at the 5% and 1% levels by t-test

The vertical growth characteristics of each root are shown in Figure 6. However, there was no significant difference in root length between the two stands. In contrast, the number of roots and root weight showed a significant difference at the 5% level. For overall horizontal root growth, the greatest biomass for both stands was in the roots, root length, and root weight within the 0 to 40 cm range (Figure 5).

In addition, there was a tendency for roots to grow less with increasing distance from the tree. For overall vertical root growth, the greatest biomass for both stands was recorded in the roots, root length, and root weight within the 10 to 30 cm range (Figure 6).

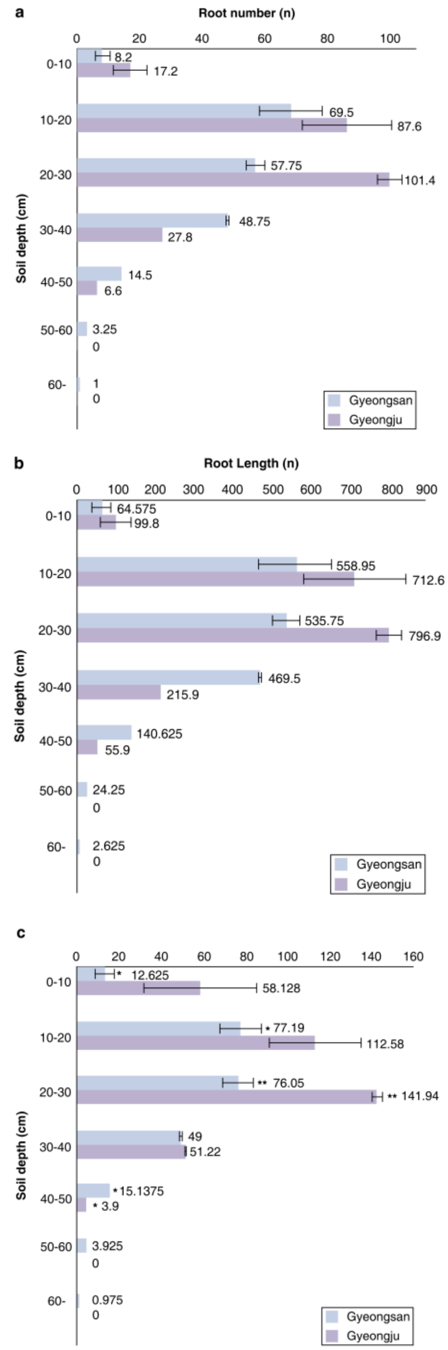

Figure 6. Distribution of the root number (a), length (b), and weight (c) along the vertical soil layer. * and ** indicate significance at the 5% and 1% level, respectively, using the t-test

4. Discussions

In the current study, we showed that the biomass of different tree parts (such as stems, roots, needles, and branches) differed with respect to environmental conditions in which the trees grew. Furthermore, previous research has demonstrated that horizontal and vertical root development is strongly related to tree health; for instance, if the biomass ratio of the root collar is high, the tree is more vulnerable to environmental conditions, such as high winds and water-related disasters (Burroughs and Thomas 1977; Gale and Grigal 1987; Tamasi et al. 2005; Lee et al. 2006).

Previous studies state that both stoniness and soil components influence both the development of roots and above-ground parts (Stage 1976; Wills and Abbott 2003). In the current study, the Gyeongju stand contained soil to a depth of 30 cm, below which was gravel. In contrast, the Gyeongsan primarily contained ash to a depth of 30 cm. The presence of a rock layer, such as gravel, has been shown to negatively influence the development of roots, due to reduced soil permeability (Gerard et al. 1982; Dexter 2004). Consequently, once the roots in the Gyeongju stand reached the rock layer, growth slowed, whereas a high growth rate was maintained in the Gyeongsan stand. For this reason, the Gyeongju stand had much lower root function compared to the Gyeongsan, supporting the findings of previous studies.

The R/S (S/R) in this study was 0.334 (2.996) and 0.285 (3.491) in the Gyeongsan and Gyeongju stands, respectively. These values indicate that the trees are young based on Art and Marks (1971). The ratio of the root to total biomass in both stands was approximately 0.2–0.3, while that of a temperate forest is approximately 0.2 (Johnson and Risser 1974; Whittaker and Marks 1975; Canadell et al. 1999; Pack et al. 2005; Na et al. 2011). Research by (Kim and Kang 2005) showed that the limbs and leaves of trees grown in closed environments fall faster compared to those grown in open environments. The results of the current study supported this work, whereby trees in the Gyeongsan stand were healthier compared to those in the Gyeongju stand. The roots of trees in the Gyeongsan stand provided sufficient nourishment to enhance needle and total biomass, with both these parameters being higher compared to those recorded for the Gyeongju stand.

In general, the taproot system represents the ideal soil composition for *A. holophylla* during the early stages of development. However, the taproot develops poorly in certain soil compositions. In such instances, a greater number of side roots and other tiny roots develop. Existing research has shown that phenomenon results in the ratio of roots to total biomass increasing during the early stages of development (Taylor et al. 1966; Lee 2004; Tosi 2007). Hence, in soils with a shallow rock layer, such as the Gyeongju stand, these findings lend support to the occurrence of less root growth (Watson et al. 1999). Therefore, in the current study, while the roots in both stands exhibited similar levels of horizontal growth, vertical growth was restricted in the Gyeongju stand, due to its high gravel content, whereas vertical growth was not impeded in the Gyeongsan stand, due to the presence of ash. However, the roots (except root stock) of the Gyeongju stand showed greater growth, due to the poorer soil conditions causing the proliferation of side roots and tiny roots from the taproot, thus enhancing overall biomass compared to the Gyeongsan stand.

Conclusion

Here, we quantitatively compared the above- and below-ground growth characteristics of 18-year-old *A. holophylla* planted in two stands (the Gyeongju and Gyeongsan stands), which differed in environmental characteristics. Differences in the biomass of different tree parts (needles, stems, roots) were then used to demonstrate how the same species has adjusted to grow under these different conditions. The two stands exhibited different growth patterns due to one stand (Gyeongju) containing more gravel in the soil compared to the other stand (Gyeongsan).

Other environmental conditions, such as soil and weather, might also influence the lifetime growth of this species. Therefore, additional research is required to assess how these factors might also affect growth patterns. Here we demonstrate that *A holophylla* is able to grow well under two very different soil conditions, through adjusting the way in which the root system grows, therefore the results of this study support the contention that *A. holophylla* is a highly suitable tree species for planting to generate secondary forests.

This research potentially serves as a guideline toward selecting the appropriate tree species for planting to generate secondary forests. The findings of this study could be applied in selecting the correct soil environments in which to plant *A. holophylla* for artificial and natural afforestation. By taking this information into consideration, appropriate afforestation management could be implemented.

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