Species-Specific Responses of Urban Tree Phenology to Climate Drivers in Denver, Colorado

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Executive Summary

1.1 Introduction

Urban trees are among the most effective natural mitigators of the urban heat island (UHI) effect—a phenomenon in which urban regions consistently exhibit higher average temperatures than nearby rural areas. The UHI arises primarily from the prevalence of impervious surfaces, such as asphalt, concrete, and rooftops, which absorb and retain solar radiation and reduce nighttime cooling (Oke, 1982; EPA, 2023). These elevated temperatures exacerbate energy demand, degrade air quality, and increase heat-related health risks for urban residents (Stone, 2012). As global temperatures continue to rise and urbanization expands, the effects of UHIs are expected to intensify in the coming decades (Stone, 2012). By providing shade and facilitating evapotranspiration, trees can reduce surface and ambient air temperatures by several degrees. Studies have demonstrated that neighborhoods with mature tree canopy cover experience measurably cooler microclimates compared to areas with limited vegetation (Ziter et al., 2019; Alonzo et al., 2021). Given the increasingly critical role of urban forests in climate resilience strategies, it is essential to understand the drivers of urban tree phenology—the seasonal patterns of leaf emergence, growth, and senescence—and how these patterns may shift as environmental conditions change. The timing and duration of these seasonal patterns are strongly influenced by climate, particularly temperature and precipitation. Elevated temperatures caused by anthropogenic climate change can lengthen the growing season of urban trees (Zhang et al., 2022; Yang et al., 2020). Higher spring temperatures typically accelerate leaf emergence, while warmer fall temperatures may delay leaf senescence, extending the period of active growth and canopy cover (Zhang et al., 2022; Zhou et al., 2020). This extended canopy period can enhance the cooling benefits of urban trees by increasing shade and evapotranspiration, helping to mitigate the urban heat island effect. However, these benefits are not guaranteed: warmer winters followed by late spring freezes can delay leaf-out, disrupt flowering, and reduce the expected benefits of extended growing seasons, particularly in species that leaf out early in spring (Chamberlain et al., 2021; Fu et al., 2024). Precipitation patterns add another layer of complexity. Spring drought can delay leaf-out and flowering, while wet conditions may accelerate growth but increase vulnerability to disease and root stress. In the fall, low precipitation or drought stress can trigger earlier leaf senescence, shortening the period of active growth and reducing canopy cover (Cleland et al., 2007; Peñuelas et al., 2004; Li et al., 2019). Critically, the interaction of temperature and precipitation determines ultimate outcomes, as insufficient soil moisture can counteract the effects of warmer temperatures, underscoring the complex challenges that climate change poses for urban tree health and their role in mitigating urban heat. Monitoring and predicting these phenological responses require appropriate observational tools. The body of research on urban phenology has evolved along multiple scales of observation. Coarse-scale studies often rely on remote sensing platforms such as MODIS, which provide high temporal but low spatial resolution data to monitor citywide phenological trends and seasonal canopy dynamics (Zhang et al., 2004; Melaas et al., 2016). At the opposite end of the spectrum, fine-scale studies use in-situ observations or near-surface imaging networks like PhenoCam to capture species-level variation and microclimate effects that are often obscured at broader scales (Richardson et al., 2018; Klosterman et al., 2018). More recently, high-resolution satellite constellations such as PlanetScope have emerged as a valuable intermediate approach, combining the spatial precision needed to resolve individual trees with the temporal frequency required to monitor phenological changes across large urban areas (Bolton et al., 2020; Alonzo et al., 2020). Researchers can now study urban vegetation dynamics at unprecedented detail and scale. This new approach also allows researchers to simulate and predict how different urban tree species may respond to future climate conditions, supporting proactive planning for urban resilience and heat mitigation.

1.2 Study Context and Objectives

These new methodological advances are particularly valuable for cities facing significant projected climate changes. Denver, Colorado provides a compelling case study, as the city confronts both substantial warming and precipitation uncertainty that will directly affect urban tree phenology and the cooling services trees provide. Understanding these dynamics is critical not only for Denver but also for similarly positioned mid-latitude cities experiencing rapid warming and uncertain precipitation futures. According to Colorado State University's Colorado Climate Center's most recent Climate Change in Colorado report, by mid-century, Denver is projected to see temperatures rise between 1.4°C and 3.1°C compared to the 1971–2000 baseline. The city has already warmed by approximately 1.1°C over the past 30 years, with the most pronounced increases occurring during summer and fall. Under moderate emissions scenarios, Denver's climate will resemble that of Pueblo, Colorado today, whereas higher emissions scenarios could make it feel more like Albuquerque, New Mexico. Summer and fall are expected to warm slightly more than winter and spring, with summer temperatures increasing by 2.2–3.3°C and winter by 1.7–2.2°C. This warming is projected to drive dramatic increases in extreme heat events: by mid-century, Denver could experience an average of 7 days per year exceeding 37.8°C (100°F) and roughly 35 days above 35°C (95°F), compared to very few such days historically. In essence, the typical year in 2050 may be as warm as the hottest years on record today. Future precipitation patterns for Denver remain highly uncertain, compounding the challenge for urban forest managers. Climate models (CMIP5 and CMIP6 under RCP 4.5 scenarios) disagree on whether precipitation will increase or decrease, with projections ranging from -7% to +7% by 2050. While northern Front Range projections, including Denver, are generally shifted toward wetter outcomes compared to southern Colorado, the consensus is weak outside of winter, when most models project an increase in precipitation. Overall, the share of precipitation falling during heavy downpours is expected to rise from about 46% to 50% by mid-century. Despite these potential increases, warmer temperatures may offset benefits by pulling more moisture from snowpacks, soils, and plants, compounding the risk of drought and reducing water availability. This risk is not hypothetical: Denver has already experienced persistent dry conditions in the 21st century, with four of the five driest years in the 128-year record occurring since 2000. Using near-daily NDVI observations for individual trees from PlanetScope images collected over Denver, combined with daily temperature and precipitation observations from 2018 to 2024, this study models phenological metrics (greenup, senescence, peak season, and dormancy) based on climate-specific variables (spring and fall temperature and precipitation) and land cover variables that control for localized microclimates. PlanetScope's 3-meter spatial resolution and near-daily revisit frequency uniquely enable individual tree monitoring at scales previously impossible, bridging the gap between coarse satellite imagery and labor-intensive ground observations. The study period captures years with average annual temperatures and precipitation both below and above the 1971-2000 baseline. For instance, 2024 was the third warmest year in Denver's recorded history, with temperatures 1.8°C above the baseline—approximating the lower range of mid-century projections—while years like 2019 and 2020 were notably drier than average. This range of climate variability, encompassing conditions like those projected for 2050, enables us to model how Denver's urban trees respond to moderate temperature increases and varying precipitation patterns under realistic future scenarios. By examining species-level variation in phenological responses, this report aims to identify which tree species may be more vulnerable or resilient to future climate conditions. These findings will inform species selection and management strategies for climate adaptation in Denver and comparable mid-latitude cities facing similar climate trajectories.