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Environmental and Management Drivers of *Magnolia silvioi* Mortality in a Tropical Andean City

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Abstract. Background: Evidence of urban tree mortality is mostly limited to temperate regions; little is known about mortality in tropical cities or threatened native trees used in greening programs. *Magnolia silvioi* (IUCN Endangered) has been widely planted in Medellín since 2009, outside its natural range. Methods: We combined Medellín's Urban Tree System (SAU) records with field assessments of 178 individuals to score survival, phytosanitary condition, site context, and management history. Random Forest classification models (500 trees) were trained using tree, site, spatial, and maintenance-related predictors. Model performance was evaluated with out-of-bag (OOB) error and class errors. Results: Overall mortality was high (119/178; 66.8%). Of the 59 survivors, 54% showed decline symptoms. Mortality remained similarly high across natural, infrastructure, and built settings (approximately 65% to 71%). A reduced model with 6 predictors (latitude, longitude, pollution index, pruning, interventions, and planting date) improved performance (OOB = 20.8%), with latitude, pruning, longitude, and interventions as top predictors. Trees receiving more interventions and pruning exhibited lower predicted mortality. Conclusions: *Magnolia silvioi* shows high mortality and widespread decline symptoms across urban areas of Medellín. Spatial variables were the strongest predictors of mortality, likely reflecting differences in geomorphology and jurisdictional management while consistent maintenance mitigates risk more than microsite variables. Management intensity, particularly pruning and repeated interventions, was consistently associated with reduced mortality risk. Findings support adaptive monitoring, risk-based maintenance, and cross-municipal coordination to sustain conservation-priority trees in tropical cities.

Keywords. Pruning; Random Forest Test; Spatial Gradients; Tropical Cities.

INTRODUCTION

Understanding the dynamics of tree establishment and survival in urban environments is crucial for designing effective green infrastructure and guiding arboricultural practices (Roman et al. 2014; Vogt et al. 2015; Hilbert et al. 2019). Urban trees face a complex interplay of biophysical and anthropogenic stressors, and mortality during establishment remains a persistent challenge. An estimated 45% of urban forestry budgets are devoted to planting and establishment, while 23% is spent on tree removal (Hauer and Peterson 2016). However, most estimates of urban tree mortality and management costs derive from temperate contexts (Hauer and Peterson 2016; Hilbert et al. 2015), leaving a critical knowledge gap for megadiverse tropical cities such as Medellín, where municipal budgets face increasing pressure to sustain large-scale urban tree programs (AMVA 2015). This highlights the importance of identifying the factors contributing to urban tree mortality and developing targeted strategies to enhance long-term survival.

Despite the growing attention to urban tree mortality, most studies have been conducted in temperate regions (Hilbert et al. 2019). Research from tropical urban ecosystems, particularly in global biodiversity hotspots such as the tropical Andes, remains extremely limited, highlighting the need for region-specific evidence. Restrepo et al. (2015) assessed the deterioration of urban trees in Medellín, Colombia (n = 11,710 individuals of 25 species), and identified heat stress, water stress, air pollution, urbanization, and pests as major drivers. Ramírez-Sánchez et al. (2020) conducted a geospatial analysis of urban trees in Bogotá, Colombia, relating decline to pollution, traffic patterns, and other variables. The municipality of Quito reported high mortality levels among the city's street trees (FAO 1997). However, none of these studies

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focused on a single species or involved mortality modeling per se. Expanding knowledge of mortality patterns in these regions is essential not only for improving urban greening strategies but also for informing conservation efforts that increasingly rely on urban spaces as refuges for native species (Goddard et al. 2010; Aronson et al. 2017).

Several studies have sought to identify the factors underlying urban tree mortality, highlighting the influence of planting site conditions, species traits, maintenance intensity, and human disturbance (Hilbert et al. 2019). Variables frequently associated with mortality include tree age, diameter, management practices (e.g., pruning frequency), and surrounding land use (Lu et al. 2010). To organize these diverse influences, Hilbert et al. (2019) proposed 3 broad categories of predictors: tree-related factors (age, size, and species), site-related factors (soil compaction, slope, air pollution, and surrounding land use), and maintenance-related factors (frequency of pruning and number of interventions). This framework provides a useful basis for assessing how interacting biophysical and management variables shape survival outcomes in urban forests.

Among site-related factors, the high heterogeneity of planting environments poses a particular challenge in urban forestry. Tree performance in cities depends on interaction among soil, microclimate, topography, and land-use conditions, all of which influence growth and survival (Chazdon and Pearcy 1991; Kjelgren and Clark 1992; Day and Bassuk 1994; Jim 1998; Martin et al. 2016; Moser-Reischl et al. 2019; Bigelow et al. 2024; Mailloux et al. 2024). Trees growing in parks or riparian zones may benefit from better soil and moisture conditions, whereas those in paved or densely built areas are exposed to greater disturbances and stress (Tirado-Corbala and Slater 2010). In Medellín, for instance, Paniagua-Villada et al. (2024) showed that urban expansion has progressively displaced green areas, creating an "unequal struggle" that limits space for tree establishment and disrupts the ecological continuity of urban vegetation.

Beyond site conditions, management practices play a crucial role in determining the survival of urban trees. Regular interventions, such as pruning, phytosanitary care, and soil maintenance, can significantly enhance tree performance, particularly during the vulnerable establishment phase (Koeser et al. 2013; Vogt et al. 2015). However, this care is often unevenly distributed, shaped by institutional priorities, land ownership, socioeconomic factors, and the perceived importance of planting sites (Roman et al. 2014; Conway and Vander Vecht 2015). The extent and frequency of management may act either as a buffer or a risk factor depending on how consistently it is applied across urban landscapes (Hauer and Peterson 2016; Hilbert et al. 2019). Understanding the influence of management intensity on tree survival is particularly relevant for native or conservation-priority species that often require sustained care to thrive in challenging urban conditions.

The integration of native and threatened species into urban landscapes aims to enhance ecosystem function and support regional biodiversity (Alvey 2006). Native trees are generally better adapted to local climatic and edaphic conditions, offering ecological advantages such as supporting native fauna and microbial communities (Jang and Woo 2022). However, urban environments impose stressors such as compacted or nutrient-poor soils, air pollution, fragmented ecological networks, and altered hydrology that may limit their viability. Species-related traits also influence tree performance in cities. Differences in growth form, physiology, and stress tolerance determine how species respond to urban conditions, and some groups are more vulnerable than others (Franceschi et al. 2023). The genus *Magnolia* exemplifies this variability: magnolias are globally valued as ornamentals and urban shade trees, yet their establishment success varies widely among species due to contrasting drought tolerance and soil requirements (Sjöman et al. 2018). In tropical Andean cities, where conservation goals often converge with greening programs, native magnolias offer an opportunity to integrate biodiversity conservation with urban forestry.

Magnolia silvioi (Lozano) Govaerts is a canopy-emergent species endemic to the premontane forests of Northeastern and Eastern Antioquia, Colombia, occurring between 400 m a.s.l. and 1550 m a.s.l. (meters above sea level)(Calderón et al. 2014). Classified as Endangered on the IUCN Red List, its wild populations are restricted to small, fragmented forest remnants affected by agriculture, mining, and timber extraction (Calderon et al. 2014). Due to its limited range and endangered status, it has been widely planted in Medellín since 2009 as part of the city's Biodiversity Plan (Area Metropolitana del Valle de Aburrá 2019), which promotes the use of native

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species to enhance urban ecosystem services and conserve regional flora. Although native to Northeastern and Eastern Antioquia, *M. silvioi* does not naturally occur in Medellín or other heavily urbanized areas, raising important questions about its suitability and survival under such altered conditions. The current range of the natural population does not include the Aburrá Valley, and there is no evidence that *M. silvioi* ever inhabited the region.

This study evaluates the relative importance of site-related and management-related factors in explaining the mortality of *M. silvioi* in Medellín's urban landscape. Urban tree mortality is increasingly understood as a multicausal process shaped by the interaction of tree-, site-, and management-related variables rather than a single limiting factor (Hilbert et al. 2019). Within this framework, *M. silvioi* has been widely planted across heterogeneous urban environments, ranging from highly impervious infrastructure (e.g., sidewalks and road medians) to relatively favorable conditions such as parks and riparian corridors. These contrasting microsites generate strong gradients in soil compaction, hydrology, pollution exposure, and management intensity, which may differentially affect tree performance and survival.

We therefore expected mortality probability to increase under higher levels of site-related stress, particularly in areas with higher pollution exposure and along spatial gradients associated with urban infrastructure and environmental stress. At the same time, we anticipated that trees receiving more frequent and sustained management interventions would exhibit lower mortality rates, reflecting the mitigating role of maintenance. Finally, we hypothesized that management-related variables would explain a greater proportion of variation in mortality than microsite conditions, highlighting the potential for active intervention to buffer environmental stress in urban environments. To evaluate these expectations, we used a Random Forest model to assess the relative contributions of spatial, environmental, and management predictors to mortality patterns in urban populations of *M. silvioi.*

MATERIALS AND METHODS

Study Area and Species

This study was conducted in the Aburrá Valley, located in the Central Andes of Colombia, encompassing Medellín and 9 surrounding municipalities. The valley ranges from 1,300 m a.s.l. to 2,200 m a.s.l. Steep slopes, shallow soils, and pronounced contrasts in drainage and microclimate predominate across hillside and riparian areas. The region has undergone rapid urban expansion, characterized by increasing impervious surface cover and the fragmentation of green spaces (Paniagua-Villada et al. 2024), resulting in heterogeneous conditions for tree establishment and survival. In late 2023, symptoms of leaf spotting and wilting were observed in *M. silvioi* individuals growing in the living collection at the Botanical Garden of Medellin (BGM). In response, BGM initiated a systematic evaluation of *M. silvioi* across Medellín and the surrounding municipalities of the Aburrá Valley.

Urban Tree Inventory and Sampling

We accessed the city's Urban Tree System (SAU, by its Spanish acronym), a georeferenced digital platform maintained by local environmental authorities to monitor and manage Medellín's urban tree population. The SAU records detailed information for each tree, including species identity, planting date, geographic location, phytosanitary condition, and a chronological log of all management actions.

The SAU database represents the official municipal inventory of planted trees across Medellín and surrounding municipalities; however, coverage may vary spatially depending on monitoring frequency and institutional capacity. Importantly, the SAU provides highly reliable and near-complete records for plantings conducted after 2009, which coincides with the introduction of *M. silvioi* into the city's urban tree system. Therefore, while the dataset provides the most comprehensive available record of *M. silvioi* plantings ($n = 583$), it can be considered a robust representation of the planted population for this species in the city.

Trees classified as "not found" were treated as dead for analytical purposes, following common practice in urban forestry studies (Hilbert et al. 2019). However, we acknowledge that some individuals may have been removed before death due to infrastructure conflicts, safety concerns, or management decisions. As such, mortality in this study reflects functional loss from the urban population rather than strictly biological death.

As of June 2024, the SAU contained 583 registered individuals of *M. silvioi*, of which 127 were marked as "not found" in previous monitoring rounds, suggesting an initial mortality rate of 21.8%. In October

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2024, from the remaining 456 "found" individuals, we randomly selected 100 trees for field assessment. For each randomly selected tree, a neighboring *M. silvioi* tree was sampled, resulting in a total of 200 trees visited. Due to access limitations, 18 trees could not be evaluated, and 4 were physically unreachable. Among the remaining 175 individuals, 59 were alive and 119 were not found and therefore considered dead (Figure 1).

For all sampled live individuals, tree height and crown width were estimated using a high-visibility measuring pole, and diameter at breast height (DBH) was measured at 1.3 m using a diameter tape. Phytosanitary conditions were assessed visually during field evaluations based on observable symptoms, such as leaf necrosis, wilting, branch dieback, and general canopy decline. Each live tree was classified as either healthy or symptomatic, depending on the presence and severity of these indicators. We included the planting date, extracted from SAU. In addition, mechanical damage was recorded when present, including pruning.

Site-Related Factors

Coordinates and elevation were recorded for each tree sampled. To characterize the site-related factors of each tree, we reconstructed the surrounding land-use context using a 3-category classification system based on field observations and SAU records: (1) natural sites include parks, green areas, and riparian corridors adjacent to urban streams; (2) infrastructure comprising areas are dominated by paved surfaces, such as sidewalks, road medians, and traffic islands; (3) built areas are highly urbanized or industrialized

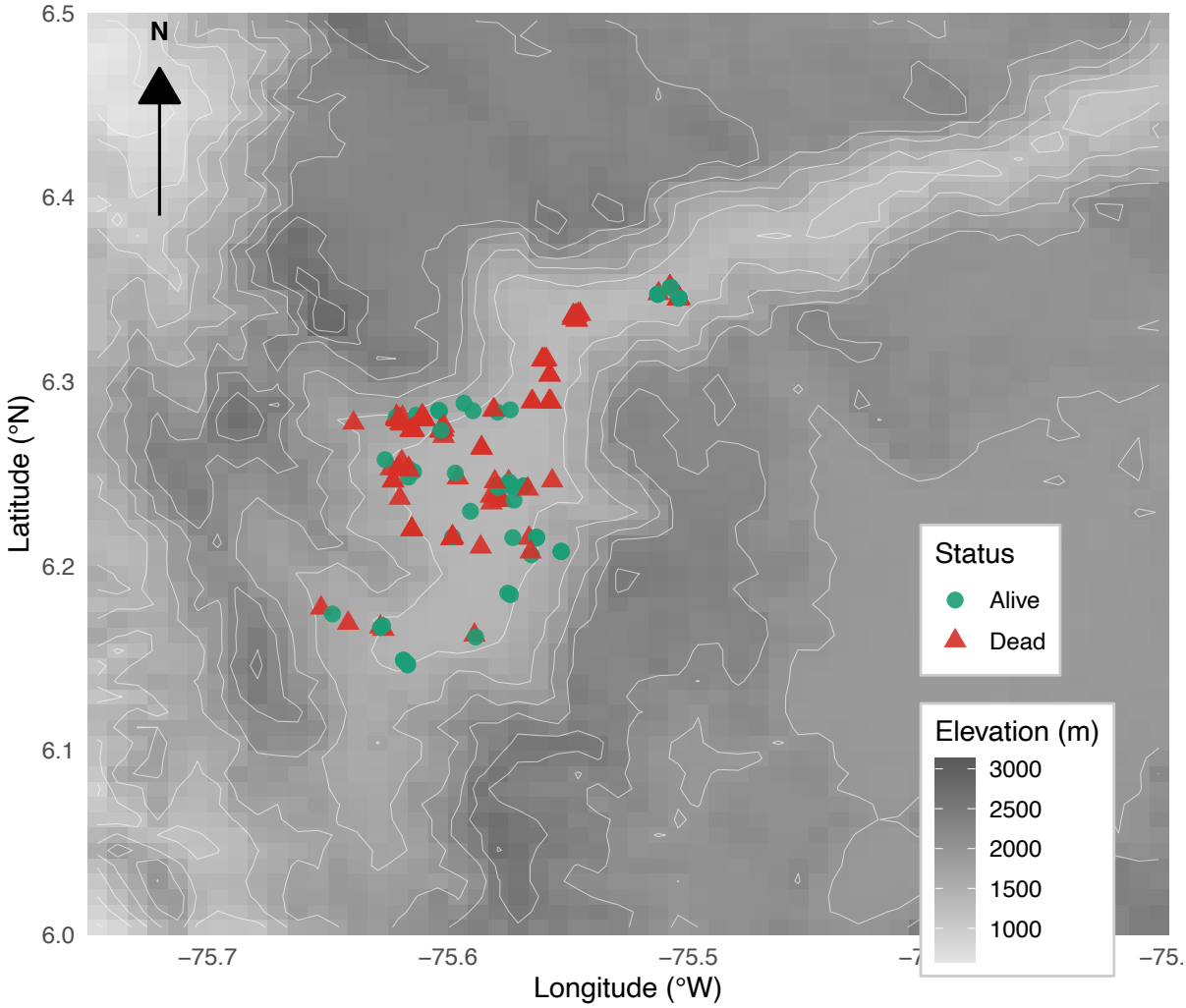

Figure 1. Map of alive (green) and dead (red) *Magnolia silvioi* trees in Valle de Aburrá, Colombia.

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areas with minimal vegetation cover. The slope at the planting site was recorded as a categorical variable with two levels (flat and inclined) based on a visual assessment of the terrain gradient. In addition, the municipality was included as a categorical factor, since the plantings were carried out across 6 municipalities of the Aburrá Valley, each implementing distinct silvicultural and management practices.

To evaluate potential environmental stressors, we assigned a pollution index to each site using a spatial model that integrates proximity to vehicular corridors, air-quality monitoring data, and prevailing wind direction (Mejía-Echeverry et al. 2018). This index served as a proxy for chronic exposure to atmospheric pollutants. Following the approach of Mejía-Echeverry and colleagues, the Aburrá Valley was divided into 6-km² quadrants and classified into high, medium, and control pollution levels based on pollutant load and the biomonitoring properties of *Tillandsia* sp.

Management Site Factors

The number of forestry interventions was obtained from historical records in the SAU, which logs every instance in which a tree receives attention from municipal or institutional personnel. These interventions include pruning, fertilization, base cleaning, visual inspection, and measurement of dendrometric variables. For this study, we compiled both (1) the total number of recorded interventions as a single cumulative variable representing the overall level of management attention received by each tree, and (2) the frequency of each intervention type to describe how management effort was distributed among activities. These variables were treated as numeric predictors and interpreted as proxies for ongoing maintenance intensity.

In July 2025 we revisited all surviving individuals to record their phytosanitary status, classifying each tree as healthy or symptomatic based on leaf necrosis, wilting, branch dieback, or canopy decline. These follow-up assessments provided an updated measure of vitality, allowing us to detect changes in condition relative to the initial survey.

Data Analysis and Modeling

Random Forest was selected for its ability to capture nonlinear relationships and interactions among predictors without requiring prior specification of the model structure (Breiman 2001). Although the dataset is moderate in size (n = 178), Random Forest has been shown to perform robustly in ecological classification problems with limited sample sizes, particularly when predictors are heterogeneous and potentially collinear.

We implemented a Random Forest classification model in R (R Core Team 2024). To identify the key, site- and management-related factors associated with the mortality of *M. silvioi*. The model was trained using the randomForest package (Liaw and Wiener 2002), and variable importance was estimated through permutation-based accuracy reduction. Data handling and import were performed using the dplyr and readxl packages (Wickham and Bryan 2023; Wickham et al. 2023). Prior to model training, the random seed was set to 123 (set.seed[123]) to ensure reproducibility. The complete model was trained using 500 decision trees ($n$tree = 500) and 12 predictors, including geographic coordinates, site conditions, management practices, and planting dates. The binary response variable, Mortality (alive vs. dead), was treated as a factor, and model evaluation was conducted using the out-of-bag (OOB) error rate and a confusion matrix. Variable importance was assessed using the importance() function and visualized via varImpPlot(). To address potential spatial redundancy, pairwise Pearson correlations were calculated among spatial variables (latitude, longitude, m a.s.l., and pollution index). This analysis revealed strong collinearity between m a.s.l. and longitude ($r < –0.70$), prompting the exclusion of altitude from the predictor set to reduce redundancy.

Based on variable importance rankings from the complete model, 5 low-contributing variables (municipality, slope, base clearing, fertilization, and surroundings) were excluded to construct a reduced model. This simplified model included only 6 predictors (latitude, longitude, pollution index, number of interventions, pruning, and planting date) and was retrained using the same Random Forest parameters. Performance of the reduced model was evaluated using OOB error and classification accuracy across classes. To examine the marginal effects of the most influential variables, we generated partial dependence plots (PDPs) using the partialPlot() function in the randomForest package (version 4.4.1)(Liaw and Wiener 2002). PDPs were computed for latitude, longitude, pollution index, interventions, pruning, and planting year, while holding all other predictors at their mean values. The plots illustrate the average predicted probability of mortality (class = dead) across the

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range of each variable, highlighting their independent contribution to model predictions. To evaluate the robustness of the Random Forest results, we fitted a complementary logistic regression model including the 6 strongest predictors. Due to multicollinearity among variables, a regularized approach was used.

To complement the Random Forest analysis, we fitted a regularized logistic regression model using the same reduced set of predictors. Due to multicollinearity among predictors and evidence of near-complete separation, regularization was applied to improve coefficient stability and model interpretability. The logistic regression was implemented in R using the glmnet package (Friedman et al. 2010).

RESULTS

Of the 178 trees successfully assessed, 119 individuals (65.2%) were not found at their registered locations and were therefore classified as dead, while 59 trees (33.1%) were confirmed alive. Among the surviving individuals, 32 exhibited phytosanitary symptoms, including leaf necrosis and wilting, and only 27 were classified as healthy. Mechanical damage was observed in 22 individuals, including wounds on trunks or branches caused by human activity, such as pruning or maintenance operations. The surviving trees had a mean height of 7 m and an average crown width of 2 m. The sampled *M. silvioi* individuals were distributed across the Aburrá Valley (Figure 1). Elevation ranged from 1,407 m a.s.l. to 1,876 m a.s.l. Planting dates ranged from 2009 September 1 to 2023 September 5, with 87 unique dates; the most frequent date was 2012 February 9 (23 trees).

In terms of site-related factors, 112 trees (62.9%) were situated on sloped sites, and 66 (37.1%) on flat terrain. Regarding the surrounding environment, 108 trees (60.7%) were in natural areas, such as parks and riparian corridors, 53 (29.7%) in built sites, and 17 (9.5%) in infrastructure locations. Mortality rates did not vary notably across these categories: in natural areas, 71 trees (66.3%) were found dead; in infrastructure areas, 11 trees (64.7%) were dead; and in built zones, 37 trees (71.2%) were also classified as dead. The pollution index ranged from 2 to 5, with a mean of 3.22.

For management-related variables, pruning was recorded in 49 trees (27.5%), fertilization in 44 trees (24.7%), and base clearing in 71 trees (39.9%). The number of interventions ranged from 0 to 10, with a mean of 2.55 per tree. Dead trees accounted for 58% of all recorded interventions (n = 262), whereas living trees accounted for 42% (n = 192). Similarly, dead individuals received proportionally more fertilization (25 vs. 19) and base-clearing (37 vs. 34) events but fewer pruning operations (16 vs. 33) than surviving trees.

The complete Random Forest model, trained with 11 site and management factors, achieved an OOB error rate of 24.7%. It accurately classified dead individuals (class error: 14.3%) but showed reduced performance for the alive class, with a higher classification error of 45.8%, suggesting a tendency to overpredict mortality. The model was built using 500 trees and 3 variables at each split. Variable importance analysis indicated that site and management factors were important. Latitude was the most influential variable (Mean Decrease Accuracy = 27.1), followed by longitude (20.9), number of interventions (16.8), pruning (19.4), pollution index (15.3), elevation (19.2), and planting date (12.6). These variables collectively contributed most to improving model accuracy. In contrast, slope, fertilization, base clearing, and surroundings exhibited low importance scores (MDA ~ 7), indicating limited predictive power. The inclusion of municipality captured minor management-level variability among local silvicultural practices but did not substantially enhance model performance (Table 1).

To enhance model parsimony and reduce redundancy, a reduced Random Forest model was constructed using the 6 most influential predictors: latitude, longitude, pollution index, interventions, pruning, and planting date (Figure 2). This streamlined model yielded improved performance, with a lower OOB error rate of 20.8%. Classification accuracy increased for both classes, with error rates decreasing to 37.3% for alive trees and 12.6% for dead trees. Notably, the simplified model preserved overall predictive capacity while improving the balance between sensitivity and specificity.

Further analysis confirmed the dominance of spatial and management variables in the reduced model (Figure 2). Latitude was the most influential predictor (Mean Decrease Accuracy = 30.49), followed by pruning (22.35), longitude (22.30), and number of interventions (20.36). Pollution index and planting date also contributed meaningfully (MDA > 18). These findings highlight that a focused set of spatial and management variables can yield a highly interpretable

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and practical model for predicting mortality in urban *M. silvioi* populations, with only a slight improvement in model performance relative to the full version.

PDPs for the 6 most influential predictors (latitude, longitude, pollution index, interventions, pruning, and planting year) showed clear spatial and management patterns (Figure 3). Mortality probability increased in the Southern, low-elevation areas of the Aburrá Valley (latitude < 6.25°) and under higher pollution levels (index ≥ 4.5). In contrast, trees receiving more interventions or pruning exhibited substantially lower predicted mortality. Older plantings (2009 to 2013) showed higher mortality than recent ones (2018 to 2023), reflecting both cumulative stress and improved management over time.

Table 1. Variable importance and performance metrics for the full and reduced Random Forest models predicting mortality in *Magnolia silvioi*. Values in parentheses correspond to the reduced model. M a.s.l. (meters above sea level).

Predictor	Mean Decrease Accuracy	Mean Decrease Gini
Municipality	9.17 (–)	2.21 (–)
Latitude	27.05 (30.49)	17.69 (22.93)
Longitude	22.88 (22.30)	12.57 (16.89)
Pollution index	15.28 (18.66)	4.95 (6.41)
Interventions	17.76 (20.36)	7.49 (9.82)
Pruning	19.36 (22.35)	5.65 (6.67)
Planting date	12.62 (18.15)	8.35 (12.60)
Slope	7.18 (–)	1.94 (–)
Base clearing	7.22 (–)	1.07 (–)
Fertilization	6.63 (–)	1.06 (–)
Surroundings	6.67 (–)	2.70 (–)
M a.s.l.	19.24 (–)	10.47 (–)

The follow-up assessment in July 2025 aimed to determine whether mortality had progressed over the previous year and to corroborate potential signs of decline. Five additional trees that had previously been recorded as alive were no longer viable: two were found standing dead, while no trace remained of the other three. Three of these individuals had already been reported in 2024 with phytosanitary symptoms such as canopy wilt and complete leaf loss, suggesting that their decline had been progressive rather than abrupt. Among the 54 individuals confirmed alive in 2025, 30 (55%) showed foliar spotting, indicating a high prevalence of phytosanitary stress in the surviving population. In addition, one tree exhibited signs of descending wilt, i.e., wilt progressing from the crown downward.

The logistic regression model yielded results consistent with the Random Forest analysis (Table 2), identifying spatial gradients and management intensity

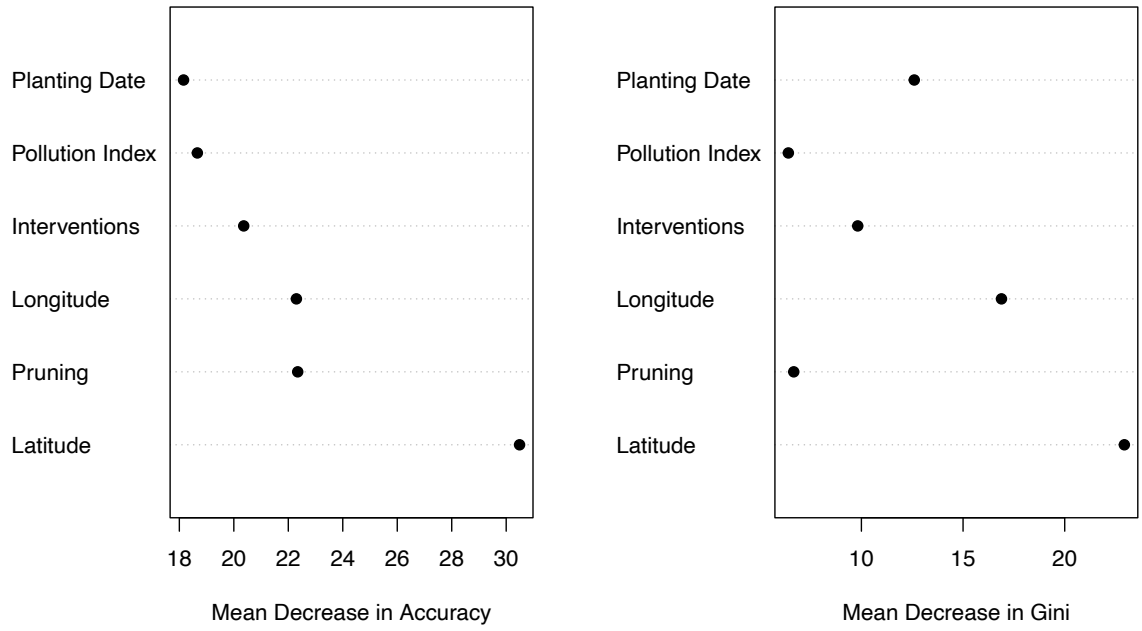

Figure 2. Variable importance in the Random Forest model predicting mortality of *Magnolia silvioi* in Medellín.

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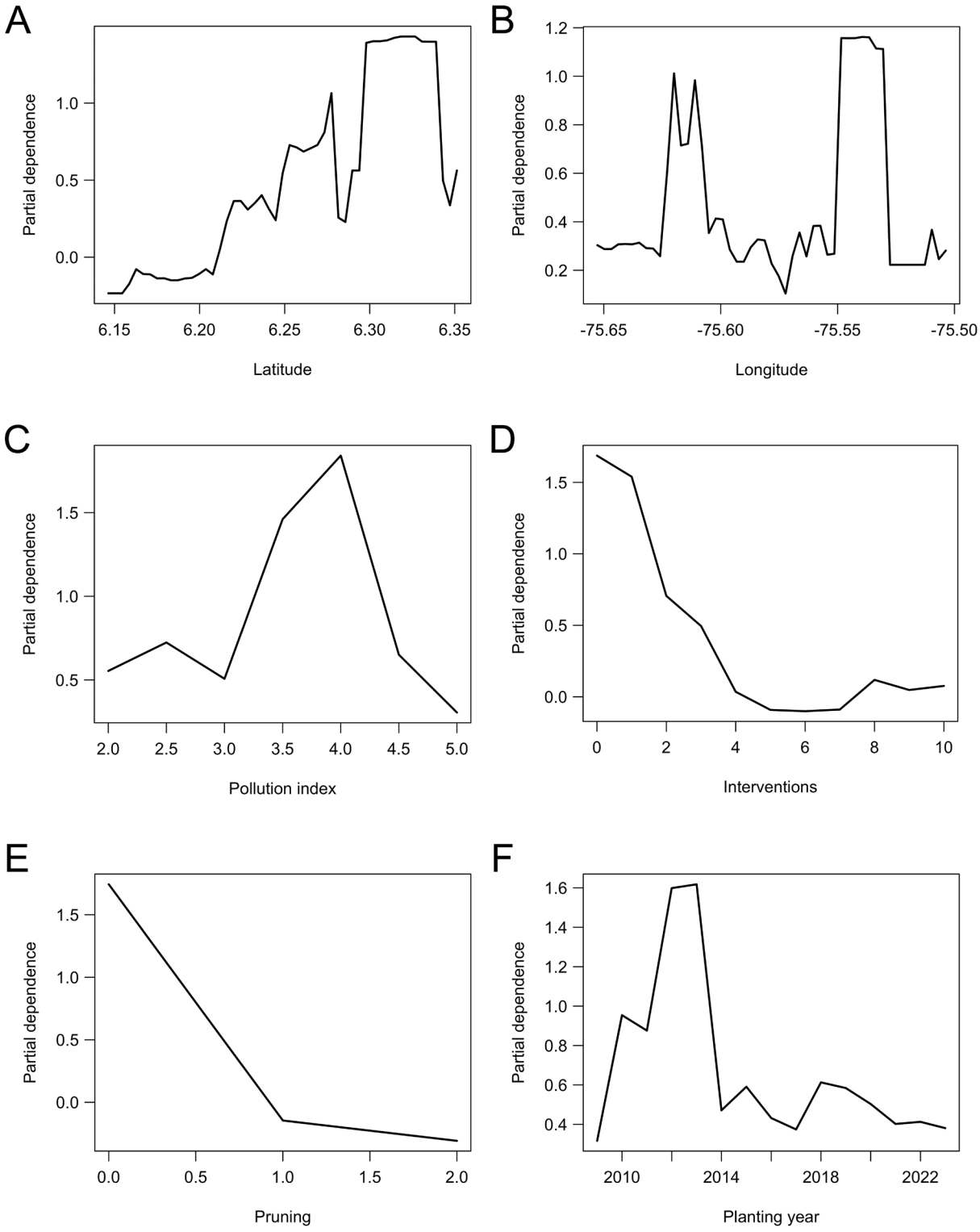

Figure 3. Partial dependence plots (PDPs) showing the effects of 6 key predictors on predicted *Magnolia silvioi* mortality. (A) Latitude; (B) Longitude; (C) Pollution index; (D) Interventions; (E) Pruning; (F) Planting year.

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as the primary drivers of mortality. Latitude showed a strong positive association with mortality (odds ratio = 3.74), whereas longitude exhibited a negative relationship (OR = 0.33), indicating opposing spatial trends across the Aburrá Valley. Management intensity had a significant protective effect: each additional intervention reduced the odds of mortality (OR = 0.46). Similarly, planting year was negatively associated with mortality (OR = 0.71), suggesting improved survival in more recent plantings. In contrast, individual maintenance variables such as pruning, fertilization, and base clearing were not significant in the full model, likely due to collinearity with cumulative intervention frequency. The logistic regression results converged with the Random Forest outputs, reinforcing the role of spatial context and management intensity as key determinants of mortality.

DISCUSSION

Our findings reveal that mortality rates for *M. silvioi* in Medellín are considerably higher than those typically reported elsewhere for temperate regions. Of the 178 individuals assessed, two-thirds (66.3%) were classified as dead, and more than half of the surviving trees showed phytosanitary symptoms, suggesting that the proportion of truly healthy individuals is much smaller than the survival statistics alone indicate. Comparable reviews from North America and Europe involving multiple species report mortality rates ranging from 30% to 50% within the first decade after planting (Roman et al. 2014; Hilbert et al. 2019), underscoring the severity of the situation in a tropical megadiverse city such as Medellín. This makes our study one of the first to provide species-specific survival analysis for an endangered tropical tree in an urban setting. Most current mortality frameworks have been developed in temperate cities and multispecies systems (Hilbert et al. 2019), whereas evidence from tropical urban environments and endangered native trees remains scarce.

Most urban mortality studies report aggregate patterns across diverse species (Roman et al. 2014; Hilbert et al. 2019), yet evidence suggests that even closely related taxa can respond very differently to environmental stressors. Within the genus *Magnolia*, Sjöman et al. (2018) compared the drought tolerance of 7 species. They found a wide range of interspecific responses and concluded that magnolias, as a group, are relatively drought-sensitive compared to other ornamental taxa. This highlights the difficulty of making broad generalizations across species and underscores the need for species-specific research to fully capture the drivers of mortality. In this context, our analysis of *M. silvioi* provides a rare example of species-focused evaluation in a tropical urban environment, offering insights that cannot be inferred from generalized multispecies datasets. While these results highlight the importance of species-specific evaluations, our analysis also shows that mortality in *M. silvioi* is not confined to particular habitats but is pervasive across urban settings, regardless of whether trees are planted in favorable or unfavorable environments.

While species-level vulnerability is clear, our analysis also shows that mortality is not confined to any particular habitat. Mortality patterns were consistently high across all site categories, including parks and riparian zones that might be expected to provide more favorable growing conditions. Rates ranged from 65% to 71% across natural, infrastructural, and built environments, highlighting the pervasiveness of urban stressors throughout the Aburrá Valley. Even trees in green areas experienced substantial decline,

Table 2. Coefficients and odds ratios from the regularized logistic regression model predicting *Magnolia silvioi* mortality.

Variable	Coefficient	Odds ratio	Direction of effect	Relative importance
Latitude	+1.32	3.74	Higher mortality southward	High
Longitude	–1.11	0.33	Spatial gradient	High
Pollution index	+0.05	1.06	Slight increase in mortality	Moderate
Interventions	–0.78	0.46	Reduced mortality with increased management	High
Pruning	0.00	1.00	No independent effect	Low
Planting year	–0.35	0.71	Reduced mortality in recent plantings	Moderate

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indicating that urban stressors such as compacted soils, altered hydrology, and poor air quality may override the benefits of proximity to vegetation. This finding echoes Hilbert et al. (2019), who emphasize that surrounding land use is not always a strong predictor of survival outcomes and suggest that active management may play a more decisive role than site characteristics in determining the persistence of conservation-priority species in urban landscapes.

Although this study was initially motivated by concerns that a fungal pathogen might be contributing to elevated mortality, our results do not allow us to confirm disease as the primary cause of death. For the vast majority of individuals, direct causes could not be established because trees, or their remains, were no longer present at the registered locations. Moreover, the monitoring records available through the SAU system document survival status but do not capture historical symptoms or proximate causes of decline. Consequently, while phytosanitary stress was evident in many surviving individuals, attributing overall mortality to a specific pathogen remains inconclusive. Our results indicate that mortality is multifactorial and is more strongly shaped by environmental stress and management than by a single biotic agent.

The Random Forest models provided further insight into the relative importance of site and management factors in explaining mortality outcomes. In the full model, spatial variables such as latitude and longitude, together with management-related factors including pruning and the cumulative number of interventions, emerged as the most influential predictors. By contrast, slope, fertilization, base clearing, and surrounding land use contributed little to classification accuracy. This pattern suggests that *M. silvioi* mortality is more strongly associated with broader spatial gradients and active management than with local microsite characteristics. While microsite preparation, such as base clearing, may indicate adequate planting procedures, its limited predictive power suggests that one-off interventions have little effect on long-term survival compared with variables representing consistent, repeated care, such as pruning or cumulative interventions. This finding is consistent with studies showing that early planting conditions are often overridden by chronic urban stressors, including air pollution, soil compaction, and hydrological alterations, unless supported by ongoing maintenance (Koeser et al. 2013; Hilbert et al. 2019). In practical terms, the weak predictive performance of microsite variables suggests that the survival of endangered species in cities depends less on how they are initially established and more on whether municipalities commit resources to sustained monitoring and adaptive management throughout the trees' life cycles.

The reduced model, which retained only 6 variables (latitude, longitude, pollution index, interventions, pruning, and planting date), confirmed latitude as the single most influential predictor, suggesting that spatial gradients strongly structure mortality risk in *M. silvioi*. This signal is unlikely to represent environmental variation alone: geomorphological contrasts within the Aburrá Valley create sharp differences between flat central zones and steep hillside areas, where shallow soils, variable drainage, and slope instability limit tree performance (Aristizábal and Yokota 2008). At the same time, municipal boundaries closely align with latitudinal gradients, and each jurisdiction applies distinct management practices based on its budget, staffing, and priorities (Restrepo et al. 2015; AMVA 2015). Restrepo et al. (2015) found that the municipality was a significant predictor of progressive tree deterioration, reinforcing the notion that governance plays a critical role in shaping outcomes. For example, municipalities such as Envigado (located in the North of Aburrá Valley) have developed their own "Plan Maestro de Zonas Públicas Verdes" (Universidad Nacional de Colombia and Alcaldia de Envigado 2015), while others rely primarily on region-wide guidelines, such as The Guide to Urban Tree Management (AMVA 2015). Thus, the strong influence of latitude may reflect the interaction of geomorphological and institutional factors, emphasizing that urban tree survival may be shaped by coupled socio-environmental processes rather than site characteristics alone. Collectively, these findings suggest that sustained management intensity may outweigh microsite conditions in determining the long-term persistence of conservation-priority trees in tropical urban environments.

In addition to spatial gradients, management intensity emerged as a decisive factor in the survival of *M. silvioi*. Trees that received more frequent interventions, particularly pruning, were consistently more likely to survive, whereas individuals with little or no recorded care showed markedly higher decline. This finding reinforces Hilbert et al.'s (2019) observation that maintenance is one of the most underestimated

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yet critical determinants of urban tree longevity, and it reinforces the notion that urban survival is contingent not only on initial site conditions but also on continuous human care (Koeser et al. 2013; Vogt et al. 2015). Our results further suggest that one-off interventions, such as base clearing or fertilization, offer limited long-term benefits compared to repeated and structured care. In practical terms, these patterns indicate that the persistence of endangered species planted outside their natural range depends less on microsite conditions and more on whether municipalities commit to sustained, adaptive management throughout the trees' life cycles. However, the model's tendency to overpredict mortality in surviving individuals also reflects the difficulty of capturing idiosyncratic effects, such as individual tree resilience, undocumented local interventions, and unaccounted variables. This may also be an artifact of unequal classes, since "dead" trees outnumber "alive" trees.

The complementary monitoring conducted in 2025 provides important insights into the dynamics of mortality and decline in *M. silvioi.* The fact that 3 of the 5 newly dead individuals had previously shown symptoms of canopy wilt and leaf loss suggests that much of the additional mortality represents the culmination of pre-existing decline rather than new acute stressors. This highlights the importance of distinguishing between sudden mortality events and progressive deterioration, which can only be captured through repeated assessments. Equally concerning is that more than half of the surviving trees (57.7%) displayed foliar spotting along with localized canopy desiccation and crown dieback. These symptoms point to a high prevalence of phytosanitary stress within the surviving population, raising the possibility that further mortality may occur in the coming years. In practical terms, these findings emphasize that survival status ("alive" vs. "dead") is an insufficient metric for evaluating the performance of threatened species in urban environments. Instead, incorporating vitality indicators into monitoring protocols provides a more sensitive measure of population health and offers earlier warning signals for intervention. Future studies might include Cox proportional hazards models, a method in survival analysis used to model the time to an event, such as mortality, rather than just whether the event occurred. Latitude/longitude were found to be strong predictors; however, future research should include spatial autocorrelation tests, such as Moran's I, or explicit linking to municipal management datasets, land-use gradients, or geomorphic layers. Although Random Forest models provided strong predictive performance, their limited interpretability requires careful consideration. The complementary logistic regression analysis yielded consistent results, identifying spatial gradients and cumulative management intensity as the strongest predictors of mortality. The absence of independent effects for individual maintenance variables in the logistic regression model likely reflects collinearity among management actions, as pruning, fertilization, and base clearing are typically recorded as part of broader intervention events. In contrast, the Random Forest model was better able to distinguish the relative contribution of correlated predictors. Together, these approaches suggest that overall management intensity, rather than isolated interventions, is the dominant factor influencing survival.

Our findings provide an empirical basis for developing adaptive monitoring protocols, risk-based maintenance strategies, and cross-municipal coordination in the Aburrá Valley. The strong influence of management variables demonstrates that the long-term survival of *M. silvioi* depends on proactive care rather than simply on initial planting. Adaptive monitoring protocols, which include standardized health assessments and systematic recording of interventions, can serve as early warning systems for decline. Risk-based strategies are also essential: individuals residing on steep slopes, in highly paved areas, or exposed to pollution should be prioritized for more frequent inspections and targeted interventions. Finally, because latitude in our models likely reflects both environmental gradients and differences in municipal management, improving cross-jurisdictional coordination is critical. Harmonizing practices among municipalities through shared standards, training, and pooled resources could reduce inequalities in care and enhance the survival prospects of threatened native species. Together, these measures advance evidence-based urban forestry and support the integration of conservation-priority taxa into tropical cities, enabling them to contribute to both biodiversity goals and the delivery of ecosystem services.

Several limitations should be acknowledged when interpreting our findings. First, urban tree mortality studies differ widely in how they handle missing trees (Hilbert et al. 2019). If a tree is removed or no longer visible, the specific cause, whether due to disease,

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pest infestation, or mechanical damage, cannot be determined. In this study, missing individuals were counted as dead, since our focus was on the binary outcome of survival versus mortality. Nevertheless, regardless of whether individuals died in situ or were removed before complete decline, these records represent a substantial functional loss of *M. silvioi* from Medellín's urban population. While this approach provides a clear metric for assessing population status, it leaves the underlying causes unresolved and highlights the need for repeated, structured assessments of target species. This issue also complicates direct comparisons across studies with varying definitions and monitoring intervals, a challenge noted in previous reviews (Hilbert et al. 2019). Second, the planting of *M. silvioi* across Medellín and neighboring municipalities occurred over more than a decade, involving multiple municipal entities, various methods, and multiple nursery stock sources. Due to this extended timeline and diversity, we were unable to establish a consistent baseline of planting practices or stock quality, despite these factors potentially having a significant influence on early establishment and long-term survival. Third, our study considered slope as a two-state classification (flat vs. sloped) and found it was not a strong predictor of survival. However, given the geomorphological complexity of the Aburrá Valley, this coarse classification likely masks important variation. Future studies should assess soil compaction, depth, and moisture more directly to clarify their role in shaping *M. silvioi* performance. Finally, although our study provides a rare species-specific perspective, it should be recognized that most comparative mortality studies in the literature (e.g., Roman et al. 2014; Hilbert et al. 2019) treat diverse species pools and focus on general drivers of urban tree mortality. By contrast, our focus on a single endangered species offers a more refined perspective but also limits the breadth of comparison across taxa. These results underscore the need for region-specific, species-focused monitoring programs in tropical cities, since mortality dynamics cannot be reliably inferred from temperate, multispecies contexts.

CONCLUSIONS

Maintenance emerged as one of the most influential factors affecting *M. silvioi* survival in Medellín's urban landscape, supporting previous findings that care intensity is critical for tree longevity (Hilbert et al. 2019). Strengthening management through the existing Valle de Aburrá framework by promoting consistent pruning, monitoring, and phytosanitary protocols would enhance coordination and continuity in tree care across municipalities. Best practices in adaptive management should include periodic monitoring protocols to track tree vitality, stress symptoms, and details of the intervention history. Such protocols are particularly crucial when using endangered species such as *M. silvioi* in urban greening programs, as they provide early warning indicators of decline and create opportunities for timely corrective action. By institutionalizing regular monitoring and structured maintenance, cities can enhance the resilience of conservation-priority species while ensuring that investments in biodiversity-based urban forestry translate into long-term ecological and social benefits.

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