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Impact of Temperature Inversion on the Distribution Shifts of Turkish Red Pine (*Pinus brutia* Ten.) and Black Pine (*Pinus nigra* Arnold.) in the Karıncalı Region, Bursa – Orhaneli

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ABSTRACT

Topographic diversity leads to climate and vegetation differences over short distances. A significant example of these differences is temperature inversion, where cold air accumulates in hollows and concave areas, resulting in lower temperatures in lower zones and affecting the distribution limits of plant species. In this study conducted in the Karıncalı region of Orhaneli, Bursa, the effect of temperature inversion on the natural distribution of Turkish red pine (*Pinus brutia* Ten.) and black pine (*Pinus nigra* Arnold.) stands was investigated. Measurements made with temperature sensors placed between 500-600 m altitude for two years showed that although black pine is generally distributed at higher altitudes, it is located below the red pine zones due to temperature inversion. Especially in the lower zones, recorded low temperatures have revealed the cold adaptation advantage of black pine. Temperature inversion affects the distribution limits of plant species, reshaping ecosystem structure and interspecies competition. This highlights the necessity of considering temperature inversion areas in forestry activities. In reforestation projects to be carried out in areas where inversion conditions are effective, the selection of cold-resistant species is of vital importance for the success of the applications.

Keywords: frost hollow; vegetation inversion; adaptation; biodiversity; afforestation

INTRODUCTION

Forest ecosystems are dynamic structures that are constantly changing under the influence of climatic and topographic factors. Microclimatic events have profound effects on the components of these ecosystems, playing a decisive role in the distribution of vegetation, growth performance of species and overall ecosystem balance. Among these microclimatic events, temperature inversion is a critical phenomenon for forest ecosystems, especially in mountainous and rugged terrains (Zhong et al. 2003, Whiteman et al. 2004). Temperature inversion occurs when cold air masses accumulate in hollows, valleys and other low-altitude areas. This phenomenon is especially intense during cloudless night hours and winter months and greatly affects ecological processes in forest ecosystems (Atalay 2008, Lareau et al. 2013, Yılmaz et al. 2021).

The effects of temperature inversion on forest ecosystems are manifested in a wide range of areas, from the distribution and growth rate of plant species to the germination of seeds and survival rates of seedlings (Hough 1945, Bárány-Kevei 1999, Oğurlu and Avcı 1999). This effect can lead to frost damage to plants due to the accumulation of cold air, especially in low-altitude areas such as hollows and valleys. As a result, some plant species become more advantageous in certain microhabitats, while the survival and competitive abilities of other species are limited (Geiger et al. 1995, Whiteman et al. 1999, Barry and Chorley 2009). Temperature inversion can shape interspecific competition by affecting the upper and lower limits of plant species, thereby significantly altering the species diversity and structure of forest ecosystems (Zhong et al. 2003).

Temperature inversion is also of great importance for forest management. Especially in forest restoration and afforestation projects, applications without considering the effects of temperature inversion may not achieve the expected results. For example, young seedlings in frost hollows can be severely damaged by cold air, which can reduce the growth rate of seedlings and reduce the effectiveness of forest restoration (Oğurlu and Avcı 1999). Therefore, predicting the effects of temperature inversion and developing management strategies accordingly is essential for sustainable forest management (Atalay 2015).

Temperature inversion can affect soil temperatures through the accumulation of cold air masses, which can alter soil structure and microbial activities, thus becoming an important factor affecting plant growth and overall forest health (Whiteman et al. 1999, Atalay 2015). These microclimatic differences affect the composition of forest ecosystems by reshaping the competitive relationships of plant species. Cold-tolerant species may gain an advantage in areas where temperature inversion is common, while more temperature-sensitive species may be forced to retreat from these areas (Zhong et al. 2003). This alters local species composition and may have long-term effects on ecological balance (Whiteman et al. 2004).

Red pine (5.212.292 ha) and black pine (4.199.623 ha) constitute approximately 41.5% of Türkiye's forests (OGM, 2021). These two species encounter and occasionally mix with each other in an indented belt thousands of kilometers long in the Mediterranean, Aegean, Marmara and Western Black Sea regions of Türkiye throughout their natural distribution. The encounter belt varies between 500 m and 1200 m from the north to the south of the country, depending on the local site conditions. Red pine is found in the lower altitudes where the Mediterranean climate prevails, while black pine is found in the cooler upper altitudes and in continental climate conditions. There are also some rare sites where these two tree species replace each other vertically around the encounter zone due to temperature inversion. On the other hand, one of the critical areas where climate change is expected to have a significant impact on the competition and boundaries of tree species in Türkiye's forests in the long term is the region where red pine and black pine meet.

In Turkish forest ecosystems, microhabitats where temperature inversion is evident are common. Temperature inversions can be effective in small areas as well as in very large areas. Bursa Orhaneli is a region where ecological and climatic variations are observed at close distances due to its geographical location and topographic structure. The region is under the influence of Mediterranean and continental transition climates and has a transitional ecosystem where different plant species coexist. The mountainous structure of Orhaneli causes the formation of various microclimatic areas and these areas make the effects of temperature inversion more apparent in places.

The Karıncalı region of the Orhaneli district is one of the special regions where the effects of temperature inversion are observed. The effects of temperature inversion are clearly observed in the red pine (*Pinus brutia* Ten.) and black pine (*Pinus nigra* Arnold.) stands in this location. Black pine, generally located at higher altitudes, has descended to lower altitudes due to the effect of temperature inversion and has started to share the same habitat with red pine, and even its natural distribution has decreased below red pine at some places. The local dynamic competition between the two species continues at the upper limit of the red pine zone (700-800 m) and at the lower limit of the red pine zone in areas where there is a temperature inversion.

Black pine is more resistant to frost than red pine. Therefore, it is distributed in the upper zone. Although it varies according to the origin, frost damage to red pine starts at -15 to -17.5°C and fatal frost damage starts at about -20°C (Yildiz et al. 2014, Semerci et al. 2019). The frost effect temperature in black pine varies between -23.3 and -28.8°C (Bannister and Neuner 2001, Kreyling et al. 2012).

This study aims to investigate the effects of temperature inversion on the natural distribution of red pine and black pine stands in the Karıncalı region of the Orhaneli district in the Bursa province. In particular, the study addresses the placement of black pine in lower zones than red pine due to temperature inversion and the relationship between this placement and temperature. Within the framework of the research, temperature measurements were recorded for two years and the inversion phenomenon in the location and its effect on the distribution of tree species were investigated.

MATERIALS AND METHODS

Study Area

This study was carried out in red pine (*Pinus brutia* Ten.) and black pine (*Pinus nigra* Arnold.) stands located at 500-600 meters altitude in the Karıncalı region of the Orhaneli district in the Bursa province (Figure 1). The region has a rich biodiversity due to topographic diversity and the coexistence of different plant species (Bağçıvan and Daşkın 2020). The vegetation inversion caused by the effect of temperature inversion is clearly observed in the field (Figure 2).

Sensor Placement and Installation

The study aimed to understand the effects of temperature inversion on the intersection zone of red pine and black pine stands. For this purpose, sensors were placed at the points determined on the vertical section to monitor microclimatic changes and temperature fluctuations in the field. A total of six temperature (T) sensors were placed every 20 meters, especially in the 100-meter elevation zone between 500 meters and 600 meters (Figure 3). GPS devices (Magellan Explorist 310 and Garmin GPSMAP 62s, with an accuracy ±1 meter) were used to accurately locate the sensors according to the coordinates (39°59'21.1"N 28°53'04.6"E).

All temperature sensors (T1-T6) were mounted 5 meters above the ground of each tree in the same row to monitor air temperatures. The HOBO U12-012 sensor was used for its ±0.35°C accuracy, operating temperature range of –20°C to 70°C, and durable, weather-resistant design, making it ideal for monitoring parameters in different elevation zones. Each sensor is sensitive to atmospheric pressure, waterproof, and can measure accurately a wide temperature range (Figure 4):

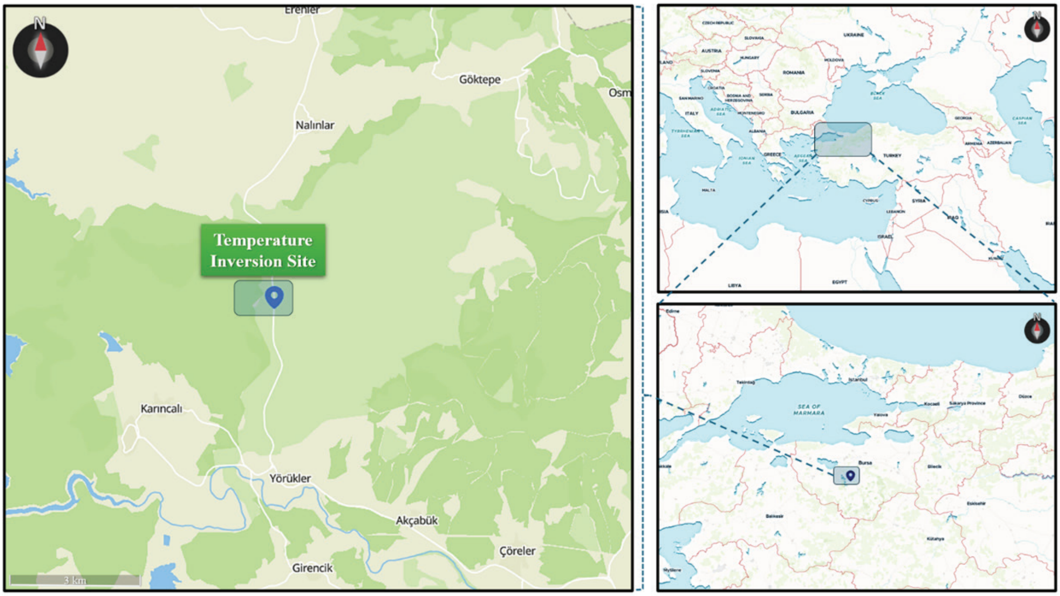

Figure 1. Temperature inversion site in the Karıncalı region of Orhaneli, Bursa.

Figure 2. Distribution of red pine (light green) and black pine (dark green) stands in the area.

- T1 and T2: The first two sensors were placed at lower parts of the forest (500 m and 520 m, respectively). These sensors recorded the microclimatic conditions in the areas where black pine stands are located;
- T3 and T4: These sensors were placed in the transitional layer between larch and red pine at mid-altitudes (540 m, 560 m). This area is where competition between the two species is most intense;
- T5 and T6: These two sensors monitored the temperature changes in the upper zones (580 m, 600 m) where the red pine stands spread.

Data Collection and Analysis

Data collection started in December 2020 and was completed in June 2022. Throughout this process, the sensors automatically recorded temperature values every 30 minutes, which were aggregated daily and made available for analysis.

The collected data were analyzed and graphed in Microsoft Excel. Data analysis was performed on parameters such as absolute maximum, absolute minimum and average temperature. In addition, the potential effects of temperature values on red pine and black pine stands were evaluated.

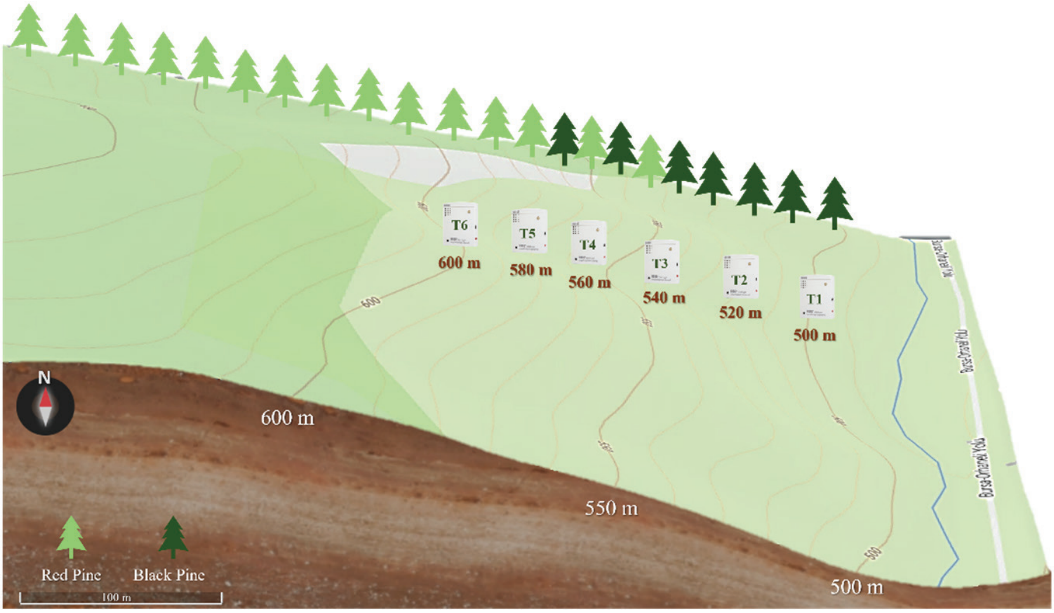

Figure 3. Contour map of red pine and black pine stands.

Figure 4. Placement of the temperature sensors.

RESULTS

The effects of temperature inversion on the intersection of red pine (*P. brutia*) and black pine (*P. nigra*) stands in the Karıncalı region of the Orhaneli district, Bursa, were investigated in this study. As an unusual situation in the area where temperature measurements were recorded, the black pine stand is located at lower altitudes than the red pine stand. In the scope of the study, temperature data obtained by sensors located at different altitude zones provide an insight into the transitions between these two species at short distances. Temperature inversion is investigated in this study as a phenomenon that is frequently observed, especially in mountainous and rugged terrains and is occasionally a determinant factor in forest ecosystems.

Regarding the minimum temperature data, significantly lower temperatures were recorded in the lower zones in black pine stands. Especially in January 2021, extremely low temperatures of -18.4°C and -18.1°C were measured at sensors T1 and T2, respectively. Minimum temperatures of -17.1°C, -16.4°C, -15.3°C, and -14.8°C were recorded at sensors T3, T4, T5, and T6, respectively. (Figure 5). These results indicate that temperature inversion increases the risk of frost in the lower zones. In these microhabitats, where frost conditions are so severe, the resistance of black pine to cold stress becomes prominent, while red pine remains vulnerable to these conditions. This may negatively affect the growth rate and survival of red pine stands, while black pine has shown to be better adapted to cold weather conditions.

When the maximum temperature data obtained were analyzed, it was observed that the temperatures measured at the sensors located in the upper zones where red pine stands spread were generally higher than the other zones. The highest temperature value recorded was 43.6°C in August at the T6 sensor where the red pine stands were located. On the other hand, the highest temperature of 38.5°C was recorded at sensor T1 in black pine stands, while high temperatures of 39.7°C and 41.0°C were observed at sensors T2 and T3, respectively (Figure 6). The cold air masses accumulated in the lower zones caused the maximum temperatures to remain relatively low, while the red pine stands in the upper zones are in an advantageous position in terms of temperature adaptation.

In the analysis of average temperature values, the values were higher in areas with red pine stands than in areas with black pine stands. For instance, in January 2022, the average temperatures recorded as 2.8°C and 3.0°C at sensors T5 and T6, respectively, were measured as 1.4°C at sensor T1. Similarly, in August 2021, the average temperatures recorded as 25.5°C and 25.8°C at sensors T5 and T6, respectively, were measured as 22.7°C at sensor T1 (Figure 7). The data obtained show that the subzones where black pine stands are located are exposed to lower average temperatures due to temperature inversion, which is decisive in the positioning and development of the species.

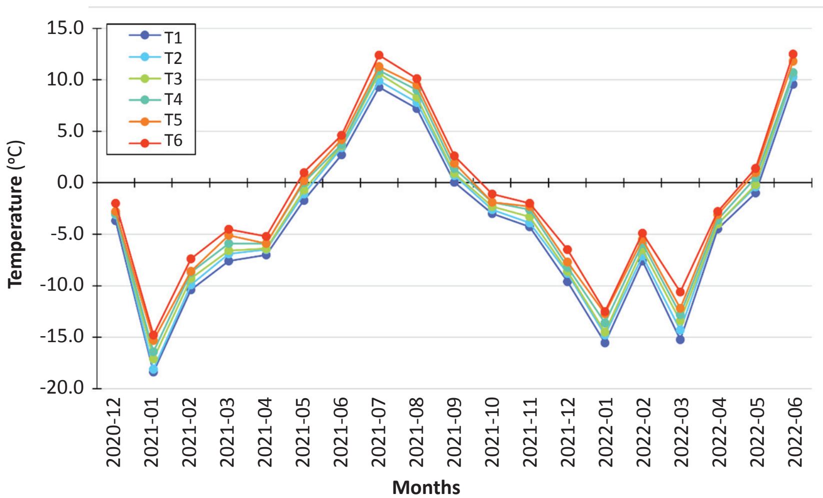

Figure 5. Absolute minimum temperature values.

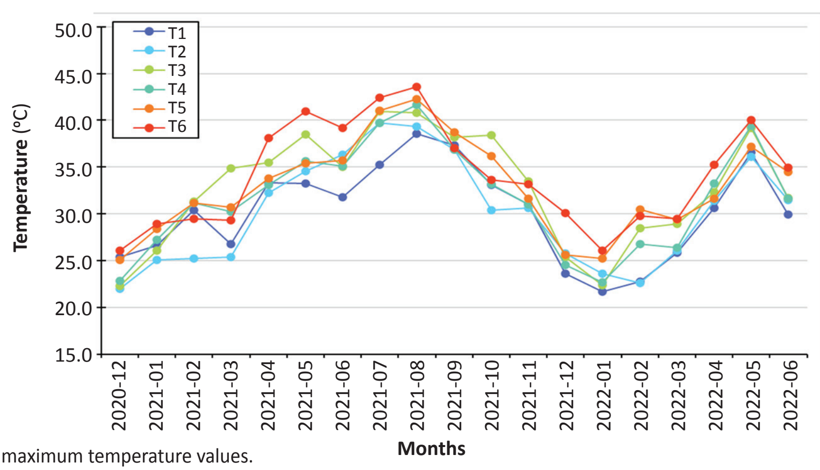

Figure 6. Absolute maximum temperature values.

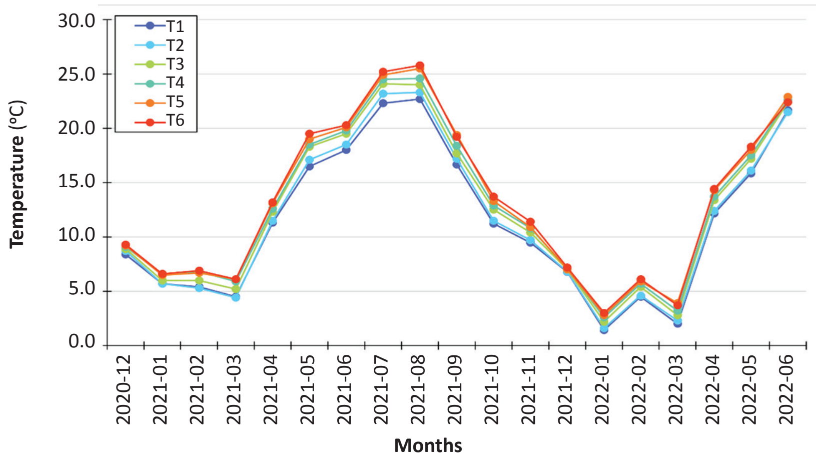

Figure 7. Average temperature values.

DISCUSSION

In this research, the effects of temperature inversion on red pine (*P. brutia*) and black pine (*P. nigra*) stands in the Karıncalı region of the Orhaneli district, Bursa, were investigated. The results show that temperature inversion causes cold stress, especially in the lower zones, which significantly affects the positioning, competition and growth dynamics between species. Temperature inversion is a climatic phenomenon caused by the accumulation of cold air masses within topographic structures such as valleys and bowls, which significantly affects the dynamics of ecosystems and the distribution and growth performance of tree species. Temperature inversion is frequently observed especially on cloudless, calm winter days, and the temperature in these inversion areas is lower than in high-altitude regions (Yılmaz et al. 2021).

Cold exposure during temperature inversion can lead to physiological damage in plants, mainly through extracellular ice formation that disrupts cell membranes and impairs key processes like photosynthesis and water transport (Sakai and Larcher 1987, Baranger et al. 2024). In frost-prone microclimates, repeated freeze-thaw cycles can cause tissue necrosis and xylem embolism, reducing growth and regeneration, particularly in sensitive species like red pine (Dy and Payette 2007, Semerci et al. 2021). These effects contribute to the dominance of more cold-tolerant species, such as black pine, in inversion-affected areas (Kreyling et al. 2012).

Ogrin (2007) reported that temperatures can decrease to -35°C in frost hollows in Slovenia and that extreme temperature decreases in these areas have decisive effects on the ecosystem. Likewise, in our two-year study, temperatures in the inversion area decreased to -18.4°C, which affected the natural positioning of black pine and red pine. After 10 years or more of temperature measurements, it is highly likely that the minimum temperatures at the same location will decrease even further. Increased accumulation of cold air in frost hollows, especially at night, triggers temperature inversions and this emerges as one of the main factors limiting the distribution and development of plants.

Black pine (*P. nigra*) and red pine (*P. brutia*) are the two most important coniferous tree species in mountainous and forested areas of Türkiye. In normal distribution, red pine is located at lower altitudes and black pine at higher altitudes. Black pine is known as a species that is more resistant to cold climates and continental conditions, while red pine generally grows successfully in warmer and temperate regions. These differences are primarily attributed to physiological traits, particularly the superior cold hardiness of black pine needles, enhanced by the accumulation of soluble carbohydrates and protective lipids that stabilize cellular structures during freezing events (Thomashow 1999, Bigras et al. 2001, Kreyling et al. 2012, Semerci et al. 2021). These traits enable black pine to maintain physiological functions and exhibit higher survival rates in colder microclimates. Therefore, in areas affected by temperature inversion, such microclimatic conditions should be carefully considered when planning afforestation, to ensure both short-term survival and long-term sustainability.

In the research area in Karıncalı, the black pine stand demonstrates its development below the altitude of the red pine, and the black pine regeneration sustains its vitality in the range of 500-550 meters. The inability of the red pine regeneration to grow below 550 meters is due to the temperature inversion caused by low temperatures, especially in the winter months. The minimum temperature in the inversion area probably decreases below the freezing temperature of red pine. Frost damage in red pine begins at -15°C, while fatal frost damage occurs at around -20°C (Semerci et al. 2019, 2021) in the medium and long term. Similarly, in a frost hollow in the Isparta-Pürenova region, serious failures were also observed in black pine and cedar (*Cedrus libani* A.Rich) plantations, but it was reported that black pine seedlings developed better than cedar due to its frost resistance (Oğurlu and Avcı 1999). Baranger et al. (2024) emphasize the importance of physiological thresholds and safety margins in understanding the distributional limits of species under climatic stresses such as frost and drought. Therefore, the frost resistance of the species to be used in afforestation projects in areas with temperature inversion should be taken into consideration.

When temperature values are examined according to local climatic conditions, the minimum temperatures measured in cold air pools can decrease below -30°C, which negatively affects the growth of especially sensitive plant species and young saplings (Whiteman et al. 2004, Ogrin et al. 2018). Ogrin et al. (2018) conducted a study in Durmitor National Park, Montenegro, where the minimum temperature values measured in karst depressions during the winter season were as low as -40°C. Such extreme temperatures prevent the existence of species whose minimum survival threshold temperature cannot reach these values. Red pine can withstand temperatures down to -16°C in the winter months but can suffer severe frost damage at lower temperatures (Semerci et al. 2021). Black pine, which is generally present in the cooler upper zone, moves down and settles in the temperature inversion areas in the red pine areas with its more cold-resistant structure.

This study supports the fact that temperature inversion has significant effects on forest ecosystems. The displacement of black pine and red pine species in the inversion area studied is an unusual phenomenon and an instructive natural sight. For afforestation in areas with temperature inversions, local climatic factors should be taken into consideration, and the success rate of afforestation should be increased by selecting the right species.

Furthermore, it is important to consider the potential long-term effects of temperature inversion on forest ecosystems. Persistent cold conditions in these specific microclimatic areas may gradually lead to the decline of cold-sensitive species and the expansion of cold-tolerant ones. Over time, such changes can alter species composition and reduce or transform biodiversity. Temperature inversion also affects vegetation patterns, stand structure, and the formation of forest openings, all of which influence habitat characteristics. In the long term, these dynamics may lead to shifts in key ecosystem functions such as carbon storage, soil moisture regulation, and habitat suitability for wildlife. Therefore, future forest management strategies should take into account not only the immediate effects of inversion but also its broader ecological consequences.

CONCLUSIONS

The overall results of the study reveal that temperature inversion creates significant effects on the structure and dynamics of forest ecosystems. These microclimatic differences observed between black pine and red pine stands play a decisive role in the growth, development, and survival rates of both species. Black pine, which normally grows at higher altitudes than red pine, has descended to the lower zone due to temperature inversion. It can be concluded that the long-term absolute minimum temperature in the lower zone in the inversion area is below the temperature threshold that the red pine can survive. In the light of these findings, temperature inversion should be considered a critical climatic factor in silvicultural practices and afforestation projects. In particular, site-specific assessments should be carried out in inversion-prone areas before species selection and planting. Establishing long-term observation plots in such areas and testing species combinations under different microclimatic conditions would contribute to more resilient and sustainable forest structures. The results also emphasize the need to integrate microclimatic criteria such as cold air pooling, frost zones, and identified inversion areas into practical afforestation planning. Therefore, temperature inversion should be acknowledged, particularly in initiatives focused on forest restoration and afforestation.

Author Contributions

Yılmaz M, Parlak S, Erken K, and Kalkan M conceived and designed the research, Parlak S, and Erken K carried out the field measurements, Yılmaz M, Parlak S, Erken K, and Kalkan M processed the data and performed the statistical analysis, Yılmaz M, Parlak S, Erken K, and Kalkan M wrote the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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