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Analysis of Environmental Factors Contributing to Sunscald in Urban Street Trees

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This study analyzed the environmental factors contributing to sunscald damage in urban street trees and proposed management strategies to mitigate its impact. A survey of Acer species, *Prunus × yedoensis*, *Machilus thunbergii*, and *Ilex rotunda* planted in downtown Suncheon, South Korea revealed that sunscald damage was particularly severe in *Acer* species and in some *Prunus* individuals with thinner bark. The damage was predominantly observed on the lower trunk (below 1 m above ground) facing south and west, with both the vertical position of sunscald and orientation significantly influencing the percentage of damaged bark area. These findings suggest that solar radiation and reflected heat from adjacent roads and buildings are major causal factors. The following were identified as effective strategies to prevent sunscald damage: reinforcing trunk protection measures, selecting tree species with higher resistance to sunscald, and adjusting planting intervals to enhance shading effects through shrub planting. Additionally, managing soil moisture and temperature with organic mulching and ensuring sufficient canopy shading through proper pruning were also considered essential.

Key words: Mulching, Solar radiation, Trunk protection, Urban environment

INTRODUCTION

In urban environments, street trees perform various ecosystem services, including reducing stormwater runoff, improving air quality, sequestering carbon, providing shade, mitigating the urban heat island effect, and enhancing aesthetics (Armson *et al*., 2012; Mullaney *et al*., 2015), thus playing a critical role in supporting sustainable urban ecosystems (Egerer *et al*., 2024). However, street trees are exposed to various environmental threats, including sunscald, insect borers, and wood–decay fungi (Roppolo and Miller, 2001; Poland and McCullough, 2006). Prolonged drought, frost damage, strong winds, and improper pruning practices (Egerer *et al*., 2024) further exacerbate tree growth and health, thereby increasing their susceptibility to pest and disease infestations (Hilbert *et al*., 2019). Among these threats, physiological stress caused by sunscald damage is a critical factor that affects street tree growth (Trowbridge and Bassuk, 2004). Sunscald refers to localized overheating of the trunk due to sunlight (radiant heat) or necrosis of tissues caused by rapid temperature fluctuations between day and night, primarily occurring during winter and summer (Roppolo and Miller, 2001; Harris *et al*., 2004; Lee, 2015).

As a result of sunscalding, bark splitting and internal tissue damage may occur, leading to an increased risk of pest and pathogen infections and overall deterioration of tree health (Egerer *et al*., 2024). Species with thinner bark are particularly vulnerable to sunscald damage, and the affected areas often exhibit limited potential for normal growth recovery (Lee, 2015). Furthermore, severe trunk damage can lead to internal decay and cavity formation over time, compromising structural stability and increasing the risk of tree failure during strong winds, which may result in human casualties and property damage.

As climate change intensifies the frequency of extreme weather events, such as severe droughts and heatwaves, urban heat island effects not only reduce the photosynthetic efficiency of street trees but also exacerbating photo–oxidative stress (Egerer *et al*., 2024). Additionally, stomatal closure aimed at conserving water can cause leaf temperatures to rise, accelerating leaf senescence and abscission. Due to these impacts of climate change, approximately 70% of tree species in 168 cities worldwide have been reported to be vulnerable to increasing mean temperatures and changes in annual precipitation patterns (Esperon–Rodriguez *et al*., 2022).

Street trees in urban environments are often planted individually along open roadsides, resulting in limited shielding and direct exposure to intense sunlight. Additionally, artificial surfaces such as asphalt and concrete absorb and reflect heat, further elevating bark temperatures (Moser–Reischl *et al*., 2019) and amplifying diurnal temperature fluctuations, thereby increasing the likelihood of sunscald. Prolonged heatwaves and drought conditions during the summer exacerbate water stress in trees (Bacelar *et al*., 2024), consequently reducing their resistance and heightening vulnerability to sunscald damage. While the cambial tissues of trees can undergo necrosis due to acute heat stress, temperature variation alone may not fully explain the occurrence of sunscald. If temperature variation were the sole cause, uniform damage across all thin–barked species would be expected; however, this is not consistently observed.

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Some researchers have suggested that sunscald may be more closely associated with heat stress in conjunction with site–specific environmental conditions and that mechanical injuries to stems and roots during pruning or transplantation could exacerbate sunscald development (Roppolo and Miller, 2001). To comprehensively understand the causes of sunscald in urban street trees, it is essential to consider its climatic, physical, and biological factors in an integrated manner.

Key factors contributing to sunscald damage include intense direct sunlight and radiant heat exposure (Roppolo and Miller, 2001), physiological traits such as bark thickness and transpiration rate (Harris *et al.*, 2004), increased thermal emissions from urban infrastructure (Moser–Reischl *et al.*, 2019), extreme seasonal temperature fluctuations (Roppolo and Miller, 2001), and tree–specific characteristics like basal diameter and crown form (Maeda *et al.*, 2017). In modern urban settings, sunscald damage is worsening due to intensified heat from artificial surfaces and shifts in precipitation patterns driven by climate change (Leers *et al.*, 2017). However, empirical research analyzing the environmental drivers of sunscald in these settings remains scarce. This study addresses this gap by analyzing external and internal environmental factors affecting sunscald–prone street trees. The goal is to inform more effective protection and management strategies for mitigating sunscald damage in urban environments.

MATERIALS AND METHODS

Selection of Sample Trees and Assessment of Sunscald Damage

A review of landscaping tree literature and preliminary surveys revealed the characteristics of sunscald damage and tree species frequently affected by it. According to Davis and Peterson (1980), Lee (2015), and Hummel and Ophardt (2016), sunscald damage is characterized by (i) vertical cracking on the trunk, (ii) occurrence mainly adjacent to roads or building walls, and (iii) damage observed within 2 meters from the ground surface. Sunscald predominantly occurs in tree species with smooth bark and poorly developed cork layers, such as *Acer* spp., *Prunus* spp., *Magnolia* spp., *Prunus mume*, *Paulownia* spp., *Juglans* spp., and *Picea* spp. Based on these conditions, the occurrence of sunscald in the sample trees (hereafter referred to as target trees) was determined when all three criteria were met. The target tree species selected for this study were *Acer* spp. (including *Acer palmatum* and *Acer palmatum* var. *sanguineum*), *Prunus* × *yedoensis*, *Machilus thunbergii*, and *Ilex rotunda*. A total of 200 trees were surveyed, consisting of 50 trees per species with sunscald damage among street trees planted in downtown Suncheon, South Korea. All target trees were street trees with a single main trunk, from which multiple branches diverged above 2 meters, forming a well–developed crown structure. The survey was conducted between May and June 2022, during the period when all target trees had fully expanded leaves.

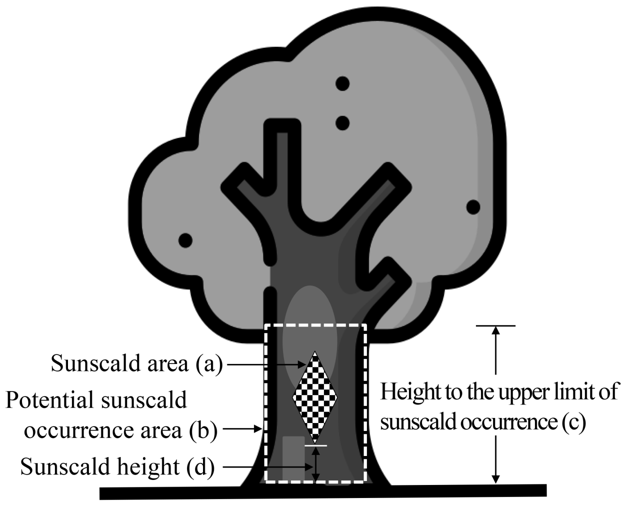

Fig. 1. A schematic diagram for investigating sunscald damage on street trees.

Since the sunscald area ((a) in Fig. 1) was irregular, it was somewhat difficult to calculate; however, it was estimated by measuring the width and height of the damaged area and assuming a rhomboid shape. However, as basal diameter increases, the amount of incident solar radiation also increases, potentially enlarging the sunscald area. Thus, the sunscald area was converted into the sunscald area ratio (%) by calculating (sunscald area / potential bark area susceptible to sunscald) × 100. Because sunscald primarily occurred on the bark facing the roadway, the potential bark area susceptible to sunscald ((b) in Fig. 1) was calculated as (basal diameter × π / 2) × the height ((c) in Fig. 1) from the ground surface to the upper limit of sunscald occurrence (Fig. 1). The reason for limiting the height to the upper extent of sunscald occurrence is that above this height, canopy foliage creates shade, thus preventing sunscald. Sunscald height ((d) in Fig. 1) was measured from the ground surface to the initial point of sunscald occurrence, and the basal diameter was measured using a diameter tape at 10 cm above the ground surface.

Investigation of External and Internal Environmental Factors

To evaluate the influence of planting environments on sunscald damage to the target trees, sunscald orientation (azimuth), the number of traffic lanes (two, four, and six lanes), and adjacent building heights were investigated. In addition, since the solar radiant heat transmitted to the bark of street trees is proportional to solar radiation, canopy openness (%) and relative solar radiation (%) were measured for each target tree. For this purpose, color hemispherical photographs were taken facing the sky with a fisheye lens (180° field of vision) mounted on a digital camera at a height of 2 meters above ground under each target tree, maintaining horizontal alignment. The captured images were analyzed using Gap Light Analyzer software (version 2) to estimate canopy openness and relative solar radiation

(Frazer *et al*., 1999). Higher canopy openness and relative solar radiation values indicated fewer obstructions from surrounding canopies or buildings, allowing more radiant heat to reach the target tree. However, since the Gap Light Analyzer only recognizes RGB colors, it may inaccurately analyze white surfaces such as building walls or glass windows, leading to potential errors. To correct for this, building areas in the images were manually colored black using Photoshop, improving recognition accuracy and adjusting for reductions in canopy openness and relative solar radiation as caused by buildings. Furthermore, relative solar radiation at different trunk heights (1 m, 2 m, 4 m, and 6 m above ground) was analyzed for each target tree to examine variations in radiant heat exposure.

Statistical Analysis

Multiple regression analysis was performed using SPSS (version 22) to identify the relationship between the sunscald area ratio and environmental factors. Key environmental variables significantly affecting sunscald damage were identified, and their quantitative impacts were evaluated.

RESULTS AND DISCUSSION

Analysis of Sunscald Area Ratio by Tree Species

Comparison of the sunscald area ratios among the target trees revealed that *Acer* species exhibited the highest value (14%), followed by *Machilus thunbergii* (8%), *Ilex rotunda* (6%), and *Prunus* × *yedoensis* (2%) (Fig. 2). These results are consistent with previous findings reported by Davis and Peterson (1980), Litzow and Pellett (1983), Roppolo and Miller (2001), and Maeda *et al*. (2017). *Acer* species tend to be more frequently affected by sunscald due to their thin bark, which makes them more vulnerable to radiant heat. When the bark is thin, strong solar radiation can be directly or indirectly transmitted to the cambium and phloem tissues, leading to tissue dehydration and cell death caused by thermal injury (Leers *et al*., 2017). Such physiological traits are believed to significantly contribute to severe sunscald damage in these trees.

In contrast, the sunscald area ratio of *Prunus* × *yedoensis* was relatively low, which may be attributed to its comparatively thicker bark and well–developed protective cork layer that mitigates heat–induced damage (Savage, 1970). The thickness of the bark and the development of protective layers are major factors that influence sunscald occurrence, suggesting that the degree of damage may vary among species even under similar environmental conditions. Young trees or species with thin bark are particularly susceptible to sunscald damage, although this vulnerability tends to decrease as the bark thickens over time (Roppolo and Miller, 2001). Therefore, when planting young trees or thin–barked broadleaf species as street trees, preventive measures should be implemented to minimize sunscald damage. Notably, the Korean nursery industry often practices dense planting to maximize yield per unit area, which can promote the development of thin bark and thus increase vulnerability to sunscald (Leers *et al*., 2017), highlighting the need for appropriate mitigation strategies during street tree planting.

Relationship Between Environmental Factors and Sunscald Area Ratio

Sunscald occurrence on trunks was higher in the northwest, southeast, south, west, and southwest orientations, with particularly severe damage observed closer to the south and west directions (Fig. 3a). This pattern is attributed to the close relationship between solar elevation angles and incident solar radiation. From the south, higher solar angles result in greater solar radiation per unit area, leading to increased direct and indirect radiant heat transmission to the bark. From the west, lower solar elevation allows direct sunlight to reach the bark, while rising afternoon temperatures further exacerbate sunscald damage. By contrast, less damage was observed on the eastern and northern sides of trunks. There was no clear pattern in sunscald damage associated with the number of traffic lanes or build-

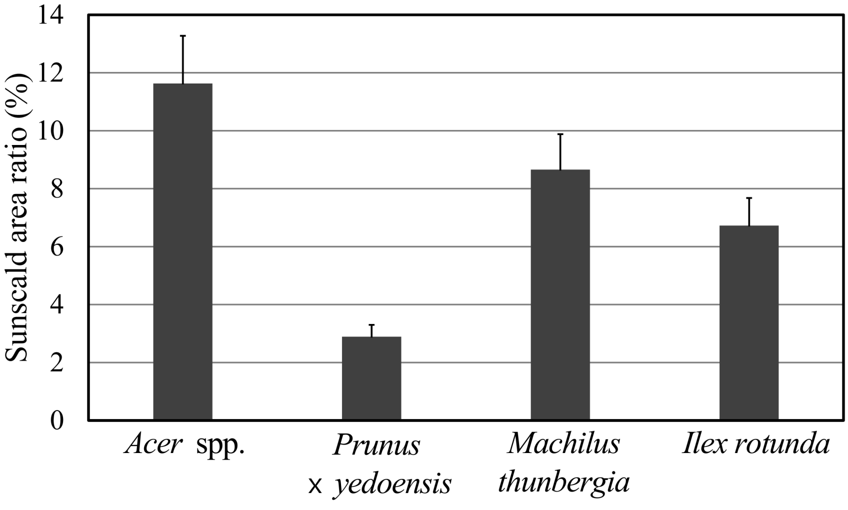

Fig. 2. Mean sunscald area ratio by tree species.

ing height (Fig. 3(b) and 3(c)). Although it was expected that wider roads would increase radiant heat from asphalt and that taller buildings would provide more shade, no distinct trend was identified in these variables. This suggests that individual tree characteristics and complex environmental factors play a greater role in sunscald development than structural elements like road lanes or buildings.

Given the strong influence of solar radiation on sunscald occurrence, the relationship between canopy openness, relative solar radiation, and sunscald area ratio was analyzed. The results revealed that trees with higher

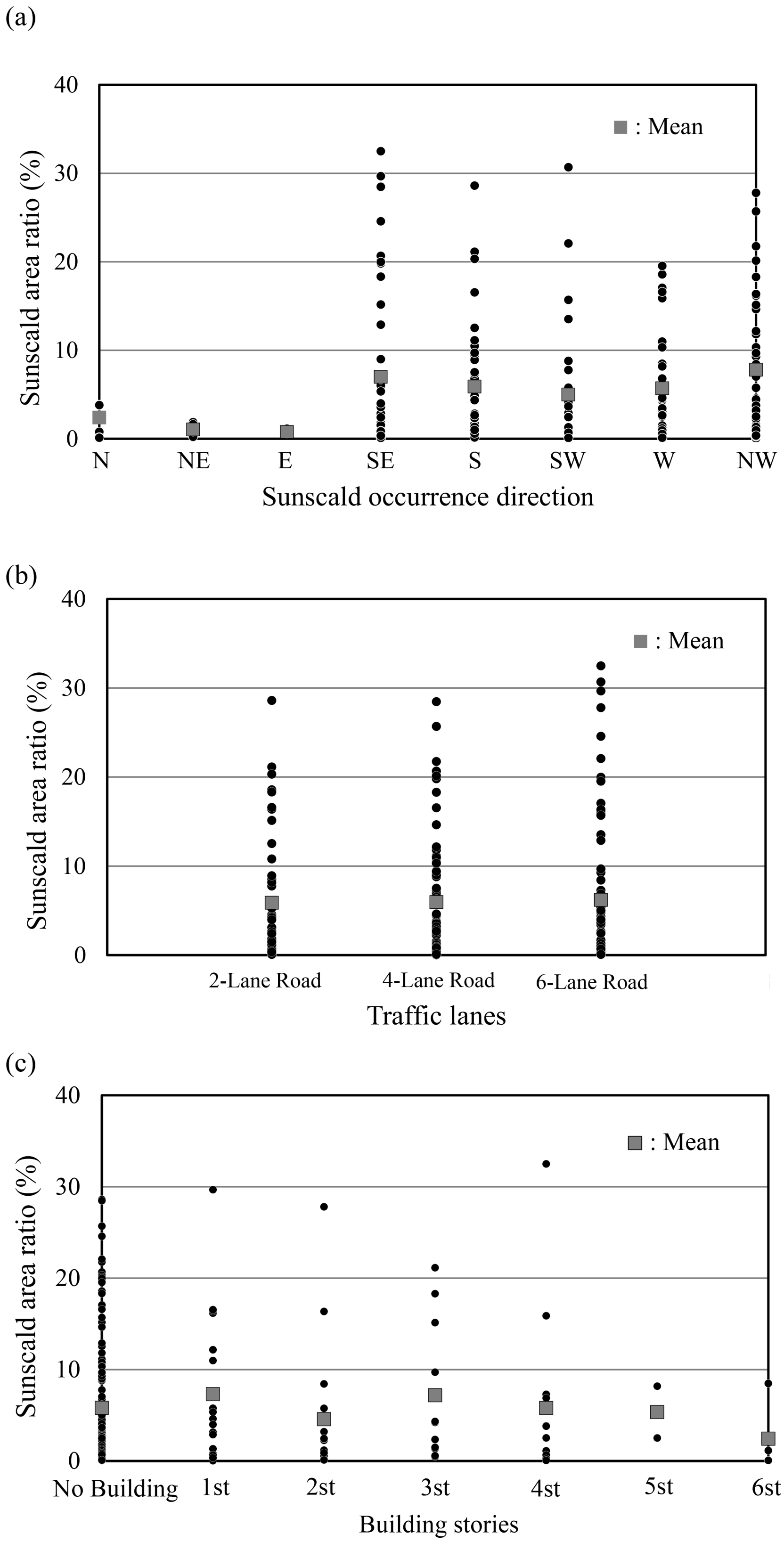

Fig. 3. Relationship between sunscald area ratio and aspect (a), number of traffic lanes (b), and number of building stories (c) by tree species.

canopy openness and relative solar radiation exhibited a clear tendency toward increased sunscald area ratios (Fig. 4). These results can be interpreted to indicate that greater solar radiation leads to increased transmission of radiant heat, causing a rapid rise in bark temperature that accelerates tissue necrosis and subsequently exacerbates sunscald damage.

Maeda *et al*. (2017) measured bark temperatures of street and park trees in Tottori City, Japan and reported that eastern–facing trunk exposures received direct sunlight between 8:00 and 10:00 AM (2 hours), whereas western exposures were subjected to direct sunlight from 2:00 to 6:00 PM (3 hours), with the western side maintaining relatively higher temperatures for a longer duration. Additionally, it is well known that tree water content peaks early in the morning and reaches its minimum around 3 PM (Brough *et al*., 1986). Thus, the western side of the trunk is exposed to prolonged direct sunlight during periods when the xylem tissues near the bark experience reduced water content. This suggests that the western trunk surface, subjected to extended solar radiation under conditions of water stress, is the area at greatest risk for sunscald occurrence.

Fig. 5(a) shows that sunscald area ratios increased markedly below 1 meter on the trunk. This implies that lower portions of the trunk are more severely affected by sunscald due to increased exposure to both direct solar radiation and indirect radiant heat reflected from road surfaces. Fig. 5(b) indicates that relative solar radiation was higher at 1–2 meters but decreased at 4 meters before increasing again above that height. Fig. 5(a) and 5(b) demonstrate consistent results, showing that lower portions of the trunk experienced greater exposure to solar radiation (radiant heat) and thus a higher likelihood of sunscald damage, whereas higher portions benefited from canopy shading, which reduced solar radiation exposure and correspondingly decreased the risk of sunscald. Particularly, sunscald damage was concentrated below 1 meter, suggesting that mitigation measures should focus on this zone.

Small tree species such as *Acer* spp. and *Ilex rotunda* tend to have narrower canopies, increasing the potential range of sunscald occurrence along the trunk. Maeda *et al*. (2017) analyzed the relationship between sunscald damage and canopy structure and found that trees exhibiting signs of large branch removal or those

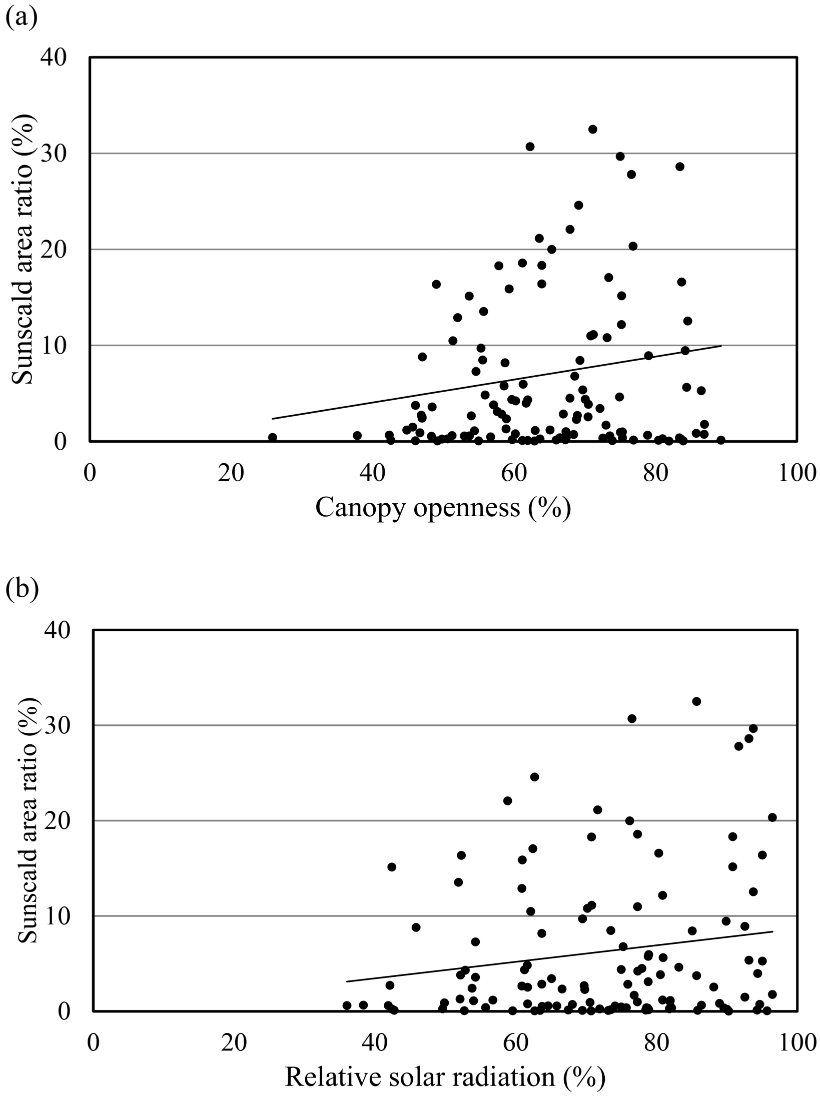

Fig. 4. Relationship between sunscald area ratio and canopy openness (a) and relative solar radiation (b) by tree species.

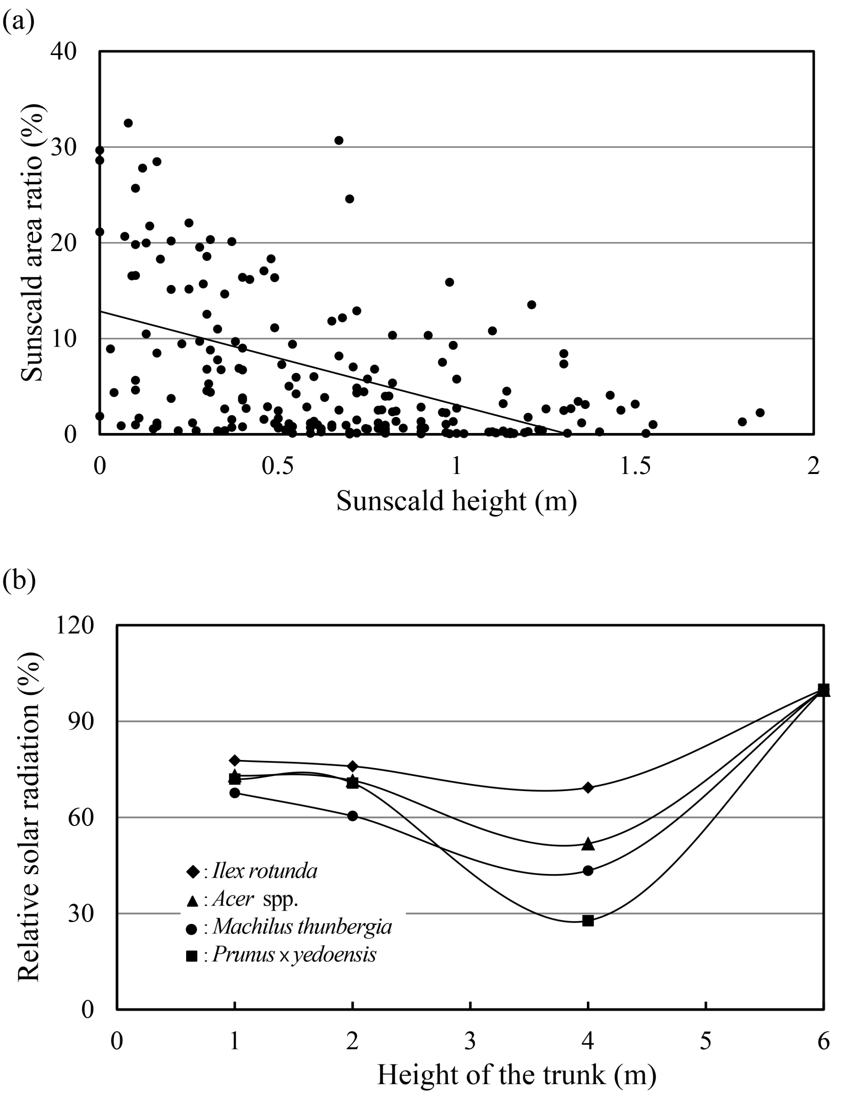

Fig. 5. Relationship between sunscald height and sunscald area ratio (a) and between tree height and relative solar radiation (b).

subjected to regular pruning in landscaped areas tend to experience greater sunscald damage. The researchers attributed this to smaller canopies that allow longer durations of direct sunlight exposure to the trunk, while reduced leaf area decreases transpiration, thereby slowing sap flow and ultimately creating conditions that promote higher trunk temperatures.

Environmental Factors Influencing Sunscald Area and Mitigation Strategies

Multiple regression analysis revealed that sunscald height (F1, $\beta = -0.417$, $p < 0.000$) and orientation (F2, $\beta = 0.247$, $p < 0.003$) were significant predictors of the sunscald area ratio (Table 1). In contrast, basal diameter, number of traffic lanes, building height, canopy openness, and relative solar radiation did not show statistically significant effects. Therefore, when planting street trees, it is important to pay particular attention to tree orientation and sunscald height, with a focus on mitigating damage to the southern and western sides of the trunk, especially at lower heights.

Roppolo and Miller (2001) identified solar radiation, reflected heat from surrounding structures, and physiological traits of trees as major factors that contribute to sunscald in urban environments. This study confirmed that radiant heat transmission to lower trunks adjacent to roads acts as a primary cause of sunscald. Hummel and Ophardt (2016) and Maeda *et al*. (2017) observed similar trends, suggesting that the pronounced sunscald damage on the western and southern sides of trunks is largely influenced by increased solar radiation and elevated atmospheric temperatures. Litzow and Pellett (1983) suggested that greater leaf area enhances the shading effect and can reduce sunscald damage; similarly, this study found that relative solar radiation decreased above 2 meters on the trunk, resulting in reduced sunscald damage.

In summary, the primary factors causing sunscald in urban street trees can be attributed to conditions in which trees are individually exposed to direct sunlight, radiant heat reflected from artificial structures such as asphalt and concrete, and differences in species– and age–specific resistance. Ongoing climate change, characterized by extreme summer heat and prolonged

Table 1. Analysis of environmental factors affecting sunscald damage using multiple regression analysis

Model	Unstandardized Coefficients		Standardized Coefficients	t–value	p–value	Collinearity Statistics	
	β	Standard Error	Beta			Tolerance	VIF
(Intercept)	6.332	2.759	–	2.295	0.024	–	–
Sunscald height (F1)	–10.501	2.029	–0.417	–5.175	0.000*	1.000	1.000
Aspect (F2)	1.36	0.444	0.247	3.063	0.003*	1.000	1.000

*Significant at the P < 0.01 level.

droughts, is likely to exacerbate sunscald damage in the future. Therefore, preventive measures and improvements in planting layouts are necessary to minimize sunscald damage. Under conventional planting practices, strengthening trunk protection measures is an effective approach (Litzow and Pellett, 1983). For young trees or species with thin bark, applying white latex paint or installing tree guards is recommended to mitigate radiant heat transfer. Additionally, selecting species with thick bark and greater resistance to radiant heat for planting along roadsides is considered optimal (Egerer *et al.*, 2024). If vulnerable species must be planted, care should be taken not to plant them individually along south– or west–facing roadsides with intense direct sunlight, and natural shading should be promoted by adjusting planting density or planting shrubs nearby.

In parallel, improvements in the urban environment are also critical. Since asphalt and concrete pavement along roadsides increases surface reflectance and radiant heat, it is necessary to suppress soil moisture evaporation and alleviate thermal stress on trees by applying mulching materials such as wood chips, bark chips, or vegetated blocks around street trees. Adaptation strategies to address climate change are also essential; as droughts and heatwaves become more frequent due to rising temperatures and altered precipitation patterns, it is necessary to introduce drip irrigation systems and prepare appropriate watering plans (Roppolo and Miller, 2001) to maintain soil moisture balance during extended drought periods. Moreover, in the management of street trees, it is important to avoid aggressive removal of upper and lower branches during pruning and to apply appropriate techniques, such as natural target pruning proposed by Shigo (1986), ensuring that wound protection measures are implemented. Excessive pruning increases the likelihood of sunscald by enhancing radiant heat exposure (Smiley and Kane, 2006) and can further deteriorate tree health by allowing the invasion of wood–decay fungi through wounds (Roppolo and Miller, 2001; Poland and McCullough, 2006).

This study is significant in that it systematically analyzed the environmental factors contributing to sunscald in street trees and proposed practical strategies for damage mitigation. Future research can further assess the sunscald resistance of various species and develop long–term urban tree management strategies that reflect climate change scenarios.

AUTHOR CONTRIBUTIONS

Y. J. Lee, J. H. Ha and S. G. Park designed the study, performed the histological experiments, analyzed the data and wrote the paper. H. J. Bang supervised the work, wrote the paper. All authors assisted in editing of the manuscript and approved the final version.

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