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Research Article

The Role of Tree Diameter in Mortality Risks During Resin Production in *Pinus brutia*

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Abstract

Aim of study: In this study, the effects of bark streak tapping resin extraction on tree mortality risk and survival rates across diameter classes in *Pinus brutia* forests are looked into.

Area of study: Research was conducted in the Korudağ Forest Sub-District, Keşan Forestry Department, and Çanakkale Forest Regional Directorate in Türkiye.

Material and method: We monitored 396 trees for 17 months, extracting resin every 15 days. We used Kaplan-Meier survival analysis to assess the mortality risks for three diameter classes: pole stage (8-19.9 cm), small wood (20-35.9 cm), and mature (36-51.9 cm.)

Main results: Smaller-diameter trees (8-19.9 cm) exhibited the highest mortality risk with a survival rate of 71.1%, while medium-diameter trees (20-35.9 cm) had a survival rate of 93.2%, and larger-diameter trees (36-51.9 cm) showed complete survival. Overall, 41 trees (89.6%) died, with significant differences in survival probabilities among diameter classes.

Research highlights: Smaller-diameter trees are more vulnerable to mortality during resin tapping, underscoring the need for sustainable management strategies.

Keywords: Forest Conservation, Kaplan-Meier Survival Analysis, Mortality Risk, *Pinus brutia*, Resin tapping, Sustainable Forest Management, Diameter Classes, Tree Mortality

Kızılçamda (*Pinus brutia*) Reçine Üretiminin Ağaç Ölüm Oranına Etkisi

Öz

Çalışmanın amacı: Bu çalışmada, kızılçam (*Pinus brutia*) ormanlarında açık yara yöntemiyle yapılan reçine üretiminin ağaçların kuruma riski ve farklı çap sınıflarındaki yaşama oranları üzerindeki etkileri incelenmiştir.

Çalışma alanı: Araştırma, Türkiye'nin Çanakkale Orman Bölge Müdürlüğü, Keşan Orman İşletme Müdürlüğü'ne bağlı Korudağ Orman İşletme Şefliği sınırlarında gerçekleştirilmiştir.

Materyal ve yöntem: 396 ağaç, 15 günde bir reçine üretilerek 17 ay boyunca izlenmiştir. Kuruma risklerini değerlendirmek için Kaplan-Meier yaşama analizi kullanılmış ve ağaçlar üç çap sınıfına ayrılmıştır: sırıklık ve direklik (8-19.9 cm), ince ağaçlık (20-35.9 cm) ve orta ağaçlık (36-51.9 cm)

Temel sonuçlar: Küçük çaplı ağaçlar (8-19.9 cm) %71.1 yaşama oranı ile en yüksek kuruma riskini göstermiştir. Orta çaplı ağaçlarda (20-35.9 cm) yaşama oranı %93.2 iken, büyük çaplı ağaçlar (36-51.9 cm) tamamen hayatta kalmıştır. Genel olarak, çap sınıfları arasında önemli farklılıklarla birlikte toplamda 41 ağaç (%89.6) kurumuştur.

Araştırma vurguları: Küçük çaplı ağaçlar, açık yara yöntemiyle yapılan reçine üretimi sırasında kuruma riskine daha duyarlıdır ve bu durum sürdürülebilir yönetim stratejilerinin gerekliliğini ortaya koymaktadır.

Anahtar Kelimeler: Orman Koruma, Kaplan-Meier Yaşama Analizi, Kuruma Riski, *Pinus brutia*, Reçine Üretimi, Sürdürülebilir Orman Yönetimi, Çap Sınıfları, Ağaç Ölümü

Introduction

Various factors shape forest health and vitality, including climate change (e.g., temperature increases, irregular precipitation, and drought), biotic stressors (e.g., pests, diseases, and invasive species), and abiotic stressors (e.g., wildfires, storms, and extreme weather events).

In addition, anthropogenic pressures, including illegal logging, overgrazing,

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agricultural expansion, urbanization, and unsustainable forestry practices, also threaten forest health (FAO, 2010). Among these factors, resin extraction can act as an anthropogenic stressor, influencing tree growth and defense responses depending on the method used (Rodríguez-García et al., 2016). Unsustainable tapping practices, such as deep incisions and excessive wounding, can reduce growth ring width and impact resin canal formation. Mechanized tapping, for instance, resulted in lower resin yield and did not significantly enhance defensive responses compared to traditional methods (Rodríguez-García et al., 2016). In contrast, sustainable approaches, such as upward tapping with traditional tools, were found to optimize resin yield while promoting the formation of resin canals, which play a key role in tree defense. This method induced a systemic response with increased resin canal frequency and area, supporting both productivity and tree health (Rodríguez-García et al., 2016).

In Mediterranean ecosystems, gymnosperms dominate semi-arid forests. Although they exhibit low drought resistance, they have a notable capacity for rapid recovery after drought events (Gazol et al., 2018). Within this region, *Pinus brutia* forests account for 25% of Türkiye's forest ecosystems and are notable for their extensive distribution and ecological resilience in the Mediterranean climate (GDF, 2019). As a fire-adapted species, *Pinus brutia* demonstrates robust natural regeneration following wildfires (Boydak, 2004). Moreover, it holds significant ecological and economic value due to its resin production potential (Caglayan et al., 2024).

Despite its historical importance, resin production in *Pinus brutia* forests has significantly declined since the 1980s, as management practices shifted focus to timber production (GDF, 2017). Resin production has long served as an important revenue source for the forestry sector, particularly in supporting rural economies (FAO, 2003). However, limited information exists regarding the long-term impacts of resin extraction methods on tree vitality and ecosystem dynamics. Addressing this knowledge gap is critical to developing sustainable forest management strategies that align economic objectives with ecological integrity.

Resin, an integral part of gymnosperms' natural defense mechanisms (Pearce, 1996; Trapp & Croteau, 2001; Garcia-Forner et al., 2021), is not only vital for tree survival but also holds economic significance (Rodrigues-Corrêa et al., 2012) through resin extraction. However, the methods used during resin tapping can have profound implications for tree health and longevity. For instance, Zevgolis et al. (2022) demonstrated that resin extraction in *Pinus brutia* reduces tree growth and increases susceptibility to fungal infections, significantly influencing forest dynamics and management strategies. Moreover, resin tapping adversely affects natural regeneration by decreasing viable seed production (Eshete et al., 2012). Additionally, Calama et al. (2024) reported that resin extraction impairs the ability of trees to cope with water stress, further reducing survival rates. Studies indicate that resin extraction imposes physiological stress on trees, diminishing growth rates, crown size, and diameter (Yousefi et al., 2020). Additionally, mechanical damage caused by tapping may concentrate growth in remaining live parts, potentially exacerbating physiological stress (van der Maaten et al., 2017). Despite its ecological and economic importance, studies investigating the long-term impacts of resin extraction on tree health and mortality remain limited. Existing research predominantly focuses on resin yield, leaving critical questions about sustainable management unanswered. Addressing these gaps is essential to ensure the resilience and sustainability of forest ecosystems in the context of resin production.

Sulfuric acid has been shown to increase resin yield (Daltry et al., 2015) however, its implications for tree mortality and decay remain poorly understood. For instance, Daltry et al. (2015) studied *Protium attenuatum* and indicated that while sulfuric acid application does not impair tree growth or overall health, the use of deeper incisions and larger wound surfaces significantly increases the risk of decay and mortality. In addition to external interventions, intrinsic tree traits such as resin canal size play a critical role in defense mechanisms (Krokene & Nagy, 2012). Lodgepole pines with larger resin canals, for example, exhibit higher survival rates against mountain pine beetle infestations, highlighting the importance of these anatomical features in tree resilience (Zhao & Erbilgin, 2019). However, external stressors such as climate change exacerbate the challenges faced by resin-producing trees. Prolonged drought and rising temperatures threaten their health, leading to widespread mortality and the loss of essential ecosystem services (Allen, 2009). These findings collectively emphasize the need for sustainable resin extraction practices that account for both physiological and environmental stressors to ensure long-term forest health and resilience.

This study aimed to investigate the long-term effects of resin production on the health of *Pinus brutia* trees, focusing on mortality risks associated with different diameter classes. To achieve this, Kaplan-Meier survival analysis was employed, offering a robust framework for evaluating tree survival over time. The research was conducted in red pine forests located within the Çanakkale Forest Regional Directorate in Türkiye. A total of 396 trees subjected to resin tapping using the open wound method were monitored over a 17-month period.

Material and Methods

Study area

The study was conducted in *Pinus brutia* forests located within the Korudağ forest sub-district directorate, Keşan Forestry Department, and Çanakkale Forest Regional Directorate in Türkiye (Figure 1). The study area has a typical Mediterranean climate, with an annual average temperatures ranging from 1.4°C to 28.6°C and an average annual precipitation of 675.5 mm (Caglayan et al., 2024). The sample plots included 396 trees classified into three diameter classes: pole stage (8-19.9 cm), small wood (20-35.9 cm), and mature (36-51.9 cm) (Caglayan et al., 2024). These diameter classes are based on standard forestry practices used in Türkiye, reflecting the developmental stages of stands.

We extracted resin using the bark streak tapping method at 15-day intervals from November 2022 to November 2023, and additionally from May to September 2024. During resin production, we applied a sulfuric acid-based paste every 15 days (Caglayan et al., 2024). We monitored tree mortality across diameter classes over the 17-month study and compared the mortality risks between these classes.

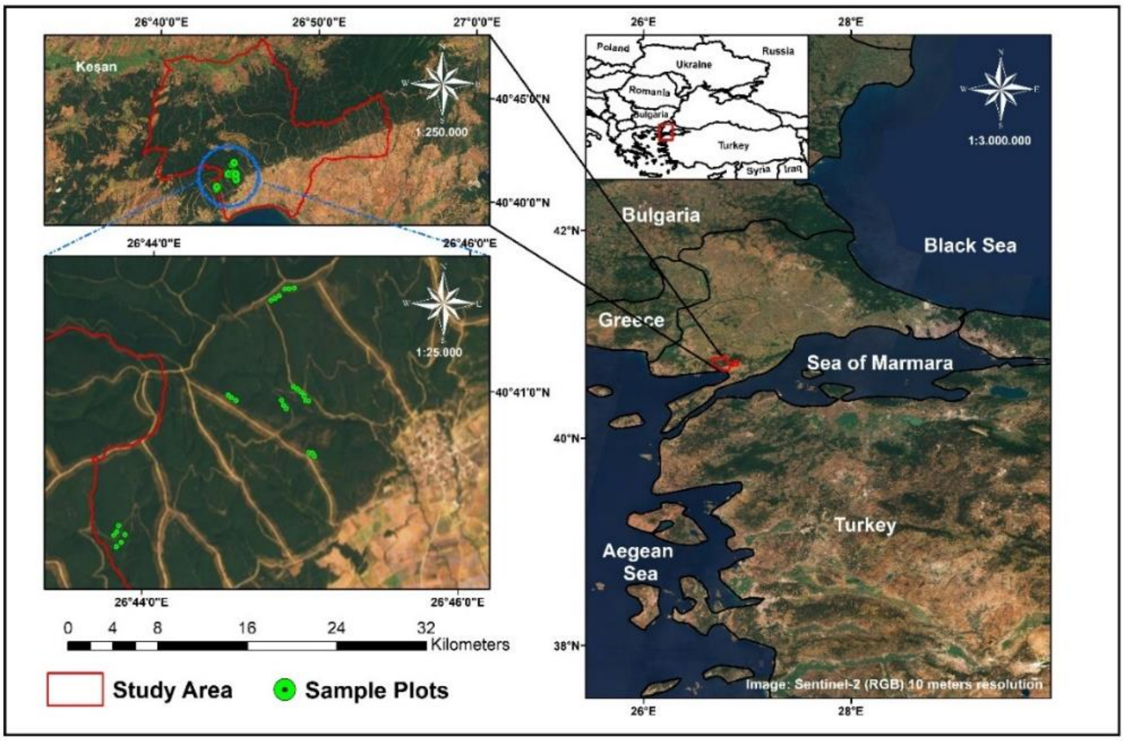

Figure 1. Study Area in Korudağ Forest, Edirne, Türkiye (Caglayan et al., 2024)

Statistical Analysis

To investigate the survival times of resin-tapped trees and assess mortality risks across diameter classes, Kaplan-Meier survival analysis was employed due to its robustness in accounting for event timing and censored data (Kaplan & Meier, 1958). This method estimates survival probabilities over time by incorporating both completed events (e.g., tree mortality) and censored observations (e.g., trees that survived during the study period). Survival curves were generated for each diameter class, and the statistical significance of differences among these groups was evaluated using the Log-Rank (Mantel-Cox) test. This method enabled a detailed comparison of survival probabilities while considering the timing of mortality events.

The dependent variable was the survival time of each tree, measured as the duration from the start of observation to the occurrence of mortality. Trees that did not exhibit mortality during the study period were treated as censored observations, indicated by a "+" symbol in the survival curves. The independent variable was tree diameter class, categorized into three groups: 8-19.9 cm, 20-35.9 cm, and 36-51.9 cm.

We used Kaplan-Meier survival curves to estimate the survival probabilities over time for each diameter class. The Log-Rank (Mantel-Cox) test was used to evaluate the statistical significance of differences in survival probabilities among the three diameter classes. This test compares the survival distributions of multiple groups over time and is particularly suitable for censored data.

All analyses were performed using IBM SPSS Statistics (Version 29).

Results

Kaplan-Meier survival analysis

A Kaplan-Meier survival analysis of 396 *Pinus brutia* trees revealed significant differences in survival probabilities across diameter classes. During the 17-month study, 41 trees died, while 355 survived, yielding an overall survival rate of 89.6%.

Table 1. Mortality and Survival Rates by Diameter Class

Diameter Class (cm)	Category	Total Trees	Mortality (Count)*	Censored (Survived) Count**	Censored (Survived) Percentage (%)***
20-35.9 (c)	Small wood	281	19	262	93.2%
36-51.9 (d)	Mature	39	0	39	100%
8-19.9 (b)	Pole stage	76	22	54	71.1%
Overall Total	-	396	41	355	89.6%

*The number of trees that died during the study period within each diameter class.
**The number of trees that remained alive at the end of the study period but were not removed from the analysis.
***The proportion of trees that survived within each diameter class relative to the total number of trees in that class.

Table 1 summarizes the mortality and survival rates across diameter classes during the study. Pole stage trees (8-19.9 cm) had the highest mortality risk, with a survival rate of 71.1%. small wood trees (20-35.9 cm) exhibited a 93.2% survival rate, while mature trees (36-51.9 cm) showed no mortality, achieving 100% survival.

8-19.9 cm Diameter Class: Of the 76 trees in this class, 22 died during the study, resulting in a survival rate of 71.1%. The first mortality event occurred in the 6th month, highlighting a higher vulnerability in this group.

20-35.9 cm Diameter Class: Among the 281 trees, 19 experienced mortality, with a survival rate of 93.2%. The first mortality event was observed in the 9th month, indicating moderate resilience in this group.

36-51.9 cm Diameter Class: All 39 trees in this class survived throughout the 17-month study, with no mortality observed, indicating complete resilience to resin tapping.

Log-Rank Test Results

Log-Rank test comparisons of survival curves revealed statistically significant differences among the diameter classes (χ^2 =38.878, df = 2, p < 0.001). These results underscore that tree size is a critical factor influencing mortality risk.

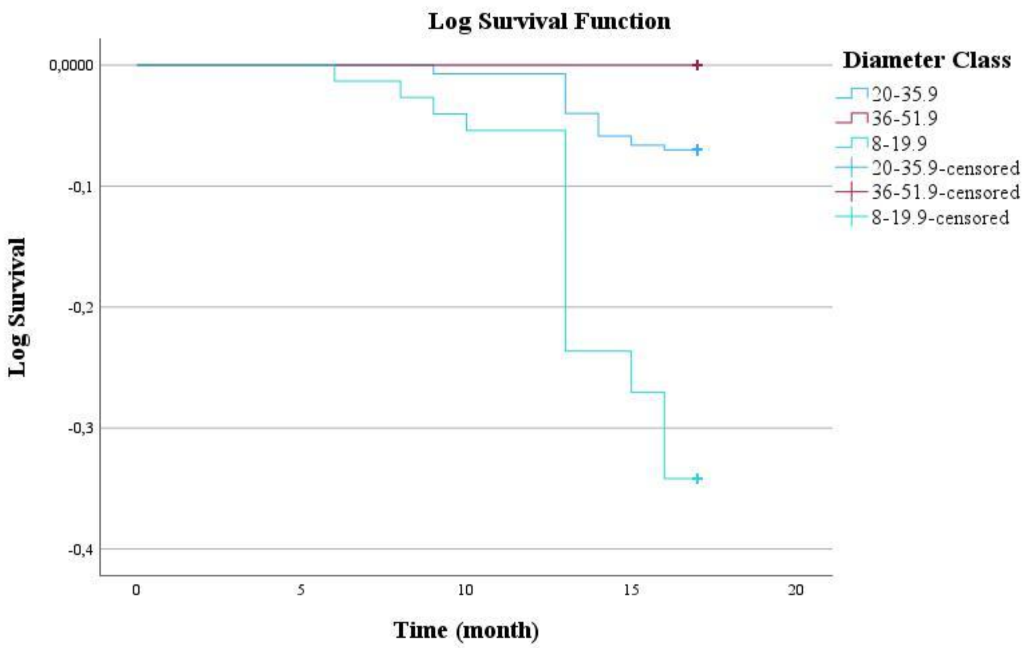

Figure 2. Logarithmic Survival Function

Figure 2 presents the logarithmic survival functions of trees across different diameter classes (8-19.9 cm, 20-35.9 cm, and 36-51.9 cm), offering a detailed depiction of mortality risks and survival probabilities over the study period. The X-axis represents time in months, starting from the beginning of the observation period and progressing until the end of the study. The Y-axis represents the logarithmic transformation of survival probabilities, where lower values indicate higher mortality risks. This visualization highlights the significant differences in tree survival dynamics during resin tapping based on diameter class.

Trees in the 8-19.9 cm diameter class exhibited earlier mortality, with survival probabilities declining sharply after the 10th month. By the 17th month, this class has experienced a substantial drop in the logarithmic survival function, indicating higher vulnerability to resin tapping. Conversely, the 20-35.9 cm diameter class experienced its first mortality in the 9th month but maintained relatively stable survival probabilities overall. By the end of the 17-month period, this class preserves much of its survival potential, reflecting moderate resilience.

The 36-51.9 cm diameter class showed no mortality during the study, as reflected by a flat survival curve and a 100% survival probability. This complete resilience to resin tapping underscores the greater robustness of larger-diameter trees, even under the physiological and environmental stresses associated with resin extraction.

The graph also includes censored observations, marked by "+" symbols, representing trees that survived until the end of the study period without mortality. These censored points are critical in survival analysis, as they indicate the presence of trees that remain alive, even though they were subjected to resin tapping stress. These censored points are distributed across all diameter classes, with a higher concentration in the larger-diameter classes, aligning with their superior survival rates.

The results depicted in Figure 1 reveal significant differences in mortality risks across diameter classes, as corroborated by statistical analysis (Log-Rank test, $p < 0.001$). Smaller-diameter trees (8-19.9 cm) face substantially higher mortality risks, while larger-diameter trees (36-51.9 cm) demonstrate complete resilience.

Discussions

This study verified the impact of resin extraction on the tree mortality risk and survival across different diameter classes of *Pinus brutia.* The findings highlight significant variations in mortality risks associated with tree diameter during the resin production process. The Kaplan-Meier survival analysis, combined with Log-Rank test results, confirmed statistically significant differences in survival probabilities among the diameter classes ($p < 0.05$). The analysis indicates that smaller-diameter trees face disproportionately higher mortality risks compared to their medium and larger-diameter counterparts, which exhibited greater resilience under similar conditions.

Results indicated significant variability in survival rates across diameter classes, with smaller trees showing the lowest survival and larger trees exhibiting complete resilience. These findings provide a critical basis for understanding the role of tree size in resilience to resin tapping. Daltry et al. (2015) highlighted that sustainable resin production methods, such as the repeated tapping of larger-diameter trees and the application of stimulants like sulfuric acid, can significantly enhance resin yields without negatively impacting tree health when applied under controlled conditions. However, traditional methods involving improper techniques, larger wounds, or inadequate management can slow tree growth, increase susceptibility to infections, and lead to higher mortality rates (Daltry et al., 2015).

The findings highlight the critical relationship between tree diameter and survival during resin tapping, demonstrating that smaller trees are more vulnerable to mortality. These results offer valuable insights into the long-term impacts of resin production on tree health and provide a foundation for developing sustainable forest management strategies.

Furthermore, it underscores the need for less invasive, more efficient extraction methods to reduce ecological damage and sustain tree health. For example, minimizing the size and depth of wounds and using chemical stimulants like sulfuric acid in controlled amounts have been shown to improve resin yield while reducing stress on trees (Daltry et al., 2015; Rodríguez-García et al., 2016). Such practices are essential for maintaining the long-term productivity and health of resin-tapped forests. Larger-diameter trees demonstrated complete resilience, likely due to their greater biological reserves and robust defense mechanisms, as noted by (Boone et al., 2011). Similarly, our study showed that larger-diameter trees exhibited complete survival, reinforcing the role of tree size in resilience. Additionally, Carbon storage is crucial for tree survival under stress, especially in larger trees with greater reserves (Wiley, 2020). Drought-induced tree mortality, primarily driven by hydraulic failure and non-structural carbohydrate depletion, has been widely observed across forested ecosystems (Adams et al., 2017). Additionally, carbon allocation plays a key role in plant responses to environmental changes, influencing secondary metabolites that contribute to defense mechanisms (Huang et al., 2020). Mediterranean forests are among the most sensitive biomes to drought-induced mortality (Calama et al., 2024), with increased temperatures and severe droughts leading to heightened water stress, carbon starvation, and weakened tree defenses (Gaylord et al., 2013; Hammond et al., 2022).

Daltry et al. (2015) highlights the benefits of sustainable resin harvesting techniques, such as using sulphuric acid stimulants and shallow, periodic cuts, to significantly increase resin yield while maintaining tree health. It emphasizes the importance of training and licensing tappers, focusing on mature trees, and implementing rest periods to balance economic gains with long-term forest conservation.

Previous research has highlighted the interplay between stand age, tree size, and environmental conditions in governing the resilience of pines subjected to resin extraction. For instance, Moura et al. (2023) observed that older *Pinus pinaster* stands experienced negligible growth reductions following resin tapping, whereas younger stands with lower physiological reserves showed reduced radial growth. Similarly, Génova et al. (2014) found that historical resin extraction did not significantly alter long-term tree-ring growth patterns in *Pinus pinaster*, suggesting that well-established trees can maintain growth and climate responsiveness even under intensive tapping regimes. In contrast, Zeng et al. (2021) reported that tapped *Pinus tabuliformis* exhibited asymmetrical growth, with narrower rings on the tapped side and heightened vulnerability to drought stress indicating that compromised water and nutrient transport may exacerbate environmental sensitivities. In line with these findings, López-Álvarez et al. (2023) emphasized the crucial role of dendrometric traits, particularly diameter at breast height, in predicting both resin yield and tree resilience. Taken together, these studies converge on the notion that larger, physiologically robust individuals are better equipped to withstand the stress associated with resin extraction, whereas smaller-diameter trees are more susceptible due to limited reserves and lower tolerance to water and nutrient constraints.

Conclusions

This study underscores the complex interplay between resin extraction methods, tree diameter, and external factors in determining tree health and mortality risks. Smaller-diameter trees were more susceptible to resin tapping due to their limited reserves and weaker defenses, while larger-diameter trees demonstrated higher resilience, likely supported by their robust physiological capacities. These results highlight the ecological impacts of resin production and the critical role of tree size in shaping resilience to extraction stresses.

The findings call for the adoption of less invasive and more sustainable resin extraction methods to mitigate ecological damage and promote forest health. Protecting smaller-diameter trees and implementing practices that minimize wounding and recovery time stress can reduce mortality risks while ensuring sustainable productivity. Addressing external stressors, such as climate-induced drought and temperature fluctuations, is equally important, as these factors exacerbate tree vulnerability during resin production.

Future research should focus on optimizing resin extraction techniques across diameter classes, investigating the long-term impacts of resin tapping on tree growth, carbon sequestration, and ecosystem sustainability. Additionally, exploring the interactions between resin production, drought stress, and biotic factors will provide valuable insights into the broader ecological implications of these practices. By integrating innovative methods and environmental considerations, forest managers can achieve a balance between economic productivity and ecological sustainability, ensuring the long-term health and resilience of resin-producing forests.

Ethics Committee Approval
N/A

Peer-review
Apparently reviewed

Author Contributions
Conceptualization, Investigation, Material and Methodology, Visualization, Writing-Original Draft, Writing-review & Editing: İ.C., The entire authors have seen and accepted to publish the version of manuscript.

Conflict of Interest
The authors declare that they have no conflict of interest.

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