Comparison of unmanaged and managed Trojan Fir–Scots pine forests for structural complexity

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Abstract: Unmanaged forests may exhibit a higher degree of biodiversity compared to managed forests. We examined and compared the stand structure, density, and volume of deadwood components of managed and unmanaged mixed forests of Trojan fir (Abies nordmanniana subsp. equi-trojani [Asch. & Sint. ex Boiss] Coode & Cullen)–Scots pine (Pinus sylvestris L.) in northern Turkey. The single-tree selection method has been employed in the managed forests. Density of large live trees ha−1, density of standing deadwood (SDW) ha−1, and volume of lying deadwood (LDW) (m3 ha−1) were calculated for both treatments (i.e. managed or unmanaged). Results showed that unmanaged forests had significantly higher density of large live trees and SDW compared to managed forests (P < 0.005). In addition, a lower amount of LDW was observed in the managed forests (P < 0.005). Our data suggest that the managed forests’ lack of Scots pine trees in small- and middle-sized diameter classes indicates the potential risk of conversion of these mixed stands into pure Trojan fir forests. Initial results highlight the importance of large tree retention in managed stands to enhance biological diversity.

Key words: Abies, biodiversity, mixed forest, Pinus, selection silviculture

1. Introduction

Biodiversity influences the quality of life on Earth; thus, its maintenance is one of the most critical tasks of forest management (Gauthier et al., 2018). A higher degree of biological diversity induces more ecological services provided by more species (Pádua and Chiaravalotti, 2012). Characteristics of stand structure may influence biological diversity, and habitat structure and biological diversity can be enhanced through the old-growth phase of stand development (Kerr, 1999). It has been suggested that unmanaged forests, compared to managed forests, may present better old-growth conditions with a higher degree of biodiversity including a greater number of large live trees as well as snags (i.e. standing deadwood [SDW]) and lying deadwood [LDW]) (Bauhus et al., 2009). However, researchers have also indicated that biological diversity can be maintained in managed forests if the forests are considered to be complex biological systems in a consistently changing environment (Kerr, 1999; Ciancio and Nocentini, 2011). Consequently, there has been growing interest in increasing structural complexity of stands through silvicultural intervention (Sullivan and Sullivan, 2016; Gauthier et al., 2018). However, such research has been limited for many forest types.

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The number of large live trees, SDW ha−1, and volume of LDW (m3 ha−1) in a stand are some of the most commonly used characteristics for identifying structural complexity (Gauthier et al., 2018). These characteristics are considered vital for the conservation, maintenance, and sustainability of biological diversity (Samuelsson et al., 1994), since they provide habitat for wildlife as well as insects and fungi (Nappi and Drapeau, 2011; Kirchenbaur et al., 2017). A greater amount of SDW and LDW in a stand usually indicates higher biological diversity (Müller and Bütler, 2010). LDW also increases soil water-holding capacity and enhances seedbed conditions for germination, resulting in increased understory plant diversity (Christensen et al., 2005). Moreover, the role of SDW and LDW in carbon (C) cycling substantiates their importance for forest ecosystems (Koster et al., 2015). Data on SDW and LDW from unmanaged forests could be utilized as reference material to determine the appropriate thresholds for managed forests; however, this information is usually limited for many unmanaged forests (Keren and Daci, 2018).

Mixed-species forests usually exhibit greater biological diversity than single-species forests (Pretzsch et al., 2017). Tree mixture in a stand may increase ecosystem
functioning and enhance ecosystem stability (Noss, 1990). Mixed forests of Trojan fir (Abies nordmanniana subsp. equi-trojani [Asch. & Sint. ex Boiss] Coode & Cullen) and Scots pine (Pinus sylvestris L.) provide various ecosystem services such as wildlife habitat, aesthetics, water quality, and recreation, as well as wood production in northern Turkey (Çalışkan, 1992). However, due to the preferred wood characteristics of these tree species (Odabaşı et al., 2004), they have been subject to intensive forestry practices within the region. Intensive forestry activities can reduce the complexity of forest ecosystems (Puettermann et al., 2009); thus, it is likely that these practices would result in decreasing structural complexity of mixed Trojan fir–Scots pine forests in the long term. Several studies have focused on quantifying and enhancing structural complexity while implementing silvicultural practices around the world (Keeton, 2006; Forrester et al., 2013; Dove and Keeton, 2015). However, to our knowledge, there have been no attempts to quantify the deadwood components associated with structural complexity in mixed Trojan fir–Scots pine forests. In addition, forest managers have expressed a growing concern for the decreasing proportion of Scots pine observed in these forests in northern Turkey and the conversion of these mixed forests into pure Trojan fir forests. Thus, appropriate management practices for mixed Trojan fir–Scots pine forests may be developed after characterizing the current stand conditions and structural complexity of these forests.

In general, the forests of northern Turkey are regarded as rich in biodiversity (Çolak et al., 2009); therefore, silvicultural prescriptions that sustain biological diversity while producing high-quality timber are essential in the region. Although interest in silvicultural treatments that enhance the structural complexity of a stand has increased worldwide (Kerr, 1999; Gauthier et al., 2018), such studies have not received enough attention in Turkey. We believe that the assessment of the current structural complexity of managed and unmanaged forests in northern Turkey would create a basis for future work that will aim to enhance and maintain key components of structural complexity linked with biological diversity. Therefore, our objectives are to examine and compare the stand structures of managed and unmanaged forests, and to determine the density of SDW and LDW of managed and unmanaged forests of Trojan fir–Scots pine mixture in northern Turkey. We hypothesized that unmanaged forests of mixed Trojan fir–Scots pine would have greater snag (i.e. SDW) densities and LDW volumes than managed forests. We also aimed to provide silvicultural recommendations for enhancing structural complexity and biological diversity in mixed Trojan fir–Scots pine forests of northern Turkey.

2. Materials and methods

2.1. Study area

Two mixed Trojan fir–Scots pine study sites (i.e. managed and unmanaged sites) were chosen in Turkey’s Ilgaz region, within the Kastamonu Regional Directorate of Forestry (KRDF) (Figure 1). Ilgaz Mountain National Park (IMNP) was examined as the unmanaged site, while the Bostan Forest Planning Unit (BFPU) was selected as the managed site (Figure 1). The IMNP has an area of 1117.6 ha, of which 90% is forested. It was certified as a national park by the Turkish Ministry of Forestry in 1976, and no silvicultural activities have been allowed within the area since that time. Forests of the IMNP are dominated by Trojan fir and Scots pine trees. The IMNP has been administrated for recreational purposes since 1976. The total area of the BFPU is 9.049 ha, which is mainly managed for timber production. In addition to the Trojan fir and Scots pine that dominate the BFPU, other tree species in the area are black pine (Pinus nigra J.F.Arnold), Oriental beech (Fagus orientalis Lipsky), and oaks (Quercus spp.).

The single-tree selection method using volume control-guiding diameter limit (VGDL) regulation (Guldin and Baker, 1998) has been employed in the mixed Trojan fir–Scots pine forests within the BFPU. These applications have used a 20-year cutting cycle and a target diameter of 52 cm at breast height (DBH). The latest selection cutting within the managed Trojan fir–Scots pine forests of the BFPU was conducted in 2017.

Common juniper (Juniperus communis var. saxatilis Pall.), oak, mastic tree (Pistacia lentiscus L.), tree heath (Erica arborea L.), common hazel (Corylus avellana L.), Cornelian cherry (Cornus mas L.), and blackberry (Rubus fruticosus L.) are the most common understory plants at both sites in the Ilgaz region. The elevation ranges from 1000 to 1900 m in the study region; the study plots were installed at elevations of 1750–1850 m. The Ilgaz region is located in the transition zone between the Black Sea climate and the terrestrial climate of central Turkey, which influences the area’s richness in terms of biodiversity. The average annual precipitation is approximately 1050 mm, and the average temperature is 5.1 °C in the Ilgaz region. The growing season lasts about 137 days starting from late April to later August. The topography is dissected, with slopes ranging from 12% to 60% across the study region. The dominant soil group of the Ilgaz region is brown calcicreus.

2.2. Data collection and analysis

In 2018, 5 separate stands were selected at each study site (i.e. BFPU and IMNP). The selected stands of the BFPU were adjacent or in close proximity to the IMNP. Next, in each stand, four 100-m² study plots were randomly installed for measurements. All live trees larger than 5 cm in DBH were measured using a diameter tape in...
each plot, and tree species were recorded. Stand basal area (BA) (m² ha⁻¹), quadratic mean diameter (QMD) (cm), and the number of live trees ha⁻¹ in each stand were calculated using the measurements taken within the plots. The numbers of understory seedlings (<1.3 m in height) were counted in each plot in order to identify each stand’s seedling density per hectare.

Within each 100-m² inventory plot, DBHs of SDW were also recorded, and their condition was categorized from 1 to 3 (i.e. SD1, SD2, and SD3) as outlined by Gauthier et al. (2018). SD1 refers to recently dead trees with intact tops and branches. SD2 is the SDW with an intact top, less than 50% of the primary branches, and bark that has fallen off. SD3 represents the SDW with a repeatedly broken top and no branches. Next, using the measurements taken in each plot, the density of SDW ha⁻¹ was calculated for each stand at each study site (i.e. BFPU and IMNP).

LDW was also divided into 3 categories (LDW1, LDW2, and LDW3) (Gauthier et al., 2018). LDW1 refers to recently downed trees with an intact top, bark, and branches. LDW2 consists of the downed deadwoods without bark, and with indication of rot. LDW3 represents
the rotten downed woods with advanced decomposition. To determine the volume of LDW (m³ ha⁻¹) at each study site, the diameter at the large end (cm), diameter at the small end (cm), and length (m) of all lying deadwood materials were measured in each study plot. For the lying downed trees that had partially fallen outside the plot, only the portions inside the study plots were included in the measurements. The volume of LDW of a lying deadwood was calculated using the equation below (Gauthier et al., 2018):

\[ CWDVolume = \left((LED^2 + SED^2)/2\right) \times L \times 0.00007854 \]

where LED is the large-end diameter (cm), SED is the small-end diameter (cm), and \( L \) is the length of the piece (m). LDW of each plot refers to the sum of volume of all lying deadwood within the plot. Next, using the measurements taken in each plot, LDW ha⁻¹ was calculated for each stand at each study site.

The 5 stands of the study sites were defined as the experimental units (i.e. replicates) in the analyses. Linear mixed-effects models were utilized in the analyses as defined below:

\[ Y = \beta_0 + Rs + Fx + \epsilon \]

where \( Y \) is the response variable (i.e. density of SDW, LDW, or BA), \( \beta_0 \) is intercept, \( Rs \) is random effect for stand, \( Fx \) is the fixed effects of treatments (i.e. managed or unmanaged), and \( \epsilon \) is the error term. It should be noted that we only tested the overall density of BA, SDW, and LDW between the treatments (i.e. managed and unmanaged). The normality and homogeneity of the variance of data were evaluated using residual analysis and no departures from these model assumptions were found. The “lme” function for the R statistical language (R Core Team, 2014) was utilized for the statistical analysis.

3. Results

3.1. Stand structure

Average stand BA of the unmanaged and managed Trojan fir–Scots pine forests were 113.2 and 50.7 m² ha⁻¹, respectively (Table 1); they were statistically significantly different (\( P < 0.005 \)). The average number of trees per hectare in the unmanaged forest did not differ from that in the managed forest (\( P > 0.05 \)). The unmanaged Trojan fir–Scots pine forest had significantly larger QMD than the managed forest across the study plots (\( P < 0.005 \)) (Table 1). The trees with the largest diameter inventoried in the unmanaged and managed forests were 85.4 cm and 59.3 cm, respectively. Moreover, a significantly greater (\( P < 0.005 \)) seedling density was observed across the managed stands (3650 seedlings ha⁻¹) when compared to the unmanaged stands (510 seedlings ha⁻¹) (Table 1). It should be noted that >95% of seedlings observed among the study sites were Trojan fir.

Diameter structures of unmanaged and managed Trojan fir–Scots pine forests are depicted in Figure 2. The unmanaged forest exhibited a bell-shaped diameter distribution pattern with fewer trees in small diameter classes (i.e. 5–15 cm) (Figure 2a). Most trees (70%) were clustered in the range of 15–45 cm diameter classes in the unmanaged forest. It should be noted that, in the unmanaged forest, small- and medium-sized trees (i.e. from 5 to 45 cm) were mostly Trojan fir, while trees larger than 45 cm in DBH were primarily Scots pine (Figure 2a). Although a smaller number of Scots pine trees per hectare were present in the unmanaged forest, the BA of Scots pine was similar to the BA of Trojan fir across the study stands due to the size distribution of Scots pine (Table 2) (Figure 2a) (\( P > 0.05 \)). Managed Trojan fir–Scots pine forest possessed a reverse J-shaped diameter distribution (Figure 2b), which is the typical structure of unevenly aged forests. A greater number of trees were present in the smaller diameter classes of the managed forest, and tree density decreased toward the larger diameter classes. While the unmanaged Trojan fir–Scots pine forest had approximately 45 trees ha⁻¹ larger than 65 cm in DBH, no trees larger than 65 cm in DBH were observed in the managed forest (Figure 2). Similar to the unmanaged forest, the managed forest lacked Scots pine trees in small and medium size diameter classes (Figure 2b). However, unlike in the unmanaged forest, Trojan fir contributed more BA to the managed stands than Scots pine (\( P < 0.05 \)) (Table 2).

Table 1. Descriptive statistics for basal area (BA) (m² ha⁻¹), trees per hectare (TPH), quadratic mean diameter (QMD) (cm), and seedling density ha⁻¹ in unmanaged and managed Trojan fir–Scots pine forests. SD and n refer to the standard deviation of the variables and number of study plots, respectively.

| Variables      | Unmanaged forest (n = 20) | Managed forest (n = 20) |
|----------------|---------------------------|------------------------|
|                | Min.  | Max.   | Mean  | SD    | Min.   | Max.   | Mean  | SD    |
| BA             | 27.9  | 164.9  | 113.2 | 29.8  | 26.25  | 75.3   | 50.7  | 16.2  |
| TPH            | 400   | 1200   | 885   | 190.4 | 300    | 1700   | 800   | 320   |
| QMD            | 29.8  | 46.6   | 40.2  | 4.0   | 19.3   | 42.4   | 29.1  | 5.4   |
| Seedlings ha⁻¹ | 0     | 2500   | 510   | 715.5 | 1300   | 16200  | 3650  | 3496  |
3.2. Deadwood

Compared to the managed Trojan fir–Scots pine forests, the unmanaged forest had significantly more SDW ha$^{-1}$ across the study stands ($P < 0.05$) (Figure 3a). The average number of SDW in the unmanaged Trojan fir–Scots pine forest was 175 trees ha$^{-1}$, while the average SDW was 22 trees ha$^{-1}$ in the managed forest. In the unmanaged forest, most of the SDW ha$^{-1}$ (97%) was in the categories of SD1 and SD2 (Figure 3a). No SDW in the SD3 category was sampled in the managed Trojan fir–Scots pine forest (Figure 3a). In terms of SDW size, there was an average of 40 trees ha$^{-1}$ larger than 36 cm in DBH in the unmanaged forest, while the average DBH of SDW was 11.3 cm in the managed forest. In the unmanaged forest, the average number of SDW larger than 50 cm in DBH was approximately 10 trees ha$^{-1}$. As for LDW volume, the unmanaged Trojan fir–Scots pine forest had significantly greater amounts of LDW ha$^{-1}$ than the managed forest ($P < 0.05$) (Figure 3b). Average LDW accumulation ranged from 2.4 to 345.2 m$^3$ ha$^{-1}$ in the unmanaged Trojan fir–Scots pine forest with an average of 76.88 m$^3$ ha$^{-1}$, while it ranged from 0 to 39.2 m$^3$ ha$^{-1}$ with an average of 11.3 m$^3$ ha$^{-1}$ in the managed forest. Most of the LDW (75%) was in the category of LDW1 in the unmanaged forest, while the amount of LDW1 in managed forest was negligible (Figure 3b).

4. Discussion

4.1. Stand structure

Old-growth forests typically possess higher biological diversity than intensively managed forests. Previous research has indicated that unmanaged forests present a greater number of old-growth structural attributes than managed forests (Angers et al., 2005; Keren and Diaci, 2018). Existing studies have also indicated that the reference conditions for old-growth forests may vary by forest type and species mixture. Youngblood et al. (2004) stated that old-growth ponderosa pine (*Pinus ponderosa* Douglas ex C.Lawson) forests contain about 14 live trees ha$^{-1}$ larger than 70 cm in DBH, as well as approximately 10 SDW ha$^{-1}$ larger than 50 cm in DBH. In similar studies, Goodburn and Lorimer (1999) found that old-growth northern hardwoods included about 10 live trees ha$^{-1}$ larger than 70 cm in DBH, while McGee et al. (1999) suggested that these old-growth forests should retain at least 6 live trees ha$^{-1}$ larger than 70 cm in DBH to emulate structural characteristics of old-growth forests. In another study, Siitonen et al. (2000) revealed that old-growth boreal mesic forests dominated by Norway spruce (*Picea abies* (L.) H.Karst.) contained about 25 live trees ha$^{-1}$ larger than 40 cm in DBH. In our study, the unmanaged Trojan fir–Scots pine forest had structures suggestive of old-growth characteristics, with approximately 30 live trees ha$^{-1}$ larger than 70 cm in DBH and 10 SDW ha$^{-1}$ larger than 50 cm in DBH. Higher stand BA is usually measured in old-growth forests compared to that found in managed forests. Keren et al. (2017) examined stand BA in old-
growth and managed European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.), and Norway spruce (*Picea abies* (L.) H.Karst.) forests in Bosnia and observed higher stand BA in the old-growth forests than in the managed forests. Managed Trojan fir–Scots pine forest presented a reverse J-shaped pattern, which is the typical structure of selection silviculture. The stand structure of mixed fir–pine stands managed using selection silviculture in previous studies conducted in Turkey (Yilmaz and Akay, 2008) is consistent with our findings.

Since mixed forests exhibit greater biodiversity than monocultures, the sustainability of mixed species stands is critical for forested ecosystems (Pretzsch et al., 2017). Although the managed Trojan fir–Scots pine forest possessed the expected diameter structure for the selection silviculture practiced (i.e. reverse J-shape), the lack of Scots pine trees in small and medium size classes may be a point of concern for the maintenance of a desired fir–pine mixture. Mixed Trojan fir–Scots pine forests are managed using single-tree selection silviculture under high stand densities in Turkey. Trojan fir is a very shade-tolerant tree species, while Scots pine is considered a shade-intolerant species. Thus, in the managed Trojan fir–Scots pine forest studied, a significant amount of advanced fir regeneration was present in the understory, while none or few Scots pine seedlings were observed. Thus, it is likely that the small-scale disturbances created by the VGDL method are not adequate to establish and recruit Scots pine seedlings in these forests. For this reason, conversion of these mixed forests into pure fir stands may not be surprising over the long term. Alternatively, the group selection method has been commonly employed in mixed forests composed of tolerant and intolerant tree species to maintain the mixture of these forests (Schlesinger, 1976; Battles et al., 2001; Grassi et al., 2004; Raymond et al., 2004). In this method, shade-intolerant species can be established in groups, while shade-tolerant species are maintained using single-tree selection cutting within the rest of the stand. For the management of mixed Trojan fir–Scots pine forests, as well as complete removal of vegetation in groups, group shelterwood with a canopy closure of 40% might be utilized in favor of Scots pine (Odabaşı et al., 2004). Current data suggest that the VGDL method currently used in mixed Trojan fir–Scots pine stands should be successful for the establishment of Trojan fir seedlings outside potential group selection openings in these forests.

### 4.2. Deadwood

Deadwood materials are essential for conservation, maintenance, and sustainability of biological diversity (Samuelsson et al., 1994). Although data from unmanaged forests are used as references to define the appropriate thresholds for managed forests, this information has been limited for many managed and unmanaged forests (Keren and Diaci, 2018), including the study region’s Trojan fir–Scots pine stands. The higher amount of deadwood in the unmanaged forest can be associated with the higher stand densities in these forests compared to the managed forest. Another reason for the lower amount of deadwood in the managed forest is that large trees are usually harvested during silvicultural activities in these forests. Significantly higher stand BA observed in the unmanaged forest of Trojan fir–Scots pine likely resulted in higher density-related tree mortality and, consequently, a greater amount of SDW and LDW. This is supported by previous research, such as that of Puhlick et al. (2016), stating that there is a correlation between live biomass and dead biomass in forests. In addition, it has been stated that high stand volume may increase the risk for insect damage, resulting

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**Figure 3.** Density (trees ha⁻¹) of standing dead trees (SDW) (a) and volume of lying deadwood (LDW) (m³ ha⁻¹) (b) in unmanaged and managed Trojan fir–Scots pine forests.
in an increasing amount of deadwood volume in the stand (Atici et al., 2008). Previous studies also substantiate our findings regarding the amount of deadwood in managed and unmanaged forests. Due to the lack of large trees in managed forests, the amount of deadwood is usually lower in these forests (Harmon et al., 1986) (Figure 4). In a similar study, Keren and Diaci (2018) monitored the deadwood components in mixed European beech–silver fir–Norway spruce forests and observed a greater amount of LDW in old-growth forests compared to managed forests subjected to selection silviculture. Moreover, Gauthier et al. (2018) monitored the numbers of SDW and LDW in managed and unmanaged sugar maple (Acer saccharum Marshall) forests, and they observed a greater amount of deadwood in the unmanaged forests.

We found larger SDW (>36 cm in DBH) in the unmanaged forest, while they were relatively small in DBH (average 11.3 cm) in the managed forest. This is likely due to the silvicultural method (i.e. single-tree selection with VGDL regulation) used in the managed forest. Similarly, Keren and Diaci (2018) examined the number of SDW ha$^{-1}$ in mixed European beech–silver fir–Norway spruce forests managed using selection silviculture and found that the SDW was mostly in small diameter classes in managed stands, while it was of all sizes in the old-growth stands. Large trees are commonly cut in selection methods to enhance future stand quality since they are considered less vigorous (Gauthier et al., 2018). Kunttu et al. (2015) stated that stands with more than 35 SDW ha$^{-1}$ represent strong continuity of deadwood, while less than 25 SDW suggests reduced continuity of deadwood. The average number of snags (i.e. 22 SDW ha$^{-1}$) in our managed Trojan fir–Scots pine forest was less than the minimum number of SDW suggested by Kunttu et al. (2015). Stokland (2001) reported that strong continuity of deadwood is usually provided by unmanaged forests. Our findings regarding the number of SDW substantiate previous research, such as that of Stokland (2001) and Kunttu et al. (2015). Müller and Bütler (2010) reviewed previous studies, which were conducted to determine the deadwood threshold values for different forest types across Europe, and stated that 20–50 m$^3$ ha$^{-1}$ of LDW is needed for ecosystem conservation. We monitored a substantial amount of LDW (i.e. about 77 m$^3$ ha$^{-1}$) in the unmanaged Trojan fir–Scots pine forest, while LDW in our managed forest was lower (i.e. about 12 m$^3$ ha$^{-1}$) than the minimum threshold recommended by Müller and Bütler (2010). Moreover, Gauthier et al. (2018) recommended a target LDW guideline of 65 m$^3$ ha$^{-1}$ to maintain biodiversity. Our unmanaged Trojan fir–Scots pine forest compares favorably to this LDW guideline, while the managed forest does not. Hence, current data suggest that further efforts are needed to develop additional numbers of large live and dead trees as well as LDW in managed Trojan fir–Scots pine forests. However, it should be noted that productivity and decomposition, and consequently the amount of deadwood, might be influenced by treatment (i.e. managed or unmanaged) as well as climate. Therefore, determination of minimum deadwood threshold values for the mixed Trojan fir–Scots pine forest is recommended.

The amount and type (i.e. SDW or LDW) of deadwood in a stand influences its potential biological diversity (Müller and Bütler, 2010). Even though unmanaged forests provide greater biological diversity than managed forests (Bauhus et al., 2009), previous research has revealed that biological diversity could be maintained using silvicultural prescriptions that manage forests as complex biological systems and aim to retain large trees in selection silvicultural methods (Goodburn and Lorimer, 1998; Kerr, 1999; Ciancio and Nocentini, 2011). There has been increasing interest in silvicultural practices that enhance deadwood components in managed forests (Christensen et al., 2005; Marage and Lemperiere, 2005). Thus, retention of large trees in managed Trojan fir–Scots
pine forests could have a favorable long-term impact on the number and amount of deadwood in these forests. In addition, Gauthier et al. (2018) suggested that minimum deadwood requirements for suitable wildlife habitats could be met in managed stands through appropriate retention practices. However, it is also worth noting that maintaining large legacy trees may have an economic impact, since Trojan fir and Scots pine trees are considered two of the most economically important tree species in Turkey (Odabaşı et al., 2004). More research is needed to determine the appropriate stand density level to maintain adequate numbers of large trees while producing high quality timber in mixed Trojan fir–Scots pine forests.

In conclusion, the stand structure, density, and volume of deadwood components of managed and unmanaged Trojan fir–Scots pine forests were examined in this study. Compared to the managed forest, the unmanaged forest had a greater amount of large live trees, SDW, and LDW.

Current data reveal the importance of large tree retention during silvicultural treatments in mixed Trojan fir–Scots pine forests. It should be noted that the plot size of 100 m² used in this study may be considered relatively small to determine the stand structure of an old growth stand (Keren and Diaci, 2018). In small plots, it is likely that one or two large trees can fill this size of a plot, and the estimation of the number of larger trees may be less precise. Based on visual observations, large trees are well distributed across the study area, mitigating the negative influence of the small size of plots. Nevertheless, a larger size for study plots is recommended for further inventories in the research area. Our findings suggest that particular attention should be given to the current silvicultural treatments and retention patterns used in these forests. Further research on the use of group selection in these mixed forests may be recommended for enhancing deadwood components and to increase recruitment of Scots pine. Findings obtained in this study will be helpful for forest managers to enhance and maintain key components of structural complexity linked with biological diversity and to promote the establishment and sustainability of mixed Trojan fir–Scots pine forests.

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