QUANTIFYING LEACHABLE PHOSPHORUS FROM COMMON URBAN TREE SPECIES

by

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Abstract

Urban runoff containing high amounts of nutrients like nitrogen (N) and phosphorus (P) has long been established as a driver of surface water eutrophication. In residential areas, a primary source of nutrients is derived from leaf litter and other organic debris. P contained in leaves is leached and transported by stormwater to surface water at end-of-pipe locations. The majority of P from leaves is in the dissolved phase which can be difficult to remove using conventional treatment practices, leaving source control as the most viable option. Additional tools are needed to help forecast how different tree species may improve or hinder contributions of nutrients to runoff. For this reason, ten street tree species that are common throughout the contiguous U.S. were chosen to evaluate the effect of species and regional climate on leachable P from tree leaves. Laboratory experiments were conducted to characterize P leaching dynamics and models were developed to predict time variable P release from different species. After 48 hours, there were significant differences in the amount of P released by different species (ranged from 2.16 to 0.03 mg P g^{-1} leaf) and by the same species from different regions of the U.S. (ranged from 1.07 to 0.03 mg P g^{-1} leaf). There were also temporal variations in leaching across species; for example, in the first 12 hours of leaching, the percentage of maximum dissolved P released ranged from 5 to 90%. On average, more than half of the P was lost in the first 12 hours of exposure to water, making guided source control important to reduce inputs to surface water from key locations. Predictive equations describing P release over time were developed and used in conjunction with ArcGIS to identify locations in Madison, WI with high potential for P leaching from street trees. Results from this study can be used to provide an assessment of current conditions and help managers gain insight by proactively tailoring future planting scenarios and other source management practices that minimize nutrients in runoff.

1. Introduction

Urban runoff containing high amounts of nutrients like nitrogen (N) and phosphorus (P) has long been established as a driver of surface water eutrophication (Howarth et al., 2000; Melcher & Horsburgh, 2017; Yang & Lusk, 2018). Eutrophication of surface water bodies has negative impacts on both ecosystem function (e.g., cyanobacteria blooms, hypoxic and anoxic water conditions, murky water, noxious odors; Carpenter et al., 1998) and human health (e.g., conjunctivitis, gastrointestinal, dermatological diseases; Zhidkova et al., 2020). In urban environments, impervious surfaces such as streets, sidewalks, and parking lots constitute a significant portion of individual watersheds, providing a hydrologic pathway to directly transfer rainfall into the storm sewer network and to surface water (Arnold & Gibbons, 1996). Impervious surfaces lead to decreases in infiltration and the 'urban stream syndrome' which includes 'flashier' hydrographs, elevated concentrations of nutrients in runoff, and altered channel morphology (Walsh et al., 2005; Hogan & Walbridge, 2007; O'Driscoll et al., 2010). Despite the widespread implementation of end-of-pipe management practices such as detention ponds, urban water quality remains an issue. Consequently, there is a growing interest in mitigating the entry of nutrients into stormwater systems from the outset (Burns et. al, 2012).

Nutrients from urban settings can enter surface runoff from a variety of sources, including but not limited to fertilizers, pet wastes, road salts, and organic debris (e.g., grass clippings, tree leaves) (Berretta & Sansalone, 2011; Hochmuth et al., 2012). Organic debris, especially in regions characterized by dense overhead tree canopies (e.g., suburban streets), is regarded as a principal source of nutrients (Waschbusch et al., 1999). During autumn months in the Northern

Hemisphere (September through November), deciduous trees lose their leaves. In urban settings, fallen leaves are often piled in street gutters where storm runoff is conveyed before entering the storm sewer network (Selbig, 2016; Janke et al., 2017). Phosphorus contained in leaves is leached and transported by stormwater to surface water at end-of-pipe locations.

Senesced leaves represent a notable source of P in suburban settings. For example, as the aerial fraction of street tree canopy increased (compared to other land cover in suburban settings, e.g., streets, lawns, and roofs), a strong positive correlation in both TP and soluble reactive P in storm runoff was observed (Janke et al., 2017). Leaching potential from leaves ranges from 84 to 244 mg of TP per square meter of street tree canopy arriving in end-of-pipe surface waters (Selbig, 2016; Bratt et al., 2017). Urban woodlands can also significantly reduce P inputs via rainwater interception and nutrient uptake (by up to a 62% reduction compared to unwooded streets; Brett et al., 2005; Alphonso et al., 2015; Barr et al., 2017) however, when left unchecked, P leached from senesced tree leaves can counteract these reductions (Hutchins et al., 2023). Importantly, one study found that a majority (85 – 100%; Wang et al., 2020) of the P leaching from tree leaves is in the dissolved phase. Dissolved P is difficult to remove from stormwater using conventional treatment practices (Hogan and Walbridge, 2007; Bell et al., 2017), leaving source control as an important mitigation practice.

Leachable phosphorus can vary considerably among different tree species (Cowen & Lee, 1973; Dorney, 1986; Wallace et al., 2008; Duan et al., 2014; Hobbie at al., 2014; Wang et al, 2020; Hill et al, 2022) (Table 1, Table 2). Not only does the leachable P vary among different species (e.g. *Fraxinus pennsylvanica* (Green Ash) vs. *Acer platanoides* (Norway Maple)), but also within the same genus (e.g. *Acer* (Maple)). For city managers to effectively make informed environmental decisions on tree selection and leaf removal, clarifying the impacts of urban tree species on phosphorus loads in runoff is important.

Table 1: Summary of leachable TDP from leaf leaching experiments.

Source	**Methods**	**Tree species**	**TDP (mg g^{-1})**
Cowen and Lee (1973)	Leaves were soaked for 1 hour, followed by 1.5 hours of percolation. Collected from Madison, WI	Oak	0.05
		Poplar	0.14
Dorney (1986)	2 hours of leaching in deionized water. Collected from Milwaukee and Shorewood, WI	Sugar Maple (*Acer saccharum*)	0.26
		Silver Maple (*Acer saccharinum)*	0.23
		Green Ash (*Fraxinus pennsylvanica)*	0.19
		Honey Locust (*Gleditsia triacanthos*)	0.18
		White Ash (*Fraxinus americana*)	0.16
		American Elm (*Ulmus americana*)	0.16
		Basswood (*Tilia americana*)	0.10
		Chinese Elm (*Ulmus parviflora*)	0.09
		Littleleaf Linden (*Tilia cordata*)	0.09
		Pin Oak (*Quercus palustris*)	0.08
		Norway Maple (*Acer platanoides*)	0.08
		Hessian Ash (*Fraxinus excelsior*)	0.07
		Weeping Willow (*Salix babylonica*)	0.04
Qiu et al. (2002)	24 hours of leaching in rotary shaker. Collected from fringing areas of five wetlands near Perth, Australia	Flooded gum (*Eucalyptus rudis*)	0.358 – 0.560
		Paperbark (*Melaleuca preissiana*)	0.176 – 0.684
		Orange wattle (*Acacia saligna*)	0.461
Wallace et al. (2008)	The leaves were soaked in reverse osmosis water for 10 days. Samples and exchange of water happened at 6 hours, 1, 2, 3, 5, 7, and 10 days. Reported filterable reactive phosphorus (FRP) values are maximal release. Collect in Southern Australia from urban recreational areas.	Grass cuttings	0.746
		London Plane (*Platanus x acerifolia*)	0.682
		River Red Gum *(Eucalyptus camaldulensis*)	0.21
		White Poplar (*Populus alba*)	0.118
		English Elm (*Ulmus procera*)	0.025
Duan et al. (2014)	90 hours of leaching with samples taken at 6, 18, 42, and 90 hours. Reported TDP is maximal release. Samples collected near Baltimore, MD.	Red Maple (*Acer rubrum*)	0.44
		Riverbank Grape (*Vinis riparia*)	0.26
		Silver Maple (*Acer saccharinum*)	0.24
		American Elm (*Ulmus americana*)	0.22
		Black Willow (*Salix nigra*)	0.06
		White Pine (*Pinus strobus*)	0.02

Table 2: Summary of leachable TDP from leaf leaching experiments (Continued).

Source	**Methods**	**Tree species**	**TDP (mg g^{-1})**
Hobbie et al. (2014)	24 hours of leaching with samples taken at 0.5 and 24 hours. Reported values are maximal release. Samples collected from urban street trees in Minneapolis, MN.	Littleleaf Linden (*Tilia cordata*)	0.98
		Swamp White Oak (*Quercus bicolor*)	0.90
		Norway Maple (*Acer platanoides*)	0.62
		Green Ash (*Fraxinus pennsylvanica*)	0.41
		Freeman Maple (*Acer freemanii*)	0.37
Wang et al., 2020	48 hours of leaching with samples taken at 0, 2, 6, 12, 24, and 48 hours. Reported values are maximal release. Samples were collected from residential neighborhoods in Madison, WI.	Norway Maple (*Acer platanoides*)	2.13
		Green Ash (*Fraxinus pennsylvanica*)	1.65
Hill et al., 2022	24 hours of leaching with sample taken at 24 hours. Reported values are total P for intact leaves. Samples collected from trees in Pocatello, ID.	Norway Maple (*Acer platanoides*)	1.63
		Littleleaf Linden (*Tilia cordata*)	0.74
		Siberian Elm (*Ulmus pumila*)	0.58
		Russian Olive (*Elaeagnus angustifolia*)	0.57
		Honey Locust (*Gleditsia triacanthos*)	0.40
		Green Ash (*Fraxinus pennsylvanica*)	0.09

Deciduous tree leaves can be separated into simple and compound leaf structures (Figure 1). Simple leaves are singular on the stem, never divided into smaller leaflet units, and are attached to the twig by their petiole (Figure 1). The margins of simple leaves can be smooth, jagged, lobed, or parted. Common examples of trees with simples leaves in North America include many maple (*Acer* genus), sycamore (*Platanus*), and sweetgum (*Liquidambar*) trees. Compound leaves have leaflets attached to a main stem, which are in turn attached to the twig (Figure 1). Common examples of trees with compound leaves include sumac (*Rhus* genus), hickory (*Carya*), and ash (*Fraxinus*).Within the compound structure, there are three types: palmate, pinnate, and double pinnate.

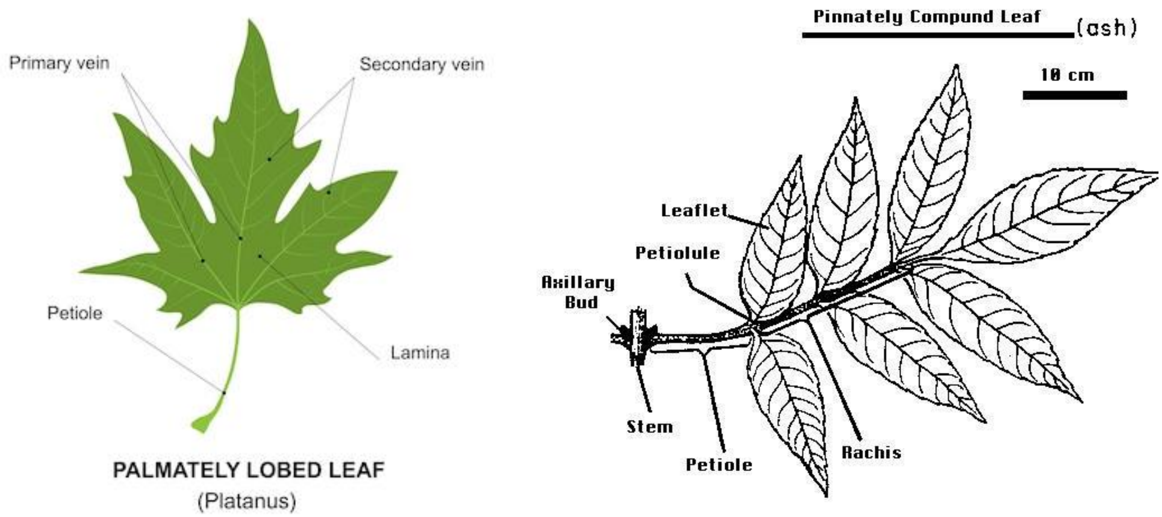

Figure 1: Diagrams of simple (left) and compound (right) leaves (UW-Madison Botany Department)

Palmate compound leaves have leaflets that radiate from the end of the stem and often resemble a hand-and-finger shape (Figure 2). The buckeye tree (*Aesculus glabra*) is a common tree in the U.S. with palmate structure leaves. Pinnate leaves have multi-divided leaflets on both sides of their main stem, which can be arranged evenly (without a terminal leaflet on the end of the stem), oddly (with a terminal leaflet, Figure 2), or alternately. Common trees in the U.S. with pinnate leaves are hickory (*Carya)*, walnut (*Juglans*), ash (*Fraxinus*), and honey locust (*Gleditsia*) trees. Double pinnate leaves have leaflets that grow off secondary stems, which extend from the main stem (Figure 2). Kentucky coffeetree (*Gymnocladus dioicus*) is a common tree with double pinnate leaves.

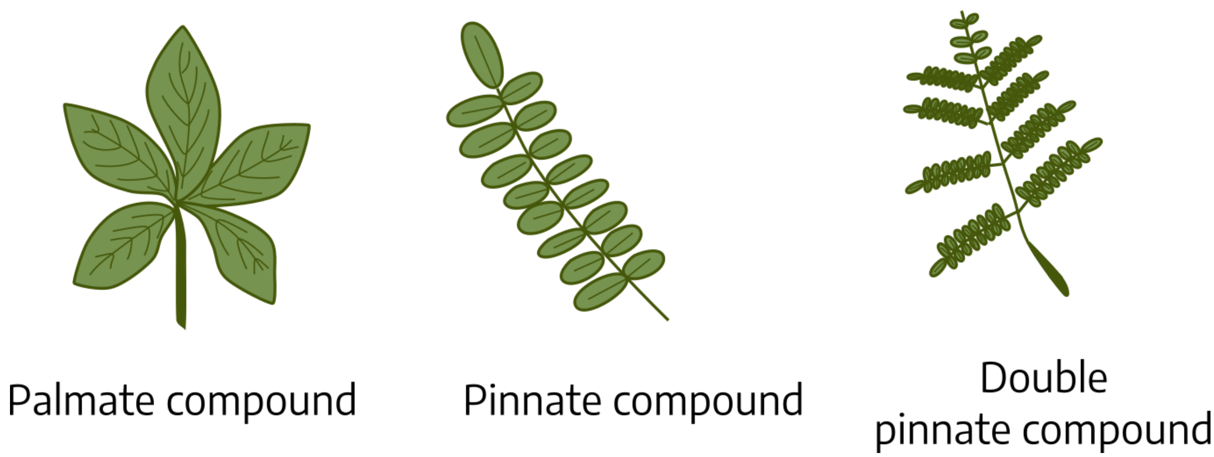

Figure 2: Examples of palmate compound (left), pinnate compound (middle), and double compound (right) leaves (Virginia Cooperative Extension Master Gardener Program Handbook, 2023).

In addition to the variability in leachable P across leave species, climate impacts the chemical composition of tree leaves. Multiple studies have established a correlation between plant litter P concentrations and mean annual temperature (MAT), mean annual precipitation (MAP), and absolute latitude (Reich and Oleksyn, 2004; Yuan and Chen, 2009; Kang et al., 2010; Boyero et al., 2017; Xie et al., 2022). P concentrations in deciduous, broadleaf, or angiosperm tree leaves (measured as mg P/g leaf or % P) generally decreased from colder to warmer MAT (Reich and Oleksyn, 2004; Yuan and Chen, 2009; Boyero et al., 2017; Xie et al., 2022). Similarly, as MAP increased, leaf litter P decreased (Yuan and Chen, 2009, Kang et al., 2010; Boyero et al., 2017;

Xie et al., 2022). Reich and Oleksyn (2004) reported leaf litter P increased from the tropics (0 degrees latitude) to the midlatitudes (30 to 60 degrees latitude; $R^2 = 0.34$, $p < 0.0001$) and then plateaued or slightly decreased at high latitudes (40 to 60 degrees latitude). This pattern was attributed to temperature-related plant physiology, soil substrate age, and biogeochemical effects associated with changing climates with latitude. In other studies, different non-linear relationships were observed; a convex relationship where minimum P concentrations in leaf were at 20 to 30 degrees absolute latitude ($R^2 = 0.06$, $p = 0.064$; Boyero et al., 2017) and a concave quadratic relationship where leaf litter P peaked from 25 to 50 degrees latitude ($R^2 = 0.060$, $p = <0.001$) Kang et al., 2010). Collectively, these studies indicate that environmental gradients such as MAT, MAP, altitude, aridity, and soil characteristics (difference in soil nutrient availability) had a greater influence on leaf litter P than latitude. Results for MAT and MAP are mixed; senesced leaf P was affected more by MAT than either MAP or latitude (Yuan and Chen, 2009) while no significant relationship was found between leaf P and MAT (even with convex quadratic relationship with latitude) and MAP had more control over leaf P than MAT (Kang et al., 2010).

The changing of leaf litter nutrient composition builds into the diverse local climate/geography of the United States (U.S.). The contiguous U.S. is mainly composed of three (dry, temperate, and continental) of the five Köppen-Geiger Climate Classification zones, with the southernmost parts of Florida considered tropical, and no polar climate (Peel et al., 2007). Changes in global climate patterns will alter regional climate regimes. For example, in 2071 to 2100, the tropical, dry, and temperate regions are predicted to encompass more of the continental U.S., as the prevalence of the continental climate will decrease and be contained to the northern Midwest and

Northeast U.S. (Beck et al., 2018). Thus, it is also important to quantify the effects of climate on leachable P to mitigate the impacts of a continually changing climate. The ultimate goal of quantifying regional climate/geographical effects on leachable P is knowing how the P is expressed in end-of-pipe P loads and thus, more accurate modeling in the U.S. Forest Service's national iTree model.

The goal of this study is to quantify leachable P from common urban tree species across different regions of the contiguous U.S. This information will provide species and region-specific information to guide urban managers in reducing end-of-pipe P loads entering surface waters. Results will be integrated into the U.S. Forest Service's iTree model used to provide accessible, accurate, and consistent information on stormwater credits for trees (USDA, 2014). Data from this study will further improve the i-Tree model by incorporating information on leaching for studied tree species; building upon a tool that provides local-specific estimates of tree species impacts on stormwater volume reduction and water quality changes to aid in species selection and stormwater credits. The resulting calculator will support environmental decisions by clarifying the impact of, and guiding species selection for trees in agricultural, urban, and natural forest areas and by assessing the potential contributions of phosphorus in leaf litter to stormwater runoff.

This study aims to answer the following research questions:

1. How do leached total P (Total Kjeldahl P) and dissolved P (Dissolved Reactive P) vary among leaves from different urban tree species?

2. How do leached TKP and DRP from leaves of the same species vary across major regions of the contiguous U.S.?

2. Materials and Methods

2.1. Selection of Tree Species

Tree species were selected from a study conducted by Ma et al. (2020) where municipal foresters were asked to report on street tree species most commonly used as suburban street trees (Table 3). In addition to the nationwide survey of tree species, common species were broken down by U.S. Census region (Midwest, Northeast, South, and West; Figure 3). The most commonly reported tree species for each region are shown in Table 4.

Table 3: Summary of most commonly reported tree species nationwide (Ma et al., 2020).

Rank	Scientific Name	Common Name
1	*Acer platanoides*	Norway Maple
2	*Fraxinus pennsylvanica*	Green Ash
3	*Gleditsia triacanthos*	Honey Locust
4	*Acer saccharinum*	Silver Maple
5	*Acer rubrum*	Red Maple
6	*Quercus virginiana*	Southern Live Oak
7	*Acer saccharum*	Sugar Maple
8	*Pyrus calleryana*	Callery Pear
9	*Liquidambar styraciflua*	Sweetgum
10	*Tilia cordata*	Littleleaf Linden
11	*Platanus x acerifolia*	London Plane
12	*Celtis occidentalis*	Hackberry
13	*Quercus palustris*	Swamp Spanish Oak
14	*Ulmus americana*	American Elm
15	*Fraxinus americana*	White Ash

Figure 3: U.S. Census regions broken up into the West, Midwest, Northeast, and South (Ma et al., 2020).

Table 4: Summary of most commonly reported tree species in each region. Selected trees for this study are highlighted in green for each U.S. Census region.

Midwest Region			Northeast Region		
Rank	**Scientific Name**	**Common Name**	**Rank**	**Scientific Name**	**Common Name**
1	*Acer platanoides*	Norway Maple	1	*Acer platanoides*	Norway Maple
2	*Acer saccharinum*	Silver Maple	2	*Gleditsia triacanthos*	Honey Locust
3	*Fraxinus pennsylvanica*	Green Ash	3	*Acer rubrum*	Red Maple
4	*Gleditsia triacanthos*	Honey Locust	4	*Acer saccharum*	Sugar Maple
5	*Acer rubrum*	Red Maple	5	*Tilia cordata*	Littleleaf Linden
6	*Acer saccharum*	Sugar Maple	6	*Platanus x acerifolia*	London Plane
7	*Tilia cordata*	Littleleaf Linden	7	*Pyrus calleryana*	Callery Pear
8	*Celtis occidentalis*	Hackberry	8	*Quercus rubra*	Northern Red Oak
9	*Quercus palustris*	Swamp Spanish Oak	9	*Fraxinus pennsylvanica*	Green Ash
10	*Fraxinus americana*	White Ash	10	*Acer saccharinum*	Silver Maple
South Region			**West Region**		
Rank	**Scientific Name**	**Common Name**	**Rank**	**Scientific Name**	**Common Name**
1	*Quercus virginiana*	Southern Live Oak	1	*Acer platanoides*	Norway Maple
2	*Acer rubrum*	Red Maple	2	*Fraxinus pennsylvanica*	Green Ash
3	*Sabal palmetto*	Sabal Palm	3	*Liquidambar styraciflua*	Sweetgum
4	*Lagerstroemia indica*	Crepe-myrtle	4	*Ulmus pumila*	Siberian Elm
5	*Acer saccharum*	Sugar Maple	5	*Acer rubrum*	Red Maple
6	*Celtis occidentalis*	Hackberry	6	*Platanus x acerifolia*	London Plane
7	*Pyrus calleryana*	Callery Pear	7	*Pistacia chinensis*	Chinese Pistache
8	*Ulmus crassifolia*	Cedar Elm	8	*Magnolia grandiflora*	Southern Magnolia
9	*Quercus phellos*	Willow Oak	9	*Gleditsia triacanthos*	Honey Locust
10	*Acer saccharinum*	Silver Maple	10	*Lagerstroemia indica*	Crepe-myrtle

Tree species were selected from these lists to accomplish the goals of the study. *Quercus virginiana* (Southern Live Oak), *Sabal palmetto* (Sabal palm), and *Magnolia grandiflora* (Southern Magnolia) were not considered as they are evergreen trees and do not lose their leaves in the fall.

Goal 1: Leachable P from common urban tree species across different regions of the U.S.

The Street Trees data layer (Figure 4) from the City of Madison Open Data (City of Madison, 2024) was used in conjunction with results from Ma et al. (2020) to select trees for Goal 1. Data was filtered by species, and the number of each species in Madison, WI was determined (Table 5). Figures 4a and 4b show an unfiltered result and attribute table from the map, but as species are filtered, blue dots disappear, and locations where specific species are located were identified. In order to qualify for selection, tree species had to be common both nationwide and in Madison, WI, for ease of collection. Thus, in addition to the previously eliminated trees, *Liquidambar styraciflua* (Sweetgum) was eliminated from consideration because it was not a common street tree in Madison, WI. (n = 12, City of Madison Open Data).

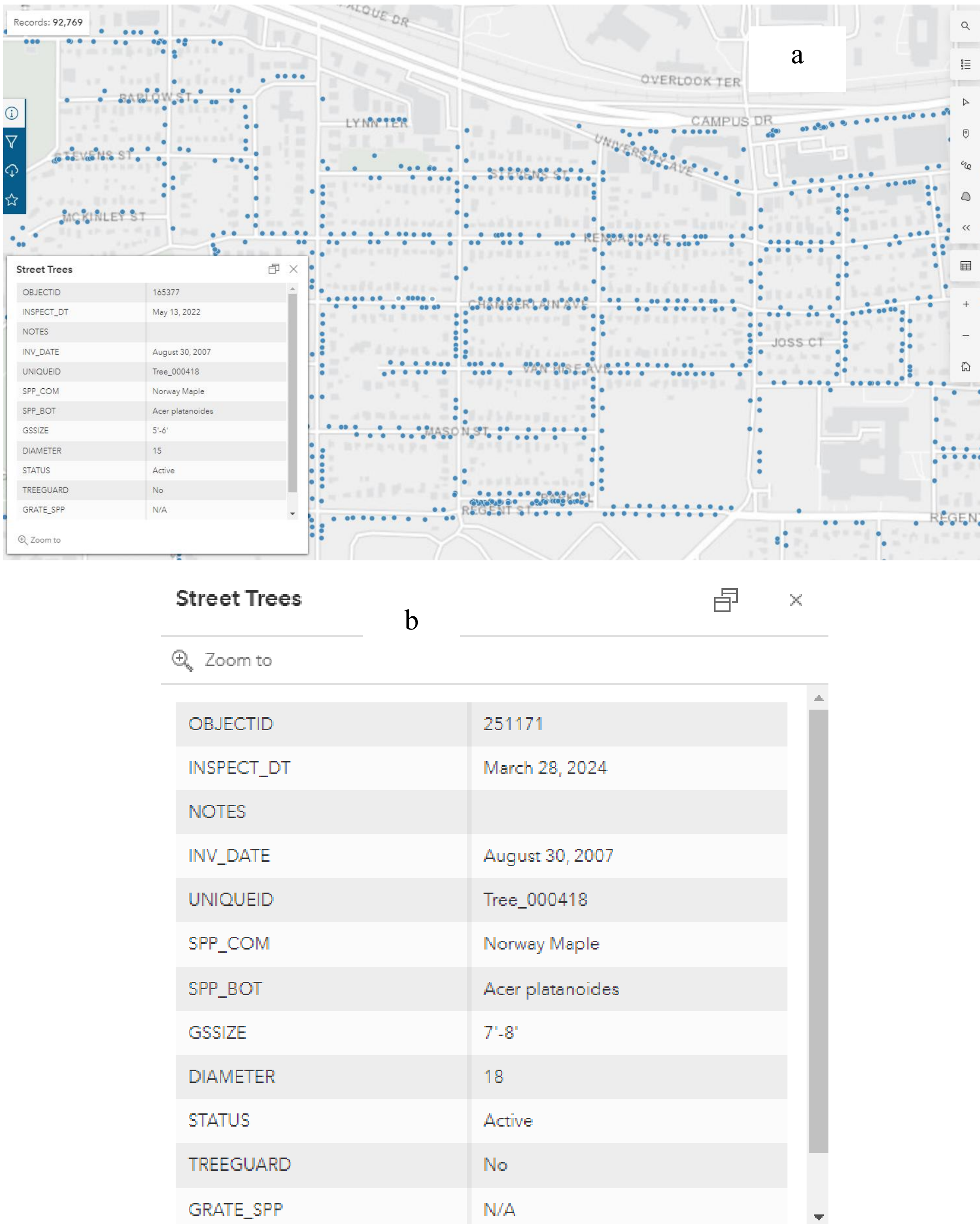

Figure 4: Example of data available at the City of Madison Open Data (4a). Important data included tree location and species type. Blue dots represent each tree with an attribute table (bottom left of image) shown for each tree (4b). Trees were filtered by species and local residences were used to identify addresses and locations for each species selected.

The ten most common species from the nationwide list were selected, after excluding the previously eliminated species. In addition to the nationwide list, the selected trees represent eight of the ten most common trees in the Midwest region, 9 of 10 in the Northeast, and 5 of 10 in the South and West (Table 4). The ultimate goal of selection was to identify species that were common nationwide, had good representation across each region, and were common in Madison, WI.

Table 5: Species selected for collection. The final column shows the percentage of each species are on record in the City of Madison Open Data layer (July 2024).

Rank (Ma et al; 2020)	Scientific Name	Common Name	Abbreviation	Number of trees in Madison, WI	% of street trees in Madison (%)
1	*Acer platanoides*	Norway Maple	NM	14,522	13.11
2	*Fraxinus pennsylvanica*	Green Ash	GA	9,300	8.40
3	*Gleditsia triacanthos*	Honey Locust	HL	15,571	14.06
4	*Acer saccharinum*	Silver Maple	SiM	1,411	1.27
5	*Acer rubrum*	Red Maple	RM	370	0.33
7	*Acer saccharum*	Sugar Maple	SuM	1,509	1.36
8	*Pyrus calleryana*	Callery Pear	CP	1,218	1.10
10	*Tilia cordata*	Littleleaf Linden	LL	3,505	3.16
11	*Platanus x acerifolia*	London Plane	LP	2,030	1.83
12	*Celtis occidentalis*	Hackberry	HB	5,844	5.28

In total, the selected trees represent 55,280 of the 110,744 (49.92%) records on the City of Madison Open Data layer.

<u>Goal 2: Evaluate the impact of regional climate on leachable P from tree leaves.</u>

To evaluate the impact of climate on leachable P, species common to each of four U.S. Census regions was selected. Red Maple (*Acer rubrum*) was selected as the control species because it is a common tree nationwide (5th overall) and prevalent in each of the four U.S. Census regions (5th most common in the Midwest, 3rd in the Northeast, 2nd in the South, and 5th in the West). Thus, Red Maple (*Acer rubrum*) leaves were also collected from the Northeast, South, and West regions in addition to Madison, WI. Table 6 shows the complete list of species selected for this study.

Table 6: Overall list of selected species for this study.

Species Name Common	**Species Name Scientific**	**Region Collected**
Norway Maple	*Acer platanoides*	Midwest
Green Ash	*Fraxinus pennsylvanica*	Midwest
Honey Locust	*Gleditsia triacanthos*	Midwest
Silver Maple	*Acer saccharinum*	Midwest
Sugar Maple	*Acer saccharum*	Midwest
Callery Pear	*Pyrus calleryana*	Midwest
Littleleaf Linden	*Tilia cordata*	Midwest
London Plane	*Platanus x acerifolia*	Midwest
Hackberry	*Celtis occidentalis*	Midwest
Red Maple	*Acer rubrum*	Midwest
Red Maple	*Acer rubrum*	Northeast
Red Maple	*Acer rubrum*	South
Red Maple	*Acer rubrum*	West

2.2. Sample Collection

<u>Goal 1: Leachable P from common urban tree species across different regions of the U.S.</u>

Using the City of Madison Open Data layer, the locations of each of the ten species of trees were determined. Collection sites in Madison, WI were selected based on the criteria that they were in medium-density urban residential neighborhoods and, if possible, had more than one of the selected species present within close proximity, for ease of collection. Ten collection sites were located for each species. Tree leaves were collected from multiple sites. Nitrile gloves were worn to prevent contamination from external sources. Leaves were collected directly from the street and not from residential lawns (Figure 5).

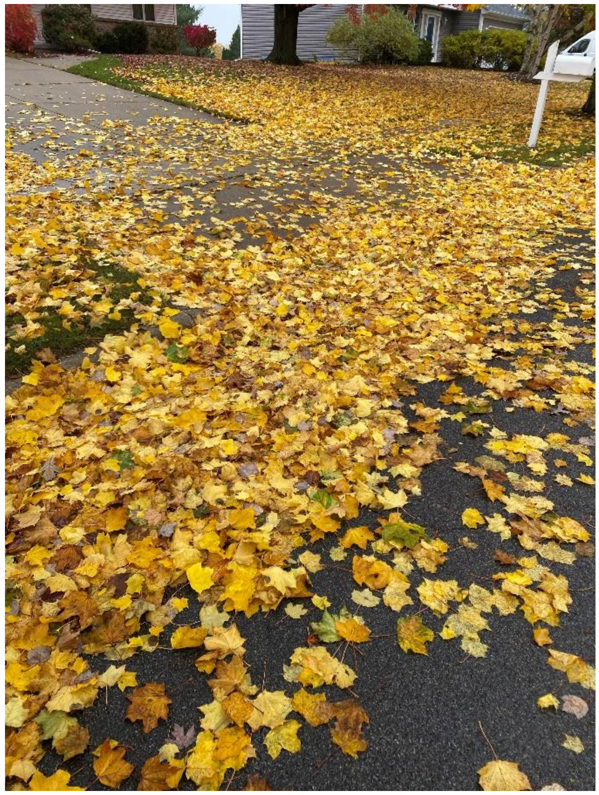

Figure 5: Leaves on the street were eligible for collection. Leaves on residential lawns were not collected.

Fresh leaves were collected, and old and decomposing leaves were avoided. Fresh leaves exhibit features such as waxy, smooth, and moist surface, with green, yellow, orange, or red color (Figure 6). Meanwhile decomposing leaves are black or dark brown in color, have dry and rough surfaces, and may have begun to skeletonize (Figures 7 and 8).

Figure 6: Fresh leaves are smooth to the touch and still exhibit bright colors.

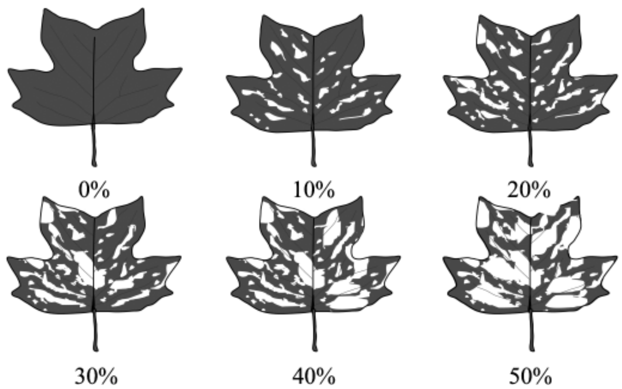

Figure 7: The skeletonizing process of decomposing leaves (Traw, 2010).

Figure 8: Decomposing leaves exhibiting dark brown and black coloring (Wang et al., 2020).

Leaves in Madison, WI were collected one to two times per week from late September to early November of 2023. Leaves were only collected after natural senescence from the tree canopy onto the street below (i.e., leaves were not shaken from a tree or taken directly from the tree canopy itself). *Fraxinus pennsylvanica* (Green Ash) and *Gleditsia triacanthos* (Honey Locust) leaves began to fall at the end of September, while *Platanus x acerifolia* (London Plane) and *Pyrus calleryana* (Callery Pear) leaves began to fall in late October to early November. In addition, leaves were not collected after recent rainfall. In total, 150 to 300 grams of leaves from each species were collected throughout the season. Collected leaves were stored separately by species in paper bags, rolled shut, in a lab space, away from direct sunlight. Leaves were allowed to air dry in the closed bag for at least two weeks before leaching experiments began.

Goal 2: Evaluate the impact of regional climate on leachable P from tree leaves.

Four cities (Figure 9), one in each of the four U.S. Census regions, were chosen to collect *Acer rubrum* (Red Maple) leaves: Madison, Wisconsin (WI), Boston, Massachusetts (MA), Raleigh, North Carolina (NC), and Sammamish, Washington (WA). Red Maple leaves collected in Boston, Raleigh, and Sammamish were collected by collaborators of the study. The absolute latitude (AL), mean annual temperature (MAT), and mean annual precipitation (MAP) for each of the four cities is summarized in Table 7 (National Weather Service, 2024).

Figure 9: The four collection locations of the *Acer rubrum* (Red Maple) leaves overlayed onto the U.S. Census regions from Ma et al. (2020).

Table 7 : The absolute latitude, mean annual temperature, and mean annual precipitation of the four collection cities. Mean annual temperature and mean annual precipitation are 30-year averages from 1993 to 2023.

Location	Absolute Latitude (AL) (°)	Mean Annual Temperature (MAT) (°C)	Mean Annual Precipitation (MAP) (mm)
Madison, WI (Midwest)	43.0722	8.5	927.34
Boston, MA (Northeast)	42.3601	11.3	1106.18
Raleigh, NC (South)	35.7796	16.2	1177.75
Sammamish, WA (West)	47.6163	11.8	964.59

Acer rubrum (Red Maple) leaves were collected from early October to mid-November in fall of 2023 in each of the four cities. Once enough leaves were collected, they were shipped to Madison, WI. For shipping, leaves were stored in paper bags, similar to Goal 1. Paper bags were placed in rigid cardboard boxes. Boxes were chosen to have ample size for the bags of leaves to minimize crushing of leaves in transit. Boxes, bags, and leaves were inspected on arrival in

Madison to check for damage to leaves. The actual leaf collection procedure was identical to the procedure in Madison, WI, as part of Goal 1.

2.3. Phosphorus Extraction

Collected leaf litter samples were hand sorted, removing spare debris (grass, sticks, rocks, etc.) and tree leaves of a different species. Overall, samples that had been collected earlier in the season (e.g., *Fraxinus pennsylvanica* (Green Ash) and *Gleditsia triacanthos* (Honey Locust)) did not experience typical decomposition during storage in the lab. All samples retained their original color and did not begin to skeletonize during lab storage. All samples were allowed to air dry naturally for at least two weeks before leaching experiments began.

The leaching experimental procedure was adapted from Wang et al. (2020). For each species, 16 grams of dry leaf litter was placed in a 3.78-L polyethylene plastic bag with 750 mL of deionized water. All samples were immersed in the deionized water while air was gently pressed out of the bag. Leaching experiments were conducted over a 48-hour period during which the sealed bags were stored away from natural sunlight and incubated at an air temperature of 20 °C ± 2 °C in the laboratory. Blank samples (deionized water without leaf litter) were used as controls. Each treatment was replicated three times. This leaching method allowed comparison across species and regions and provided a “worst case” scenario for potential P leaching from leaves.

At times of 0 (sample collected within 15 minutes of start time), 2, 6, 12, 24, and 48 hours, two 20-mL aliquots were collected using a syringe after gently shaking the bag. One aliquot was used for total Kjeldahl phosphorus (TKP) analysis. The second aliquot was filtered immediately through a 0.25-μm filter for dissolved reactive phosphorus (DRP) analysis. Samples were preserved with sulfuric acid and refrigerated at 4°C according to U.S. Environmental Protection Agency (USEPA) 365.1, Rev. 2.0 (1993) (O'Dell, 1993). TKP samples were manually diluted five times before sulfuric acid tube digestion. TKP and DRP were analyzed using the EASYCHEM 200 Discrete Analyzer in the Soil and Environmental Sciences Department at the University of Wisconsin-Madison. TKP was chosen as a reasonable estimation for Total Phosphorus because of the low concentrations of organic-P previously shown to exist in leaf litter leachate (Wang et al., 2020), compared to inorganic-P (USEPA, 1974). A total P digestion analysis was run by inductively coupled plasma (ICP) mass spectrometry by the Soil and Forage Laboratory (Soil and Plant Analysis Laboratory, 2005), University of Wisconsin - Madison Extension on leaf litter samples collected in Fall 2023. This test was done to determine a total leaf P content (hereafter referred to as "initial P content"), which sets the maximum amount of P in leaf litter that could potentially be extracted by water.

2.4. Data analysis and statistics

The volumetric concentrations of TKP and DRP (mg P L^{-1} solution) at each sampling time were converted to a mass concentration (mg P g−1 leaf mass) using the dry leaf mass. A generalized negative exponential equation (Eq. (1)) was fit to DRP concentrations (mg g^{-1}) as a function of time over the 48-hour period for all replicates following the method of Wang et al. (2020) using R (R Core Team, 2020). This method assumed DRP release is a first-order rate process, and that accumulated DRP in solution is estimated as:

$$y = a(1 - e^{-bt}) \tag{1}$$

where y is DRP concentration (mg g^{-1}) at any time, *a* is the maximum amount of DRP release (mg g^{-1}) and *b* is the first-order rate constant (h^{-1}) which described the relation between DRP concentration and the rate of DRP extracted by water. The coefficients of *a* and *b* were obtained for each treatment using a nonlinear regression model based on Eq. (1) for all DRP concentrations measured over the 48-hour period.

The standard error of the mean (σ_M) was calculated for TKP or DRP concentration (mg g^{-1}) at each sampling time as:

$$\sigma_M = \frac{\sigma}{\sqrt{N}} \tag{2}$$

where σ is the standard deviation of TKP or DRP concentration at each sampling time and *N* is the number of replicated. For each treatment, the analysis of variance (ANOVA) split plots model analysis with post-hoc Tukey test (significance level of $\alpha = 0.05$) was used to determine significant differences in DRP among species and regions (Luke, 2017). The analysis was conducted in R (R Core Team, 2020). The auto-regressive order 1 (AR1) model was selected, based on Akaike information criteria (AIC) results (Akaike, 1974), among compound symmetry model and spatial power (CAR1) model to further obtain p-values, using R packages of nlme (Pinheiro et al., 2020) and emmeans (Russell, 2020).

3. Results and Discussion

3.1. General shape of graphs/release characteristics

Across most species, the general pattern of cumulative TKP and DRP released (mg g^{-1}) over the 48-hour leaching period was similar. The release of P was initially rapid, decreased over time, and approached a constant value in most cases. Leaching results for Norway Maple are shown in Figure 10 as an example of the general temporal pattern of phosphorus release.

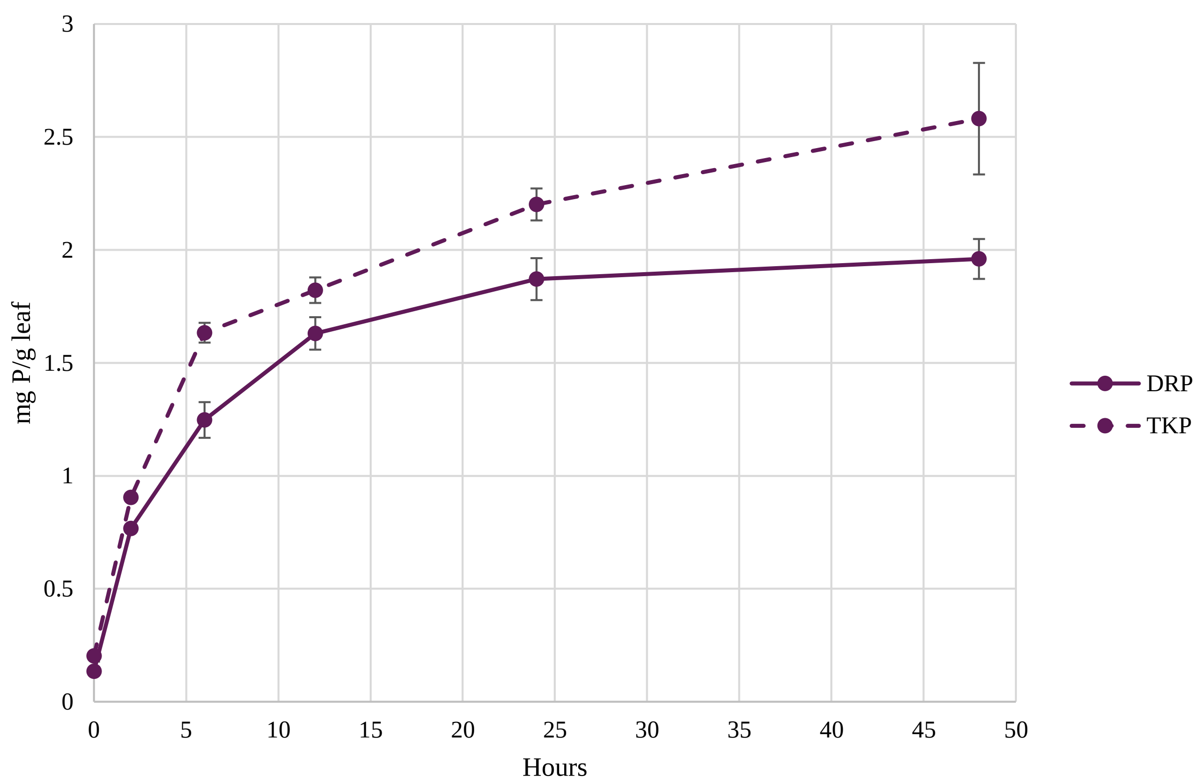

Figure 10: Results of leaching experiments for Norway Maple leaves, error bars represent one standard error.

Table 8 shows DRP as a percentage of TKP at each time interval for all species collected in Madison, WI. With the exception of Callery Pear and Hackberry, more than 60% of the leached P at 48 hours was in the dissolved phase. In general, species that leached the most TKP at 48 hours (e.g., Silver Maple and Norway Maple) had a higher percentage of TKP as DRP early on in the leaching process. Species that lost the least amount of TKP (e.g., Callery Pear and Hackberry) also had low percentages of TKP as DRP early on.

Table 8 : Percentage of TKP that is DRP at each time interval (Madison, WI species).

	Time (hr)					
Species	**0**	**2**	**6**	**12**	**24**	**48**
RM	31%	74%	96%	93%	86%	69%
NM	67%	85%	76%	89%	85%	76%
GA	10%	59%	78%	76%	82%	75%
HL	25%	58%	89%	87%	74%	80%
SiM	54%	77%	90%	82%	79%	80%
SuM	20%	65%	67%	77%	74%	75%
CP	1%	4%	14%	13%	28%	33%
LL	9%	50%	60%	66%	65%	66%
LP	8%	32%	53%	51%	62%	62%
HB	0.14%	0.5%	1%	2%	1%	14%

Species that lose more DRP relative to TKP can be classified as a higher priority in street sweeping management decisions because of the difficulty in removing dissolved P after it is picked up by stormwater runoff (Hogan and Walbridge, 2007; Bell et al., 2017). In addition, studies have shown that orthophosphate is much more bio-available than particulate-bound P. In general, greater than 90% of dissolved P is considered bio-available (Ellison and Brett, 2006) while the bioavailability of particulate-bound P ranges from 6 to 25% across studies (Ususitalo et al., 2003; Ellison and Brett, 2006; Abell and Hamilton, 2012; Prestigiacomo et al., 2015). The bioavailability of P is crucial because it determines how easily it can be utilized in natural processes, such as eutrophication. Thus, given the overall high percentage of TKP that is DRP in the species studied, the difficulty of removing dissolved P from stormwater, its high bioavailability in comparison to particulate P, and the aim of this research to provide guidance on preventing P from entering surface water at its source (rather than treating it in transport), the results and discussion will focus primarily on DRP.

Table 9 shows the percentage of maximal DRP release (i.e., the amount of DRP released at a given time as a percentage of the total DRP release at 48 hours) over time for each species. Across all species, the median percentage of maximal DRP release at 12 hours was 67% and at 24 hours was 85%. This indicates that leaves were losing more than half of the maximal dissolved P in a quarter of the total leaching time, and more than three-quarters in half of the total leaching time.

Table 9: Percentage of maximal DRP release at each time for the ten species.

	Time (hr)					
Species	**0**	**2**	**6**	**12**	**24**	**48**
RM	3%	19%	48%	72%	93%	100%
NM	7%	39%	64%	83%	95%	100%
GA	1%	7%	30%	56%	82%	100%
HL	2%	9%	24%	41%	65%	100%
SiM	7%	45%	84%	90%	93%	100%
SuM	2%	19%	53%	85%	96%	100%
CP	1%	3%	14%	23%	64%	100%
LL	2%	19%	44%	67%	85%	100%
LP	1%	10%	28%	46%	74%	100%
HB	0%	1%	3%	5%	6%	100%

3.2. Differences between species

Maximal P release (i.e., the amount of TKP or DRP released at 48 hours) was significantly different across species collected in Madison, WI (Figure 11, Table 9). Figure 11 shows that the maximal release of DRP varied from 2.16 mg P g^{-1} for Silver Maple to 0.03 mg P g^{-1} for Hackberry and the maximal TKP release varied from 2.69 mg P g^{-1} for Silver Maple to 0.23 mg P g^{-1} for Hackberry. More information of the DRP and TKP leaching values for each species can be found in Appendix Table 1. Table 10 shows the *p*-values for the maximal release of DRP for all species collected in Madison, WI.

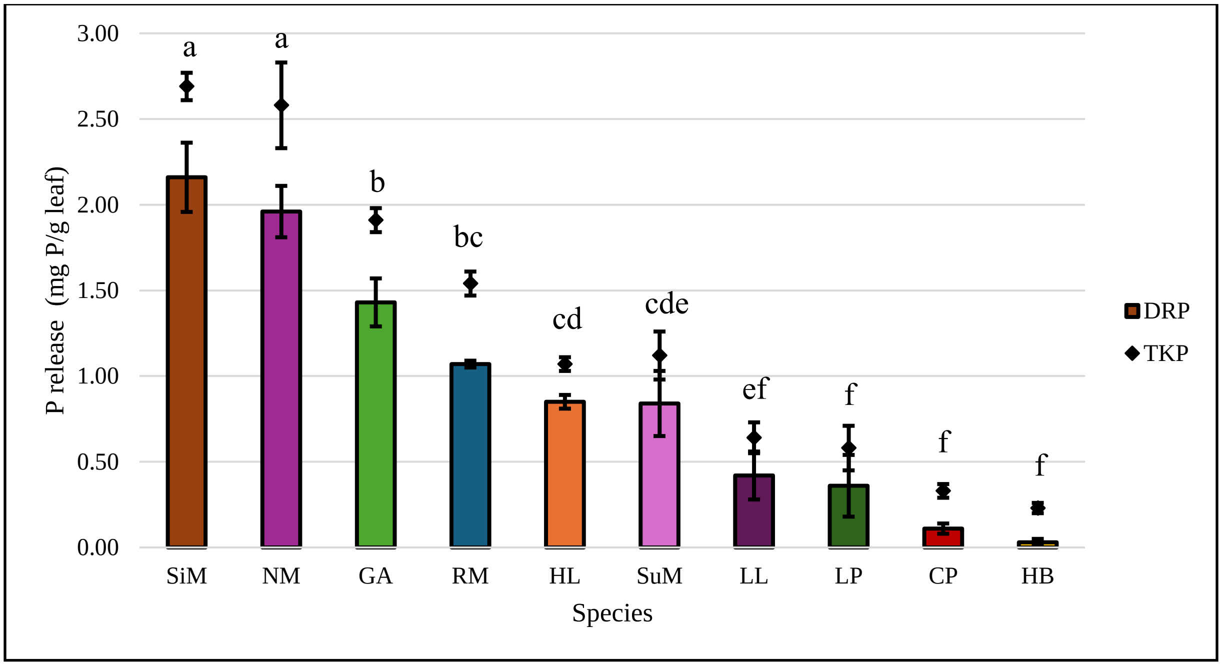

Figure 11: Maximal P release (time = 48 hours) for all species collected in Madison, WI. Bar charts show maximal DRP release while diamonds show maximal TKP release for all species. Error bars represent one standard error.

Table 10: Significance values for the maximal release of DRP (time = 48 hours) for all species collected in Madison, WI compared to other species.

Species	GA	HB	HL	LL	LP	NM	RM	SiM	SuM
CP	<0.0001 ***	1.00	<0.0001 ***	0.40	0.69	<0.0001 ***	<0.0001 ***	<0.0001 ***	0.0002***
GA		<0.0001 ***	0.004**	<0.0001 ***	<0.0001 ***	0.0095**	<0.0001 ***	0.0002***	0.003 **
HB			<0.0001 ***	0.13	0.29	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***
HL				0.06,	0.02*	<0.0001 ***	0.86	<0.0001 ***	1
LL					1	<0.0001 ***	0.0009***	<0.0001 ***	0.08,
LP						<0.0001 ***	0.0003***	<0.0001 ***	0.03*
NM							<0.0001 ***	0.89	<0.0001 ***
RM								<0.0001 ***	0.80
SiM									<0.0001 ***

Significance codes: 0 to 0.001 '***' highly significant, 0.001 to 0.01 '**' moderately significant, 0.01 to 0.05 '*' significant, 0.05 to 0.1 ',' insignificant, 0.1 to 1 ' ' highly insignificant.

The species were sorted into four clusters using hierarchical clustering with Ward's Method, with maximal release of DRP as the comparison variable. Species were sorted into clusters to discuss similarities and differences in trees' physiology, taxonomy, and release patterns, among trees that leached similar amounts of P. Figure 12 shows the maximal leaching values for each tree species, with their associated clusters labeled. The number of clusters was chosen such that average maximal release of DRP for each group is significantly different from the other clusters (Table 11, Table 12). The distance matrix associated with each species as determined by Ward's Method can be found in Appendix Table 2. More information about the statistical significance of species within each group is detailed in Sections 3.2.1 – 3.2.4.

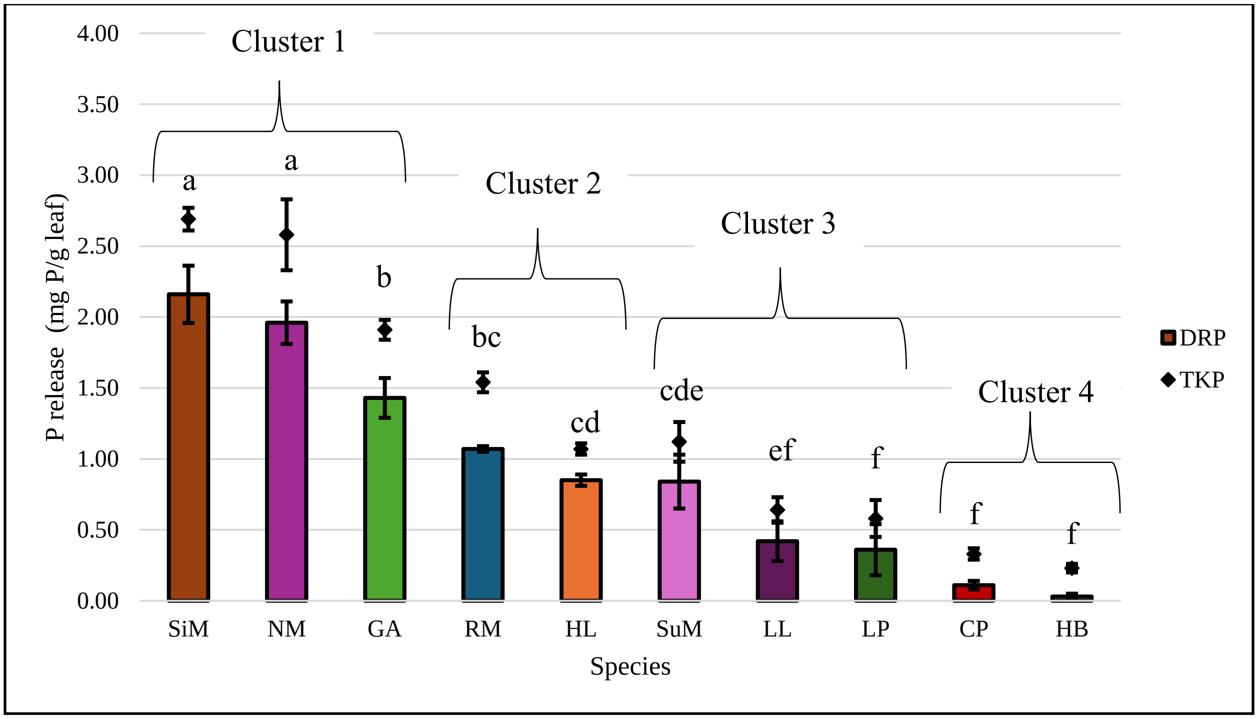

Figure 12: Tree species sorted into their clusters.

Table 11: p-values for the average DRP release of each cluster.

	Cluster 2	**Cluster 3**	**Cluster 4**
Cluster 1	<0.0001***	<0.0001***	<0.0001***
Cluster 2		0.03*	<0.0001***
Cluster 3			0.01**

Significance codes: 0 to 0.001 '***' highly significant, 0.001 to 0.01 '**' moderately significant, 0.01 to 0.05 '*' significant.

Table 12: Grouping of species as determined by Ward's Method.

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**
Species	Silver Maple (SiM)	Red Maple (RM)	Littleleaf Linden (LL)	Callery Pear (CP)
	Norway Maple (NM)	Honey Locust (HL)	London Plane (LP)	Hackberry (HB)
	Green Ash (GA)		Sugar Maple (SuM)	

3.2.1 Cluster 1 - Silver Maple, Norway Maple, and Green Ash

Silver Maple, Norway Maple, and Green Ash had maximal DRP release of 2.16, 1.96, and 1.43 mg P g^{-1}, respectively (Table 13). Within Cluster 1, maximal release of DRP for Silver Maple and Norway Maple was not significantly different (p = 0.89). However, maximal release of Green Ash was significantly different from both Silver Maple (p = 0.0002) and Norway Maple (p = 0.009). Silver Maple and Norway Maple were significantly different than all seven species outside of Cluster 1 (p < 0.0001) in maximal DRP release while Green Ash was significantly different (p ranging from <0.0001 to 0.004) from all other species except Red Maple (p = 0.20).

Within Cluster 1, there were differences in DRP release patterns among the three species (Figure 13, Table 13). Silver Maple and Norway Maple had more rapid initial release (90% and 83% of maximal release in the first 12 hours for Silver Maple and Norway Maple, respectively), than Green Ash which only released 56% of its maximal value in the first 12 hours. Additional information on DRP and TKP release patterns for all species can be found in Appendix Table 1 and Figure 1.

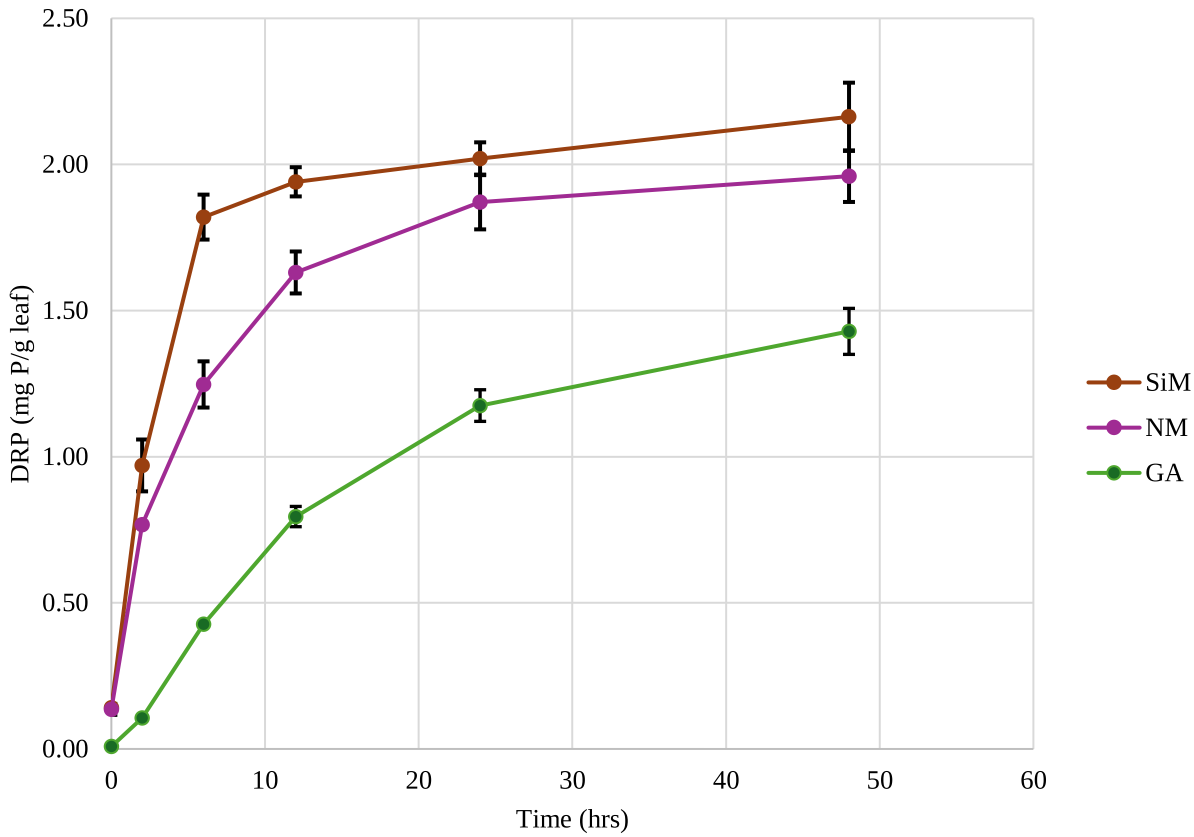

Figure 12: Cumulative DRP release over time for Cluster 1 species.

Table 13: Cumulative DRP released for all clusters (mg P g^{-1} leaf), standard errors are shown in paratheses.

		Time (hr)					
		0	**2**	**6**	**12**	**24**	**48**
Cluster	**Species**	**DRP (mg P g^{-1} leaf)**					
1	**SiM**	0.14 (0.01)	0.97 (0.09)	1.82 (0.08)	1.94 (0.05)	2.02 (0.06)	2.16 (0.12)
	NM	0.14 (0.02)	0.77 (0.01)	1.25 (0.08)	1.63 (0.07)	1.87 (0.09)	1.96 (0.09)
	GA	0.01 (0.0005)	0.11 (0.01)	0.43 (0.003)	0.80 (0.03)	1.18 (0.05)	1.43 (0.08)
2	**RM**	0.03 (0.01)	0.20 (0.02)	0.52 (0.03)	0.77 (0.03)	0.99 (0.01)	1.07 (0.01)
	HL	0.01 (0.001)	0.07 (0.004)	0.20 (0.01)	0.35 (0.01)	0.55 (0.02)	0.85 (0.02)
3	**SuM**	0.01 (0.003)	0.16 (0.02)	0.44 (0.06)	0.72 (0.08)	0.80 (0.10)	0.84 (0.11)
	LL	0.01 (0.0009)	0.08 (0.01)	0.18 (0.03)	0.28 (0.04)	0.36 (0.07)	0.42 (0.08)
	LP	0.01 (0.001)	0.03 (0.01)	0.10 (0.04)	0.17 (0.07)	0.27 (0.09)	0.36 (0.10)
4	**CP**	0.0006 (0.0004)	0.003 (0.002)	0.02 (0.005)	0.03 (0.01)	0.07 (0.02)	0.11 (0.02)
	HB	0.00005 (0.00002)	0.0004 (0.0001)	0.001 (0.0002)	0.001 (0.0003)	0.002 (0.0001)	0.03 (0.01)

Silver Maple and Norway Maple trees are both members of the Soapberry (*Sapindaceae)* family, however, they have different leaf characteristics. Green Ash is a member of the Olive (*Oleaceae*) family. Silver Maple leaves are relatively small (6.4 to 12.7 cm; Gilman et al., 2019) in size and have incised leaf margins, while Norway Maple leaves are larger (10.2 to 20.3 cm; Gilman and Watson, 2014) and have lobed margins (Figure 14). Both leaves are a part of the Maple genus, where commonly, leaves are simple (one leaf per stem), and star shaped. Green Ash leaves are more similar in size (5.1 to 10.2 cm; Gilman et al., 2019) to Silver Maple, but are ovate in shape and pinnate (more than one leaflet per stem) in structure. All species turn yellow in color during the fall.

Figure 13: Picture of Silver Maple (left), Norway Maple (middle), and Green Ash (right) leaves.

Norway Maple and Green Ash trees are among the most common trees in urban settings throughout the U.S., ranking #1 and #2, respectively, compared to Silver Maple trees which is #4 (Ma et al., 2020). Similarly, in Madison, WI, Norway Maple and Green Ash combined account for 21.5% of street trees while Silver Maple trees are less common (only 1.3%) (City of Madison Open Data, 2024).

Wang et al. (2020) followed a similar experimental procedure as this study and reported similar maximal release values of total dissolved P for Norway Maple (2.13 mg P g^{-1}, 8.3% difference between studies) and Green Ash (1.65 mg P g^{-1}, 14.3% difference between studies). Table 14 summarizes findings from other leaf leaching studies that included Silver Maple, Norway Maple, and Green Ash. For all studies except Wang et al. (2020), experimental procedures varied substantially in leaching method and timing of samples, leading to differences in maximal release values. The "Rank within study" values represent where each species ranked in terms of maximal leaching among the species studied in the respective study (e.g., 1 of 10 means the maximal release was highest out of the ten species in that study). It indicates whether the leaching for a certain species is in the higher, middle, or lower end compared to other trees, regardless of leaching procedure.

Table 14: Summary of maximal DRP release for Silver Maple, Norway Maple, and Green Ash leaching studies. Rank within study provided in parentheses.

		Maximal release (mg P g^{-1} leaf) (Rank within study)		
Study (Author(s) and Year)	**Location (City, State)**	**Silver Maple**	**Norway Maple**	**Green Ash**
This study	Madison, WI	2.16 (1 of 10)	1.96 (2 of 10)	1.43 (3 of 10)
Hill et al. (2022)	Pocatello, ID	--	1.63 (1 of 6)	0.09 (6 of 6)
Wang et al. (2020)	Madison, WI	--	2.13 (1 of 2)	1.65 (2 of 2)
Hobbie et al. (2014)	Minneapolis, MN	--	0.62 (3 of 5)	0.41 (4 of 5)
Duan et al. (2014)	Baltimore, MD	0.24 (3 of 6)	--	--
Dorney (1986)	Milwaukee, WI	0.23 (2 of 13)	0.08 (11 of 13)	0.19 (3 of 13)

Generally, Silver Maple and Norway Maple ranked high in terms of maximal DRP release when compared to other species studied. Green Ash was more variable in maximal release (0.09 to 1.65 mg P g^{-1} leaf) and rank across studies. Given the different experimental methods employed by these studies to represent different hydrologic processes (e.g., first flush vs. sustained inundation vs. rainfall percolation), the range of results is not surprising. For example, this study and both Wang et al. (2020) and Hill et al. (2022) simulated sustained inundation while Dorney (1986), simulated a first flush effect on leaves, followed by sustained runoff exposure. It indicates the importance of understanding how different eco-hydrologic interactions (especially in different climates) affect nutrient availability and release among species, particularly Norway Maple and Green Ash, because of their popularity in urban areas.

3.2.2. Cluster 2 - Red Maple and Honey Locust

Red Maple and Honey Locust had maximal DRP release of 1.07 and 0.86 mg P g^{-1}, respectively (Table 13). Within Cluster 2, the maximal release of DRP for Red Maple and Honey Locust was not significantly different ($p = 0.86$). Red Maple maximal release was significantly different (p ranging from <0.0001 to 0.0009) from all other species collected in Madison, WI except Green Ash ($p = 0.20$) and Sugar Maple ($p = 0.80$). Honey Locust maximal release was significantly different from (p ranging from <0.0001 to 0.02) from all other species outside of Cluster 2 except Sugar Maple ($p = 1.00$) and Littleleaf Linden ($p = 0.06$).

Red Maple and Honey Locust had different release patterns: initial release for Red Maple was more rapid (72% maximal release in the first 12 hours) than Honey Locust (only 41% of its maximal P in the first 12 hours) (Figure 15, Table 9, Table 13).

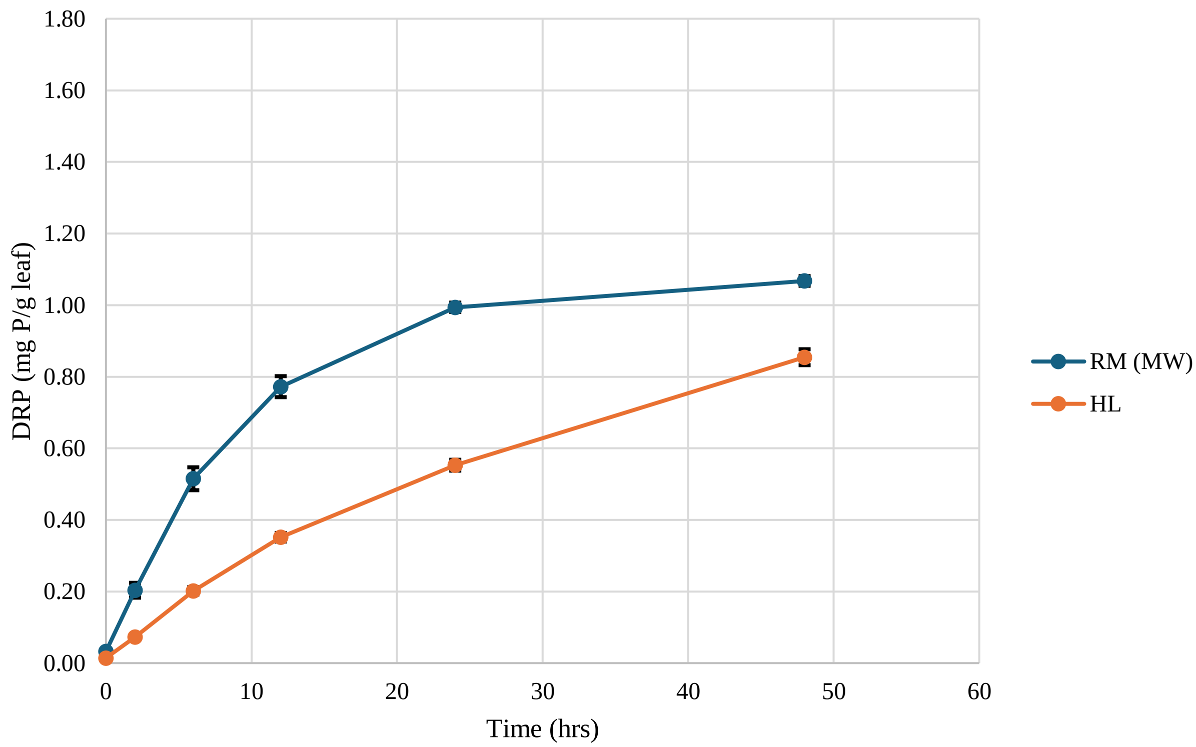

Figure 14: Cumulative DRP release over time for Cluster 2 species.

Red Maple and Honey Locust are members of different families (*Sapindaceae* and *Fabaceae* , respectively), and thus have different leaf physiology. Red Maple leaves are typically 5.1 to 12.7

cm in size (Gilman et al., 2019), with serrated margins, and turn red, yellow, or purple in the fall. Honey Locust leaves are much smaller (< 5.1 cm; Gilman and Watson, 2014), oblong in shape, compound on the stem, and turn yellow in the fall (Figure 16).

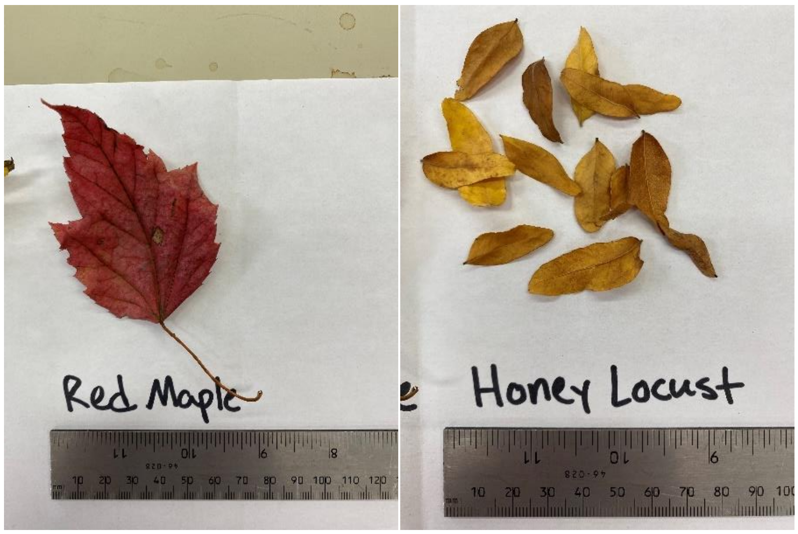

Figure 15: Pictures of Red Maple (left) and Honey Locust (right) leaves.

Honey Locust trees are common in urban settings (Rank #3 in Ma et al. (2020) and 14.1% of street trees in Madison, WI; City of Madison Open Data, 2024). Red Maple trees are also common nationwide (Rank #5, Ma et al., 2020) but much rarer in Madison, WI (0.33% of street trees, City of Madison Open Data, 2024). Honey Locust leaves tended to rank in the middle of studies species (Table 15) while Red Maple leaves ranked highest among species studied in Duan et al. (2014).

Table 15: Summary of maximal DRP release for Red Maple and Honey Locust leaching studies. Rank within study provided in parentheses.

		Maximal release (mg P g^{-1} leaf) (Rank within study)	
Study (Author(s) and Year)	**Location (City, State)**	**Red Maple**	**Honey Locust**
Klaubauf et al. (202X)	Madison, WI	1.07 (4 of 10)	0.85 (5 of 10)
Hill et al. (2022)	Pocatello, ID	--	0.40 (5 of 6)
Duan et al. (2014)	Baltimore, MD	0.44 (1 of 6)	--
Dorney (1986)	Milwaukee, WI	--	0.18 (4 of 13)

Of note, Honey Locust and Green Ash (Cluster 1) both had slower initial P release (41-56% at 12 hours) when compared to the three previously mentioned maple species (72-90% at 12 hours) and are both smaller in size and compound in structure on the stem. It is possible that a faster P release may be associated with how singular leaves store their P (inorganic P vs. metabolic-P vs. lipid P vs. nucleic acid-P), and how available it is (Suriyagoda et al., 2022). The amount of inorganic phosphate in a leaf (as a percentage of the total P in a leaf) has been shown to range from 18 to 48% depending on the family of a leaf. The same study reported greater variability in forms and concentrations of leaf P among families of plants compared to species within families, the regions in which the plants grew, or the type (brush vs. tree vs. grass) of plant (Suriyagoda et al., 2022). Families of trees with elevated levels of inorganic P in their leaves may be species at higher risk of having their P leached quickly, or leaching large amounts of P.

3.2.3. Cluster 3 - Sugar Maple, Littleleaf Linden, and London Plane

Sugar Maple, Littleleaf Linden, and London Plane had maximal DRP release of 0.84, 0.42, and 0.36 mg P g^{-1}, respectively (Table 13). Within Cluster 3, the maximal release of DRP was not significantly different between Littleleaf Linden and London Plane (p = 1.00) or between Sugar Maple and Littleleaf Linden (p = 0.08), however Sugar Maple and London Plane were significantly different from each other ($p = 0.03$). Sugar Maple maximal release was significantly different (p ranging from <0.0001 to 0.003) from all other species collected in Madison, WI except for Honey Locust ($p = 1.00$) and Red Maple ($p = 0.80$). Littleleaf Linden maximal release was significantly different (p ranging from <0.0001 to 0.0009) from all other species collected in Madison, WI except for Callery Pear ($p = 0.40$), Hackberry ($p = 0.13$), and Honey Locust ($p = 0.06$). London Plane maximal release was significantly different (p ranging from <0.0001 to 0.02) from all other species collected in Madison, WI except for Callery Pear ($p = 0.69$) and Hackberry ($p = 0.29$).

Initial release for Sugar Maple and Littleleaf Linden was more rapid (85% and 67% maximal release in the first 12 hours, respectively) than London Plane (only 46% of its maximal P in the first 12 hours) (Figure 17, Table 9, Table 13).

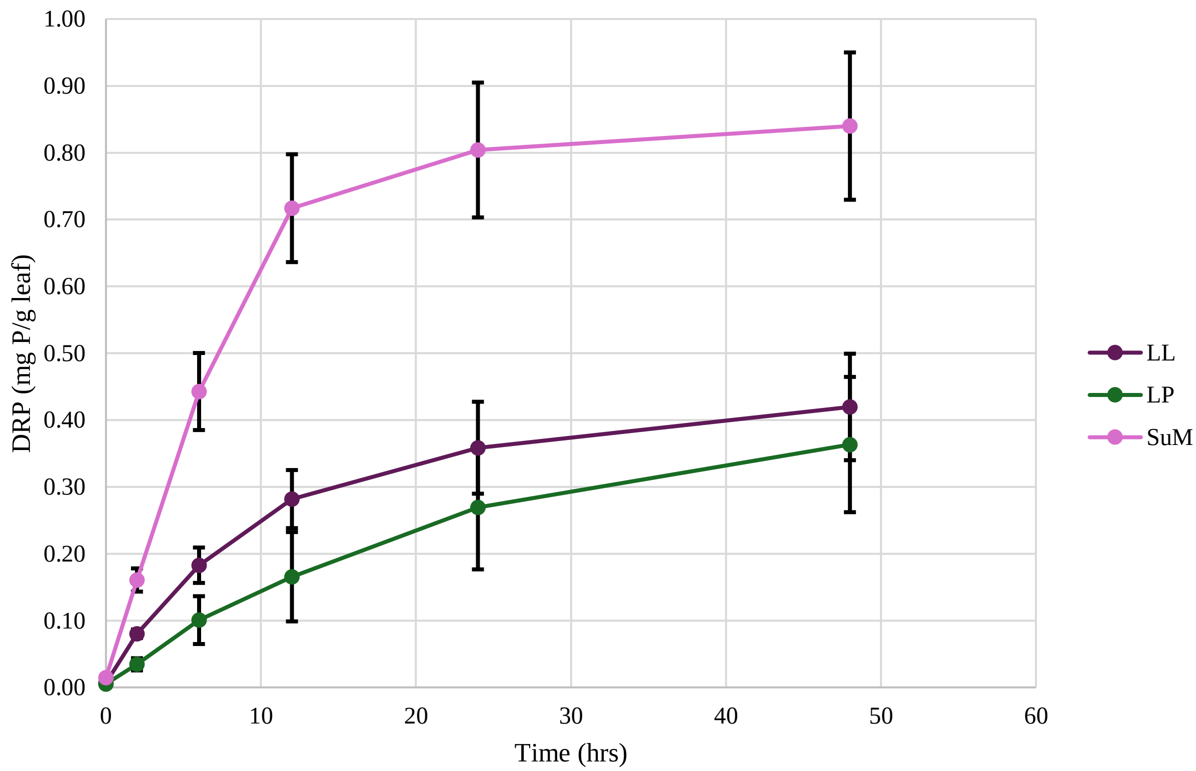

Figure 16: Cumulative DRP release over time for Cluster 3 species.

All three species in Cluster 3 are members of different families: *Sapindaceae* (Sugar Maple), *Malvaceae* (Littleleaf Linden), and *Platanaceae* (London Plane), with differences in leaf physiology. Sugar Maple leaves are typically 10.2 to 20.3 cm in size (Gilman and Watson, 2014), star-shaped, lobed, singular on the stem, and turn red, yellow, and orange during the fall. Littleleaf Linden leaves are smaller (5.1 to 10.2 cm; Gilman and Watson, 2015) orbiculate in shape, pinnate on the stem, and turn yellow during the fall. Finally, London Plane leaves are large (20.3 to 30.5 cm; Gilman and Watson, 2015) star-shaped with incised lobes, and turn yellow or orange during the fall, depending on the variant (Figure 18). The wide range of leaf physiology (and similar P release, particularly between London Plane and Littleleaf Linden) from Cluster 3 indicate that leaf family may be important in addition to a leaf's shape and size, as predictors of leachable P (Suriyagoda et al., 2022).

Figure 17: Photo of Sugar Maple (left), Littleleaf Linden (middle), and London Plane (right) leaves.

Sugar Maple trees were the most common nationally (among Cluster 3 species) (Rank #7 in Ma et al. (2020) but represent only 1.4% of street trees in Madison, WI (City of Madison Open Data, 2024). By comparison, Littleleaf Linden trees were less common nationally (Rank #10, Ma et al., 2020) but more common in Madison, WI (3.2% of street trees, City of Madison Open Data, 2024). London Plane were the least common nationally (Rank #11, Ma et al., 2020) and less common in Madison, WI (1.83% of street trees, City of Madison Open Data, 2024).

Sugar Maple P, in the one comparison study, ranked #1 in terms of P leaching (among species studied; Dorney, 1986) in a similar location to Madison, WI (Milwaukee, WI). Littleleaf Linden tended to rank higher in studies, except for this study and Dorney (1986). Leaching for London Plane was reported in one other study and ranked second overall among those species (Table 16). DRP release for Cluster 3 species was less than for clusters 1 and 2 (except for Sugar Maple, which was similar in P release to Honey Locust in Cluster 2).

Table 16: Summary of maximal DRP release for Sugar Maple, Littleleaf Linden, and London Plane leaching studies. Rank within study provided in parentheses.

		Maximal release (mg P g^{-1} leaf) (Rank within study)		
Study (Author(s) and Year)	**Location (City, State/Country)**	**Sugar Maple**	**Littleleaf Linden**	**London Plane**
Klaubauf et al. (202X)	Madison, WI	0.84 (6 of 10)	0.42 (7 of 10)	0.36 (8 of 10)
Hill et al. (2022)	Pocatello, ID	--	0.74 (2 of 6)	--
Hobbie et al. (2014)	Minneapolis, MN	--	0.98 (1 of 5)	--
Wallace et al. (2008)	Adelaide, Australia	--	--	0.68 (2 of 5)
Dorney (1986)	Milwaukee, WI	0.26 (1 of 13)	0.09 (9 of 13)	--

3.2.4. Cluster 4 - Callery Pear and Hackberry

Callery Pear and Hackberry had maximal DRP release of 0.11 and 0.03 mg P g^{-1}, respectively (Table 13). Within Cluster 4, the maximal release of DRP was not significantly different (p = 1.00) between Callery Pear and Hackberry. Callery Pear maximal release was significantly different (p ranging from <0.0001 to 0.0002) from all other species collected in Madison, WI except for Littleleaf Linden ($p = 0.40$) and London Plane ($p = 0.69$). Hackberry maximal release was significantly different ($p < 0.0001$) from all other species collected in Madison, WI except for Littleleaf Linden ($p = 0.13$) and London Plane ($p = 0.29$).

Both species had irregular release patterns when compared to other species. Neither species reached an asymptote in release, and Hackberry released almost no DRP until 48 hours (Figure 19). The slower release of P (23% of maximal release at 12 hours for Callery Pear and 6% for Hackberry), may be associated with the way P is stored in these leaves. For example, the *Rosaceae* family (of which Callery Pear is a member) ranked last in leaf litter inorganic P composition out of the 16 families studied by Suriyagoda et al. (2022), which could explain why it lost little DRP compared to other species.

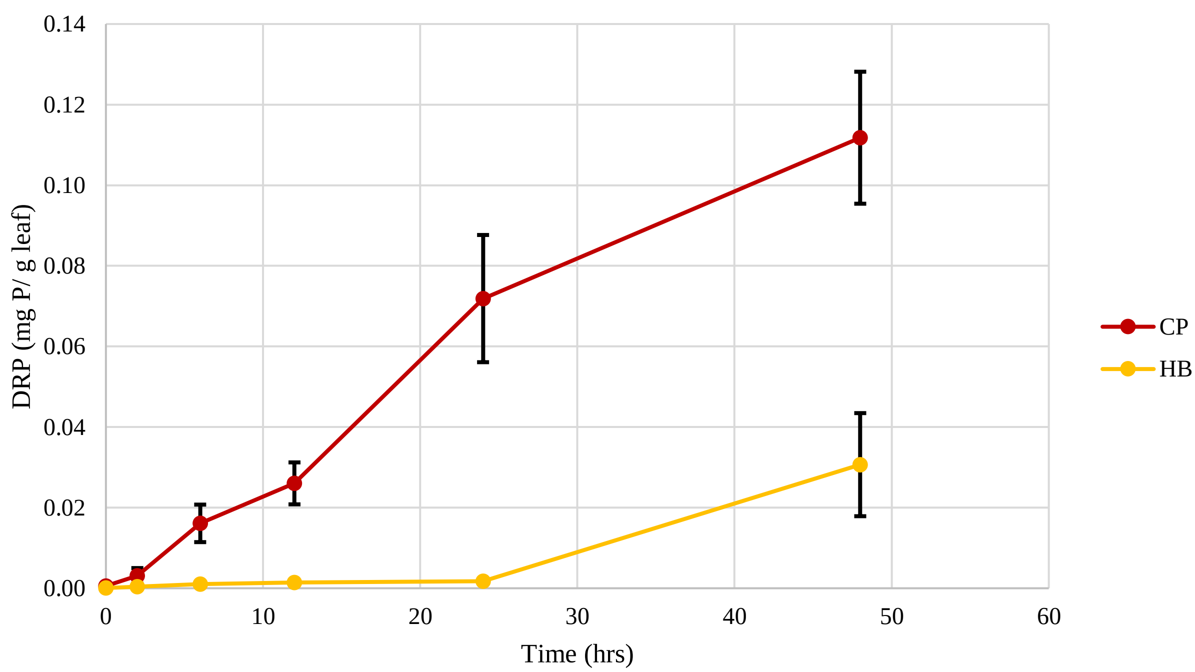

Figure 18: Cumulative DRP release over time for Cluster 4 species.

Callery Pear and Hackberry are members of different families (*Rosaceae* and *Cannabaceae*, respectively). Callery Pear leaves are thick, smaller (5.1 to 10.2 cm; Gilman and Watson, 2015), ovate in shape, and turn a deep red in the fall. Hackberry leaves are thin, typically 5.1 to 10.2 cm in size (Gilman and Watson, 2014), elliptic in shape, and turn yellow in the fall (Figure 20).

Figure 19: Photos of Hackberry (left) and Callery Pear (right) leaves.

Callery Pear trees rank in the middle of occurrence in urban settings nationally (Rank #8 in Ma et al., 2020) but are uncommon in Madison, WI (1.10% of street trees, City of Madison Open Data; 2024). Hackberry trees are less common nationally (Rank #12 in Ma et al., 2020) but a common tree in Madison, WI (5.28% of street trees, City of Madison Open Data; 2024).

3.3 Implications of species' leaching differences on management decisions

Species that leach the most P (Cluster 1) and are common in urban settings likely pose more of a threat to surface water bodies through the leaching of P from their leaves. In Madison, Norway Maple stands out among the ten species studies because of its high P leaching potential (second overall) and as a common street tree throughout the city. Also in Cluster 1, Silver Maple is common nationwide but less common in Madison, WI. From an urban management and water quality perspective, it is most efficient to focus efforts on species that lose the most P and are common street trees (Figure 21). Honey Locust, Norway Maple, and Green Ash are all common street trees in Madison and were in either Cluster 1 or Cluster 2. Thus, these species should be targeted in management efforts. Hackberry was the fourth most common species in Madison, but lost extraordinarily little DRP, while Silver Maple leached the most DRP but is uncommon in Madison. It may be inefficient to spend resources managing Hackberry or isolated Silver Maple trees. The factors that affect P leaching from leaves and street tree management are complex and include more than leachable P and commonality of a tree in urban settings (e.g. rainfall/runoff amount/duration, leaf mass accumulation), but the comparisons among species in this study can be used by urban managers to inform their decision making and management efforts.

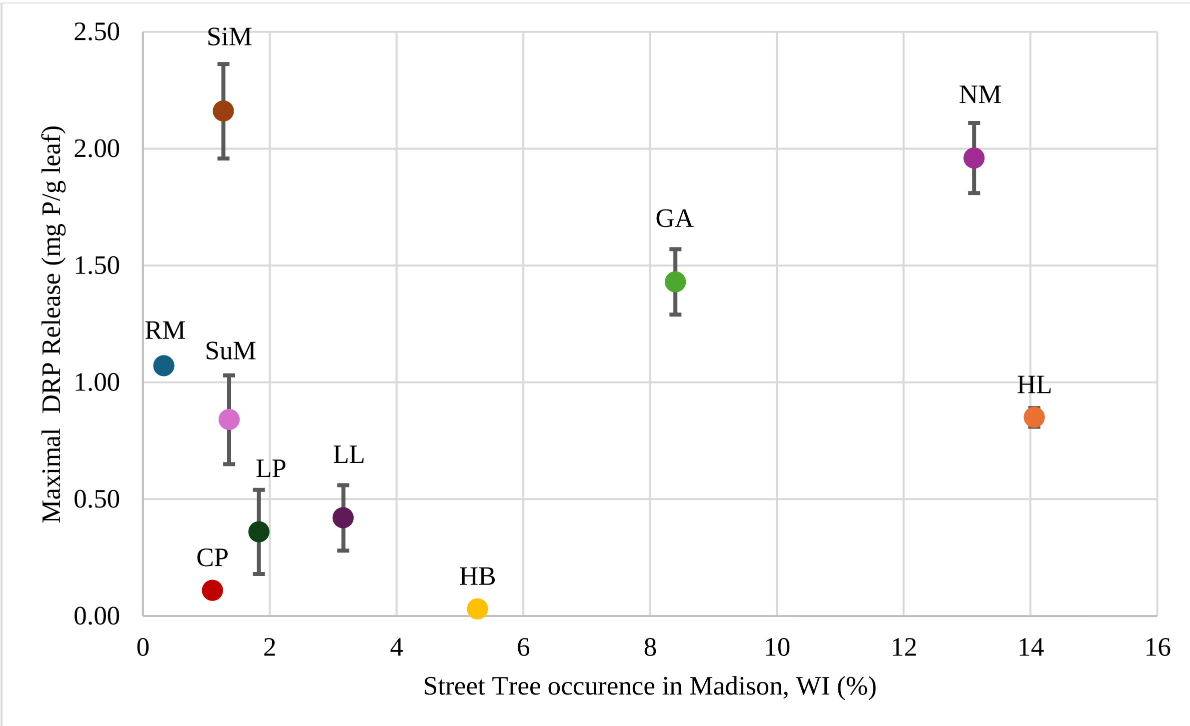

Figure 20: Maximal DRP release (mg P/g) of each species studies in Madison, WI plotted against the occurrence of each species as a street tree in Madison, WI (%). Error bars represent one standard error.

3.4. Differences between regions

Urban street trees are a common feature in suburban neighborhoods nationwide, thus it is important to understand the potential impacts of climate and geography on leaching dynamics. Management recommendations based on leaching experiments from one climatic/geographic region (Madison, WI in this case) may not be applicable nationwide. Thus, leaching experiments were performed on Red Maple replicates collected from each of the four U.S. Census regions (Figure 3). Red Maple tree leaves were collected from the suburban neighborhoods in cities in the Midwest, Northeast, South, and West U.S. Census regions (Table 17). While not known at the time of selection, the maximal leaching value for Red Maple was mid-range (4 of 10) among the 10 species in Madison, WI, further supporting its robustness for regional comparison.

Table 17: The absolute latitude, mean annual temperature, and mean annual precipitation of the four collection cities. Mean annual temperature and mean annual precipitation are 30-year averages from 1993 to 2023.

Location	**U.S. Census Region**	**Absolute Latitude (AL) (°)**	**Mean Annual Temperature (MAT) (°C)**	**Mean Annual Precipitation (MAP) (mm)**
Madison, WI	Midwest (MW)	43.0722	8.5	927
Boston, MA	Northeast (NE)	42.3601	11.3	1106
Raleigh, NC	South (S)	35.7796	16.2	1178
Sammamish, WA	West (W)	47.6163	11.8	965

Red Maple leaves from the Midwest had the greatest maximal release (1.07 mg P g^{-1} leaf), followed by Northeast (0.47 mg P g^{-1} leaf), South (0.32 mg P g^{-1} leaf), and West (0.03 mg P g^{-1} leaf) (Table 18, Figure 22). Maximal release for the Midwest replicate was significantly different ($p < 0.05$) from all other regional replicates. Replicates from the Northeast and South were not significantly different ($p = 0.23$); however, both were significantly different from the West ($p = 0.002 – 0.02$; Table 19).

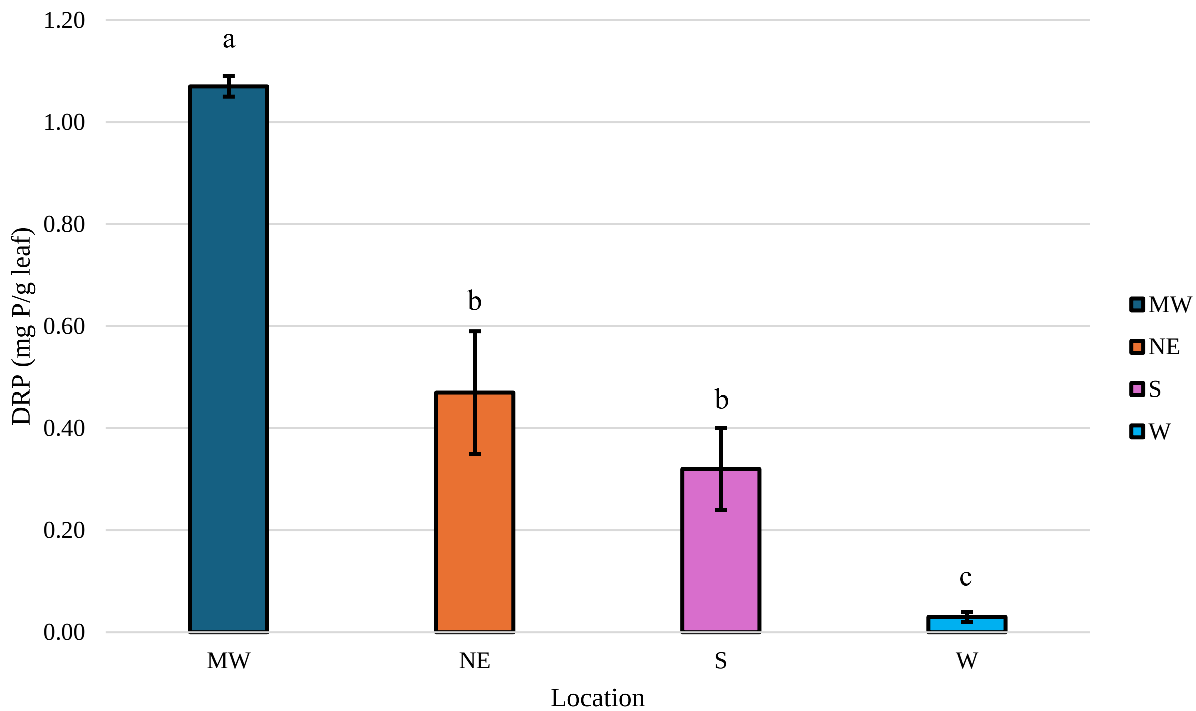

Figure 21: Maximal DRP release (time = 48 hours) for Red Maple replicates.

Table 18: Cumulative DRP released for Red Maple replicates (mg P g^{-1} leaf), standard errors are shown in paratheses.

	Time (hr)					
	0	**2**	**6**	**12**	**24**	**48**
Regions	DRP (mg P g^{-1} leaf)					
MW	0.03 (0.01)	0.20 (0.02)	0.52 (0.03)	0.77 (0.03)	0.99 (0.01)	1.07 (0.01)
NE	0.02 (0.01)	0.11 (0.04)	0.25 (0.06)	0.35 (0.08)	0.42 (0.09)	0.47 (0.07)
S	0.01 (0.002)	0.06 (0.01)	0.14 (0.03)	0.22 (0.02)	0.27 (0.04)	0.32 (0.05)
W	0.00 (0.00)	0.00004 (3.3E-05)	0.0006 (0.0004)	0.007 (0.0008)	0.02 (0.002)	0.03 (0.004)

Table 19: p-values for Red Maple Replicates.

Region	**NE**	**S**	**W**
MW	0.0002***	<0.0001***	<0.0001***
NE		0.23	0.002**
S			0.02*

Significance codes: 0 to 0.001 '***' highly significant, 0.001 to 0.01 '**' moderately significant, 0.01 to 0.05 '*' significant, 0.05 to 0.1 ',' insignificant, 0.1 to 1 ' ' highly insignificant.

The release patterns for replicates from the Midwest, Northeast, and South leaves were similar; rapid initial release (68 – 74% by 12 hours) followed by an asymptote. Red Maple leaves from the West released almost no DRP during the first 6 hours of leaching, and only 23% of maximal release by 12 hours (Table 20, Figure 23).

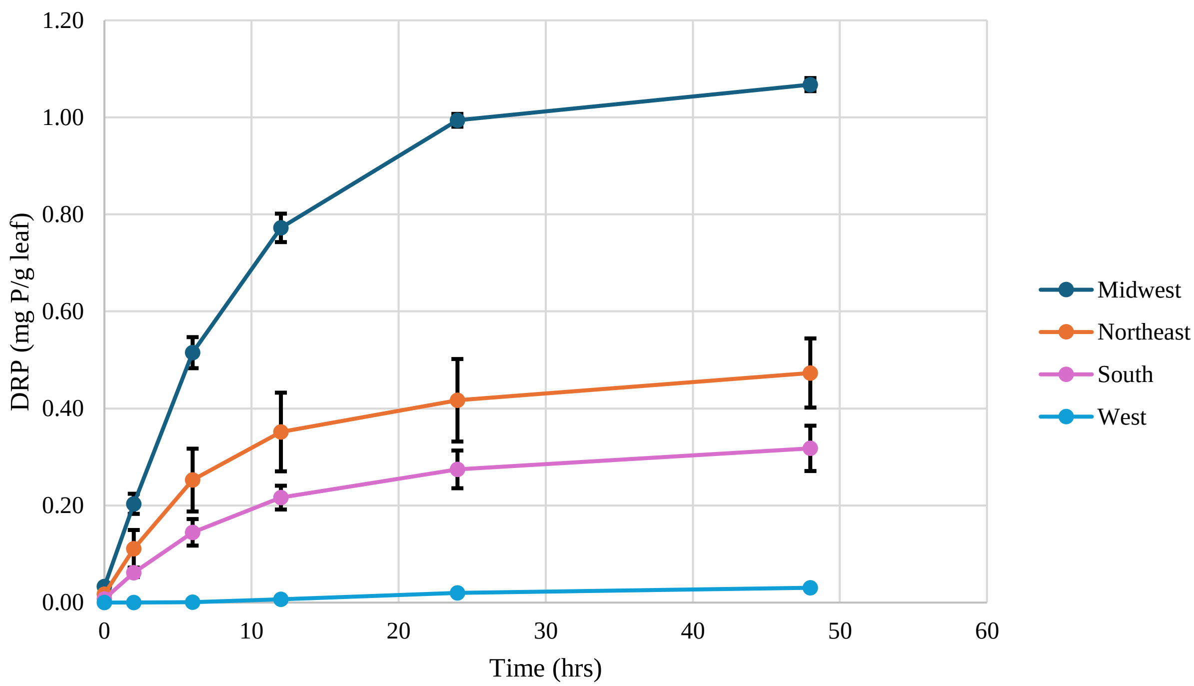

Figure 22: Cumulative DRP release over time for Red Maple replicates.

Table 20: Percent of maximal TDP release per time interval per Red Maple replicate.

	Time (hr)					
Region	**0**	**2**	**6**	**12**	**24**	**48**
MW	3%	19%	48%	72%	93%	100%
NE	4%	23%	53%	74%	88%	100%
S	2%	19%	46%	68%	86%	100%
W	0%	0%	2%	23%	64%	100%

3.5 DRP Release as a Function of Latitude, Temperature and Precipitation

Studies have reported different relationships between leaf litter P or leached P and absolute latitude. It should be noted that relationships reported in the literature are for leaf litter P content while this study's results focus on leached P from leaves. While not the same, the assumption was made that leached P is affected by the P content of the leaves. Other local factors (e.g., tree disease, soil texture, and altitude) have been shown to have a significant impact on the P content of leaves Gong et al., 2020; Ferreira et al., 2022). These factors were not evaluated in this study but may have also influenced P leaching. One study found that leaf litter P rapidly increased from the equator (0 degrees latitude) through the tropical latitudes (up to 30 degrees latitude), plateaued through the midlatitudes (30 to 60 degrees latitude), and then slightly decreased in the upper midlatitudes (45 to 60 degrees latitude; Reich and Oleksyn, 2004). In the current study, the Red Maple replicate locations were in the midlatitudes range, thus a linear regression was applied to maximal P release vs latitude (Figure 24). The relatively flat slope of the linear fit is similar to that observed by Reich and Oleksyn however the Coefficient of Determination was low ($R^2 = 0.0196$).

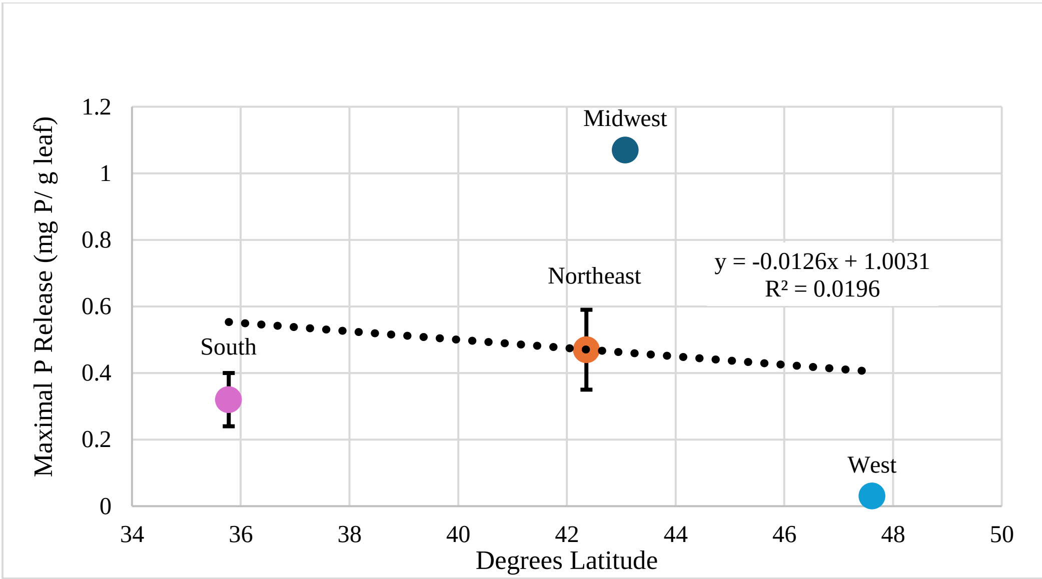

Figure 23: Absolute latitude and maximal release, linear correlation. Error bars represent one standard error.

Other studies report a quadratic relationship between leaf litter P and absolute latitude (Kang et al., 2010; Boyero et al., 2017). These relationships describe a similar rapid increase in leaf litter P from the equator but then a peak in the mid-latitudes, followed by a rapid decrease in leaf litter P into the upper midlatitudes. Figure 25 shows a best-fit quadratic equation to the Red Maple replicates with a much stronger R^2 (0.6418) which is similar to the concave relationship found by Kang et al. (2010); with an increase from the lower latitudes, a peak in the midlatitudes and then a decrease in the upper midlatitudes.

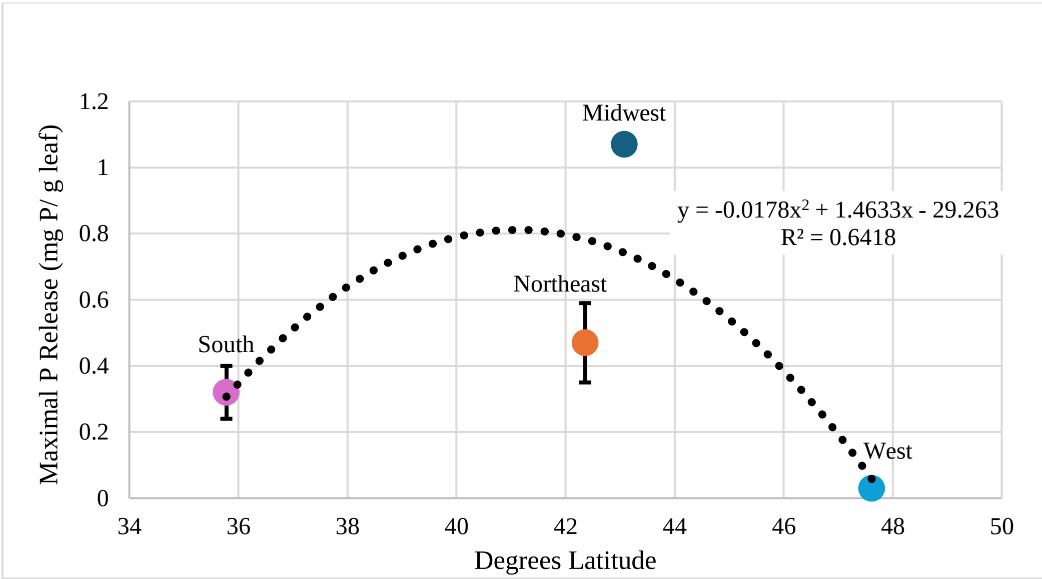

Figure 24: Absolute latitude and maximal DRP release, quadratic correlation. Error bars represent one standard error.

In addition to absolute latitude, leached P from the Red Maple replicates was related to mean annual temperature and mean annual precipitation. Maximal release of P decreased as mean annual temperature (MAT) increased, with moderate correlation ($R^2 = 0.3983$; Figure 26).

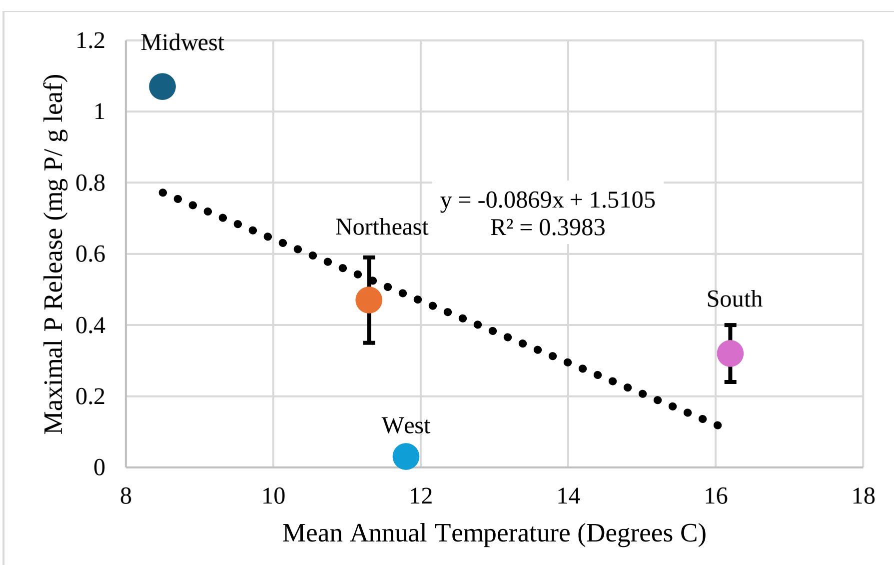

Figure 25: Mean annual temperature and maximal DRP release. Error bars represent one standard error.

Similar relationships (i.e., a decrease in leaf P content or P release as MAT increased), were reported in the literature (Reich and Oleksyn, 2004; Yuan and Chen, 2009; Boyero et al., 2017; Xie et al., 2022). These similar relationships indicate that as predictions are made for leachable P from leaves across the U.S., MAT may be a valuable indicator.

As mean annual precipitation (MAP) increased, there was a decrease in maximal release of DRP from Red Maple leaves, however the correlation was weaker than for MAT ($R^2 = 0.1266$; Figure 27). Comparable results were reported in the literature (Yuan and Chen, 2009, Kang et al., 2010; Boyero et al., 2017; Xie et al., 2022), for leaf litter P or P release. MAP may also be a useful indicator for predicting leached P from leaf litter nationwide. Given the apparent influence of multiple variables, a multiple linear regression model was also evaluated using absolute latitude, MAT, and MAP as independent variables and maximal P release as dependent variable. The results of that analysis are shown in Appendix Table 3.

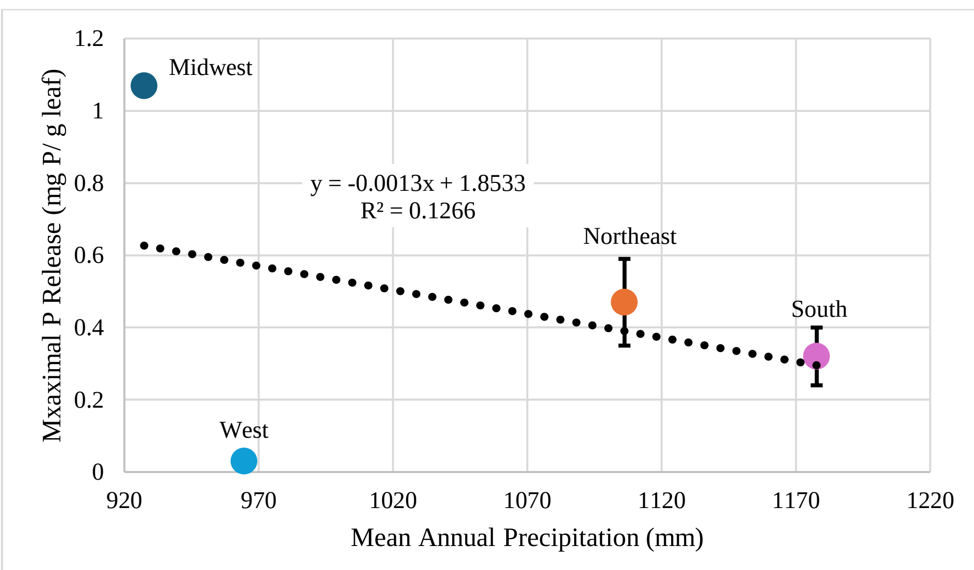

Figure 26: Mean annual precipitation and DRP maximal release. Error bars represent one standard error.

The multiple linear regression analysis revealed a strong, statistically highly significant relationship between maximal DRP release and two predictors (latitude and MAT; $p < 0.0001$ for both), and a statistically marginally significant relationship between DRP release and MAP ($p < 0.053$). Maximal leached DRP (mg P/g leaf) decreases as AL (°), MAT (°C), and MAP (mm) increase (Equation 3):

$$Maximal\ Leached\ DRP = -0.105 * (AL) - 0.154 * (MAT) - 0.001 * (MAP) + 8.1 \qquad (3)$$

Overall, the multiple linear regression provides a good fit (R^2 of 0.96 and adjusted R^2 of 0.95), explaining 96% of the variance in maximal DRP release. 47.9% of the variance is explained by AL, 43.7% by MAT, and 4.4% by MAP. The residual standard error is low (0.0911), and the F-statistic is much greater than 1 (69.05), further supporting the model's robustness. The results of this model indicate that latitude, MAT, and MAP together can be used as predictors of P release (with latitude and MAT having a more substantial impact compared to MAP), however additional data are needed to evaluate the model outside the conditions for which it was developed. The multiple linear regression could be improved by increasing the number of locations of leaf collection for Red Maple leaves, ideally representing more climates and geographical regions than the four examined in this study. Additionally, including different tree species would increase the applicability of the model.

3.6. Implications for leaf litter management

3.6.1. Fitted Equations

Generalized negative exponential equations (Equation 1) were developed to approximate the release of dissolved P as a function of time over the 48-hour leaching period.

$$y = \alpha(1 - e^{-\beta t}) \quad (1)$$

The fitted coefficient α (mg g^{-1}) corresponds to the maximal DRP release for each species. A higher value for α indicates a greater DRP maximal release. The coefficient β (h^{-1}) provides an indication of DRP leaching rate over the 48-hour leaching period, rather than individual leaching rates at specific times. Higher values for β indicate a more rapid initial DRP release after inundation with water and a shorter time before DRP release approaches maximal release. Figure 28 shows an example of a best fit equation with Norway Maple data. Table 21 shows the α, β, and R^2 for each fit equation of each species replicate.

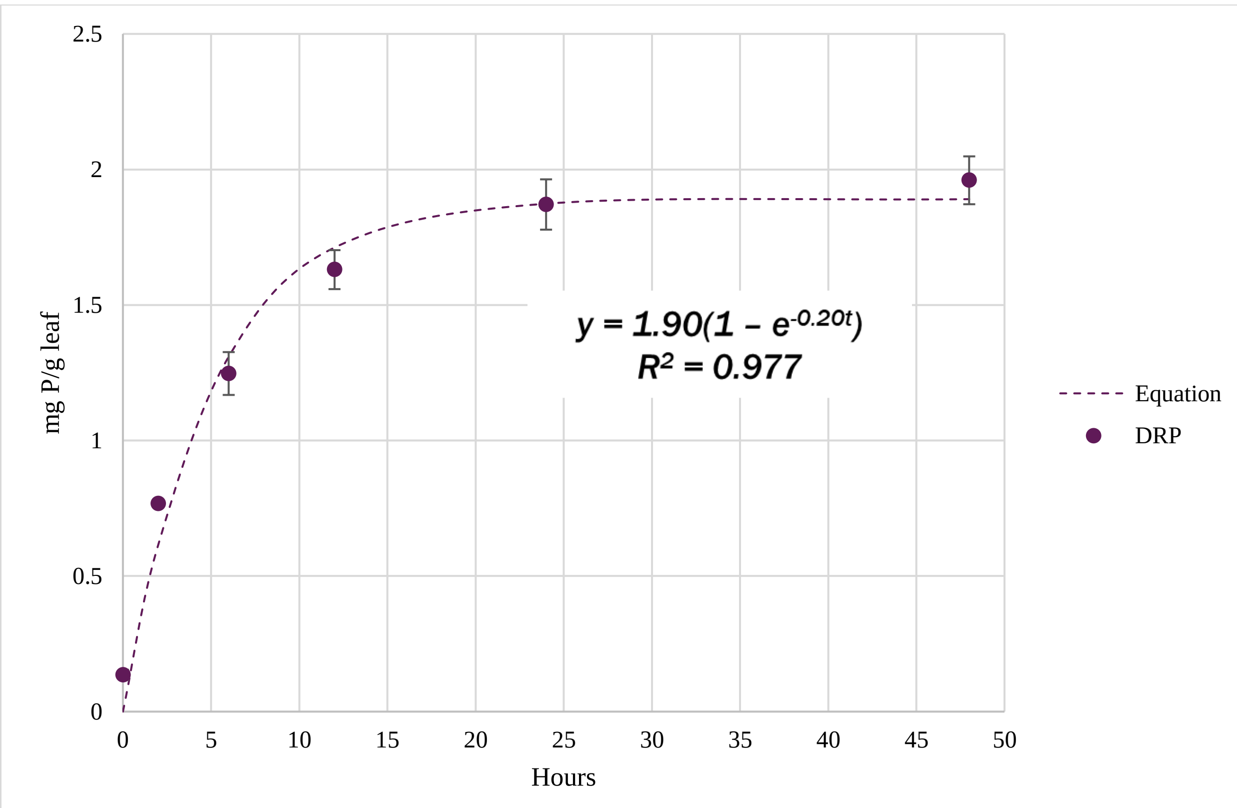

Figure 27: Norway Maple DRP release pattern with fitted equation.

Table 21: α, β, and R^2 values of fitted equations for each species.

Tree Species	α (mg g^{-1})	β (h^{-1})	R^2
SiM	2.07	0.33	0.987
NM	1.89	0.20	0.977
GA	1.54	0.06	0.996
HL	1.09	0.03	0.998
RM (MW)	1.07	0.11	0.999
SuM	0.85	0.13	0.993
RM (NE)	0.46	0.13	0.993
LL	0.42	0.09	0.997
LP	0.41	0.04	0.999
RM (S)	0.31	0.10	0.996
CP	0.25	0.01	0.985
HB	0.19	0.003	0.748
RM (W)	0.062	0.01	0.960

Across species collected in Madison, WI, α ranged from 0.19 to 2.07 and β from 0.003 to 0.33. Most equations fit the associated data well ($R^2 > 0.96$), except for Hackberry ($R^2 = 0.75$). This indicates that Equation 1 is a useful tool to predict P release at intermediate times not measured during leaching experiments (i.e., time not at 0, 2, 6, 12, 24 and 48 hours, in this study), and to provide insight into the shape of the P release curve. Tree species with high β-values can reach their maximal release faster, which may be important for shorter rainfall events. Tree species with both high maximal release and β-coefficient (e.g., Silver Maple and Norway Maple) could be a concern for urban managers when developing street sweeping programs because they have both a high capacity to lose P, but also their rapid initial release.

3.6.2. Hot Spot Analysis of P Leaching in Madison, WI Street Trees

Using available street tree data from the City of Madison Open Data layer, the tree species in this study were brought into ArcGIS Pro software to provide insights on the spatial distribution of the species and their P leaching potential. Only the species evaluated in this study were analyzed in

ArcGIS which represents ~54,000 of the 110,744 (of which ~7,940 are vacant locations where trees used to be located but have since been removed) entries in the online database.

The spatial distribution of trees and their phosphorus (P) leaching potential was analyzed by assigning α-values and β-values (Table 21) to each species. The α-values represent conditions in which leaves are exposed to water for a prolonged period, indicating areas where the most P could be lost if leaves were on the ground for a sustained period of time. In contrast, β-values represent conditions areas where P could be lost more rapidly. These areas could lose a high amount of P during short storms and would be critical targets for proactive street sweeping programs.

Hot spot analysis was conducted using the Optimized Hot Spot Analysis tool in ArcGIS Pro, which identifies statistically significant clusters of high values (hot spots) and low values (cold spots). In this study, hot spots indicate areas with a high concentration of tree species that have elevated α-values and/or β-values. The tool automatically analyzes the data to determine the optimal settings for identifying these clusters, much like a camera adjusts its settings based on lighting and focus to capture the best image (ESRI, 2024).

Shown in Figure 29a are the results of the hot spot analysis in Madison, WI using the α-values as the optimization parameter. Red (99% confidence), orange (95% confidence), and yellow (90% confidence) dots represent trees in “hot” spots (areas of high spatial concentrations of high maximal P leaching values). Dark blue (99% confidence), blue (95% confidence), and cyan (90% confidence) dots represent trees in “cold” spots (areas of high spatial concentrations of low maximal P leaching values). Small grey dots are trees that are not in a significantly hot or cold spot. Figure 29b shows the results of the same process, but with β-values used as the optimization parameter for each tree species. Both analyses reveal statistically significant hot and cold spots in Madison, WI. Generally, the densest hot spots are concentrated in the center of Madison, while cold spots are found along the isthmus and the far west and east edges of the city. This may represent different planting patterns between the older parts of the city and newer developments on the outskirts of the city.

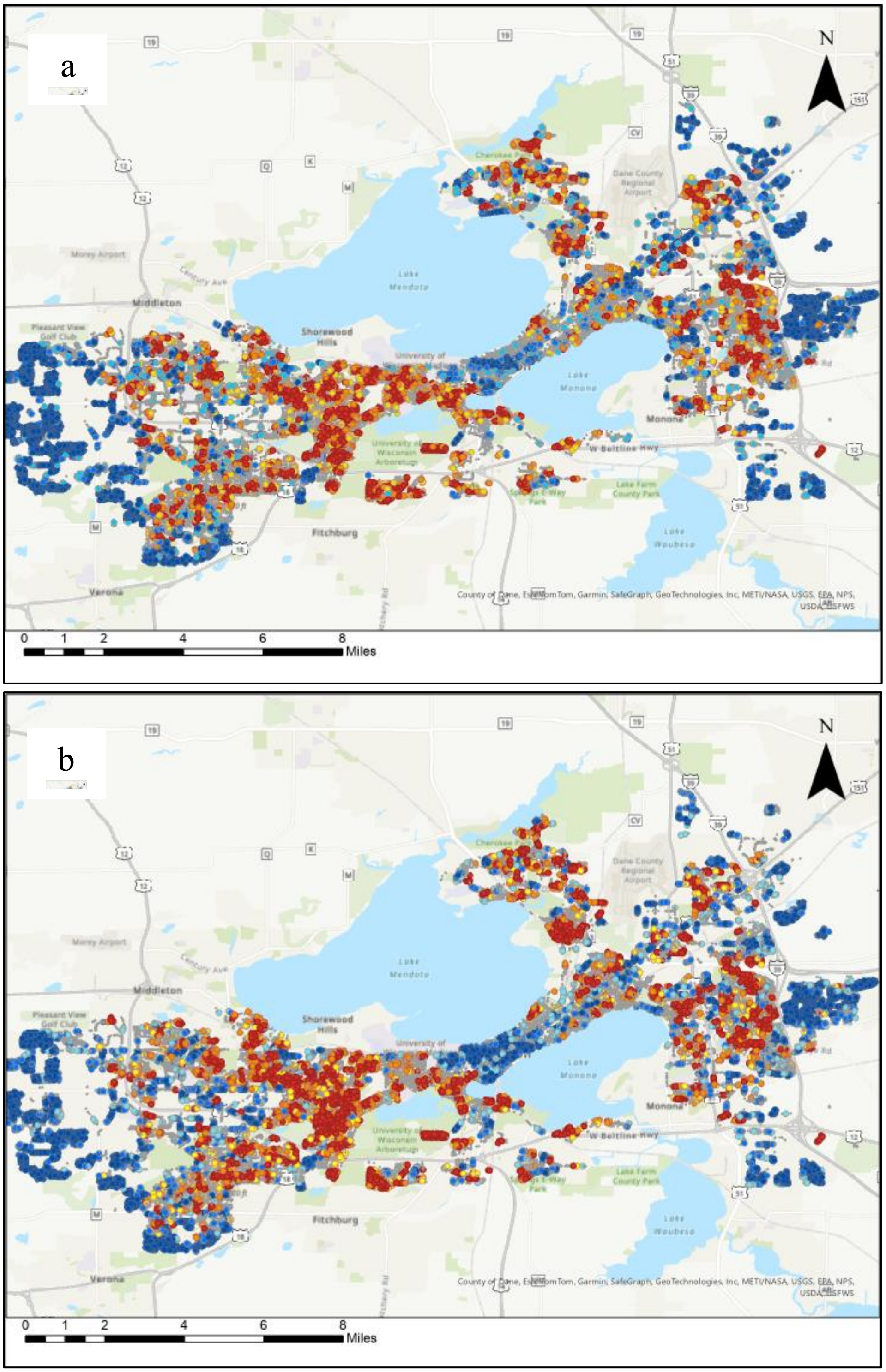

Figure 28: City-wide results of optimized hot spot analysis in Madison, WI, using α-values (a, top) and β-values (b, bottom) as the optimization parameters.

Hot spots (example shown in Figure 30) tend to be streets of Norway Maple trees with Silver Maple and Green Ash also present. While other trees (including species with low leaching potential) are intermingled, Norway Maple tends to be the dominating tree species because of its high leaching potential and high frequency. Cold spots (example shown in Figure 31) tend to be a mix of Hackberry, Sugar Maple, Honey Locust, and London Plane.

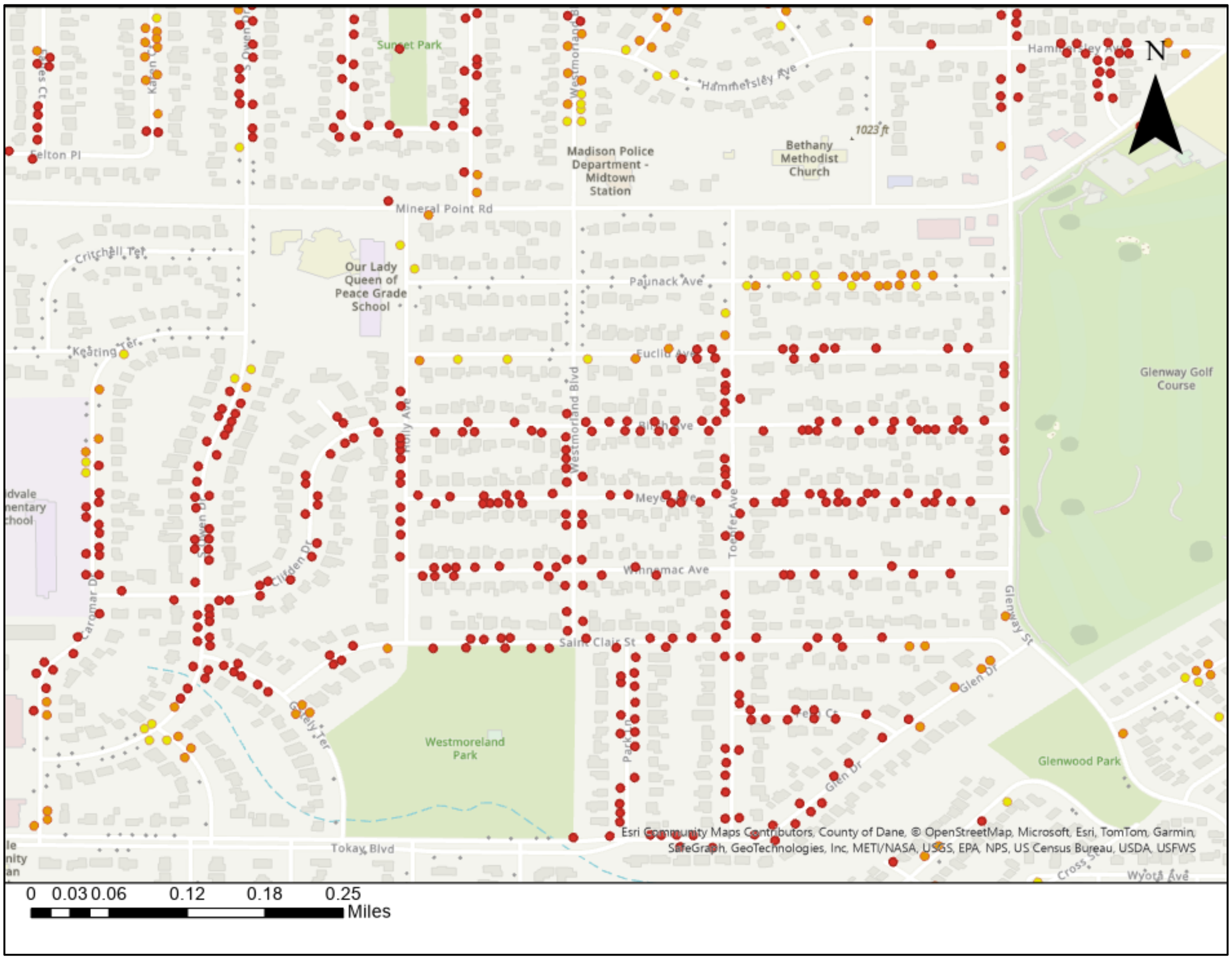

Figure 29: Example of a "hot" spot identified by analysis. Red dots show 99% confidence, orange show 95% confidence, and yellow spots show 90% confidence.

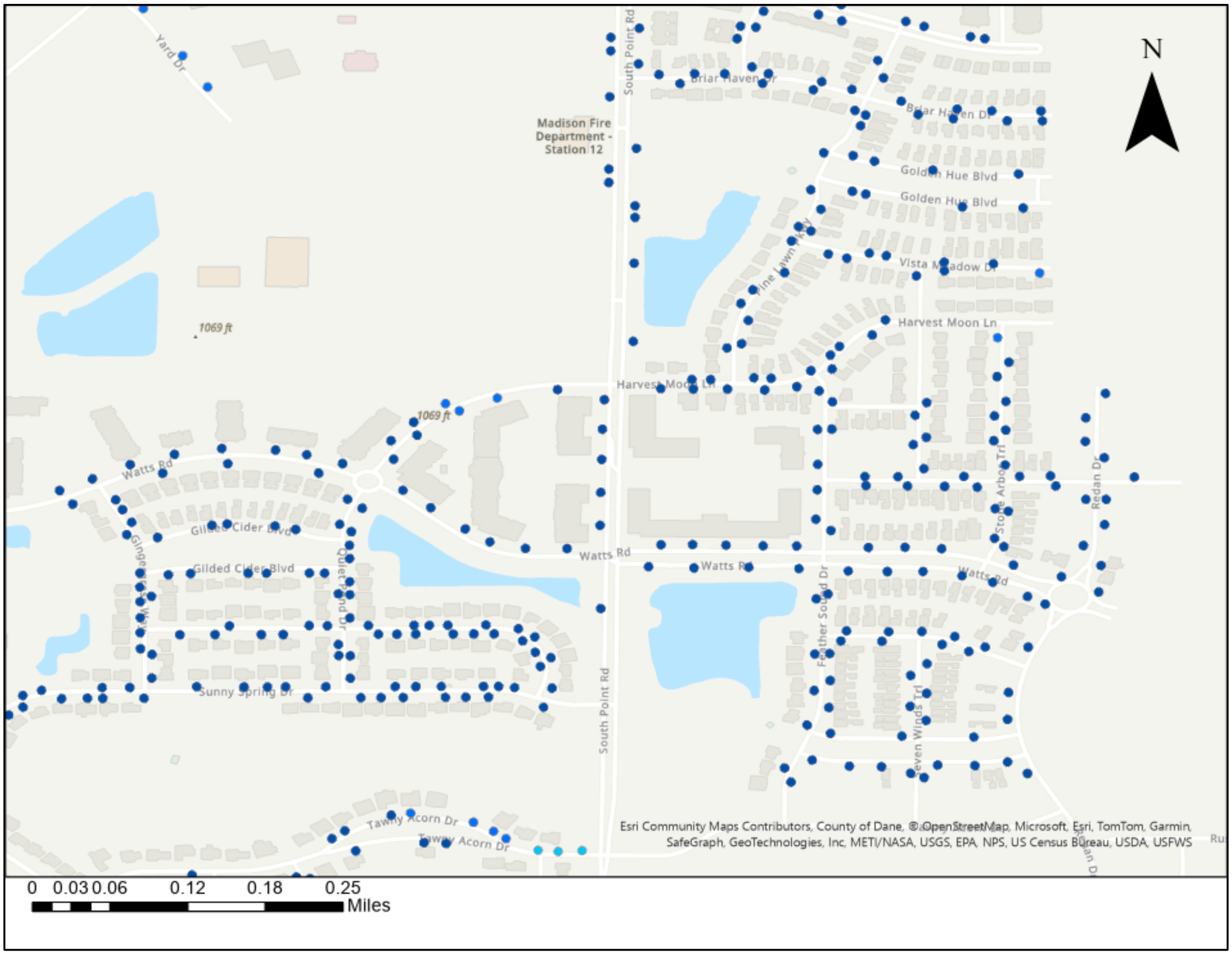

Figure 30: Example of a "cold" spot identified by analysis. Dark blue dots show 99% confidence, blue show 95% confidence, and cyan spots show 90% confidence.

Since the two optimization scenarios represent, to some degree, different runoff exposure periods - prolonged (α, maximum release) and short-term (β, rate of release) – and because different release patterns were observed for the species studied, it is important to compare their similarities. Some species lost P rapidly (Norway Maple and Silver Maple) and others slowly (Green Ash and Honey Locust), thus these differences may change spatial distribution of P release during different runoff exposure periods. To compare the optimizations, the Hot Spot Analysis Comparison tool in ArcGIS was used for a categorical analysis. Figure 32 displays the overlap between the β-values optimization (short storms) and the α-values optimization (long storms). For instance, 76% of the Cold (99% confidence) spots identified in the β-values optimization are also Cold (99% confidence) spots in the α-values optimization. Similarly, 74% of the Hot (99% confidence) spots in the β-values optimization are Hot (99% confidence) in the α-values optimization, and 75% of the non-significant spots in the β-values optimization are also non-significant in the α-values optimization. This comparison reveals an average similarity value of 0.798 ± 0.0012 (1 SE) between the two optimizations. This similarity value indicates a high degree of overlap, suggesting that areas identified as significant in one runoff exposure scenario are likely to also be significant in the other, reflecting consistent spatial patterns of phosphorus leaching potential.

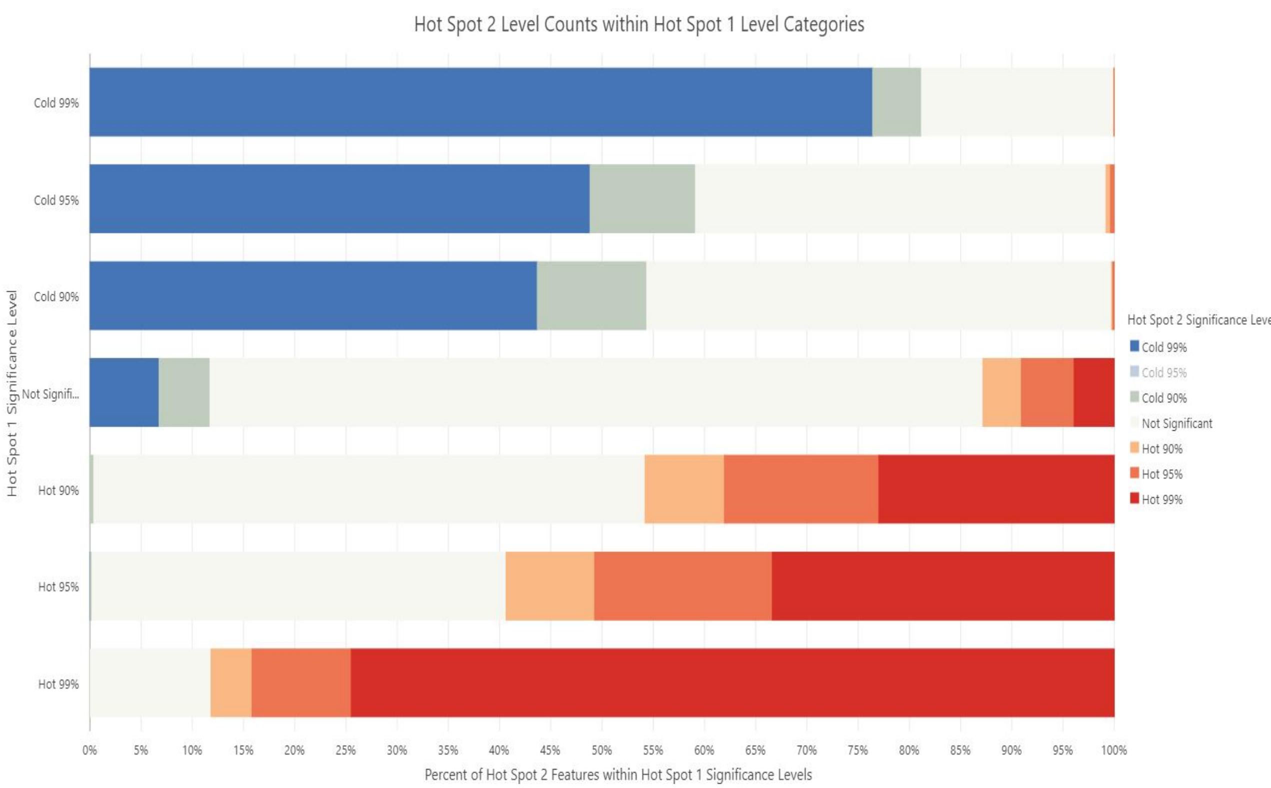

Figure 31: Results of similarity analysis of Optimization 1 and Optimization 2.

5. Conclusion and Future Work

In this study, the leachable phosphorus of ten different species of tree leaves were studied. Significant differences in the amount of leachable P were identified across the species, as well as differences in the release pattern of P among species. In addition, significant differences in the leachable P for the same species from different regions of the U.S. were identified. Leaching models were developed and evaluated to predict the temporal release of P and the estimated model parameters can be used to inform tools and decision making by urban managers.

The Hot Spot Optimization Analysis is a good starting point for the identification of P "hot spots" in Madison, WI, and demonstrates the potential for how quantifying differences in P leaching among tree species can help inform management.

There are several opportunities for future work in this area. First, quantifying P leaching dynamics for more species will provide additional information for stormwater models. Additionally, quantifying the mass of leaf fall from different species of trees will improve P load predictions and guide street sweeping practices (e.g. priority could be given to areas with trees that lose large amounts of leaves in the fall and have high potential for P release). Identifying the timing of leaf fall would improve the temporal optimization of street sweeping beyond the spatial optimization highlighted in this study. Different species lose their leaves at various times in the fall, thus street sweeping efforts could be focused on areas where leaves are being lost earlier in the fall, and shifted to different areas as other species lose their leaves. Overall, results from this study can be used to limit the contribution of urban leaf litter to eutrophication of surface water bodies.

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Appendices

Appendix Table 1: Average DRP and TKP data for each species at each time interval. Values in parentheses represent one standard error.

	DRP						TKP					
	0	**2**	**6**	**12**	**24**	**48**	**0**	**2**	**6**	**12**	**24**	**48**
RM (MW)	0.03 (0.01)	0.20 (0.02)	0.52 (0.03)	0.77 (0.03)	0.99 (0.01)	1.07 (0.01)	0.10 (0.01)	0.28 (0.002)	0.54 (0.02)	0.83 (0.06)	1.15 (0.10)	1.54 (0.07)
RM (NE)	0.02 (0.01)	0.11 (0.04)	0.25 (0.06)	0.35 (0.08)	0.42 (0.09)	0.47 (0.07)	0.10 (0.02)	0.23 (0.03)	0.43 (0.05)	0.60 (0.07)	0.68 (0.04)	0.75 (0.03)
RM (S)	0.01 (0.002)	0.06 (0.01)	0.14 (0.03)	0.22 (0.02)	0.27 (0.04)	0.32 (0.05)	0.08 (0.001)	0.17 (0.01)	0.28 (0.03)	0.36 (0.03)	0.43 (0.04)	0.46 (0.05)
RM (W)	0.00 (0.00)	0.00004 (0.00003)	0.0006 (0.0004)	0.007 (0.0008)	0.02 (0.002)	0.03 (0.004)	0.06 (0.01)	0.07 (0.005)	0.09 (0.01)	0.12 (0.002)	0.15 (0.004)	0.16 (0.003)
NM	0.14 (0.02)	0.77 (0.01)	1.25 (0.08)	1.63 (0.07)	1.87 (0.09)	1.96 (0.09)	0.20 (0.02)	0.90 (0.01)	1.63 (0.04)	1.82 (0.06)	2.20 (0.07)	2.58 (0.25)
GA	0.01 (0.0005)	0.11 (0.01)	0.43 (0.004)	0.80 (0.03)	1.18 (0.05)	1.43 (0.08)	0.08 (0.005)	0.18 (0.01)	0.55 (0.02)	1.04 (0.04)	1.43 (0.06)	1.91 (0.07)
HL	0.01 (0.001)	0.07 (0.04)	0.20 (0.01)	0.35 (0.01)	0.55 (0.02)	0.85 (0.02)	0.06 (0.02)	0.12 (0.03)	0.23 (0.06)	0.40 (0.04)	0.75 (0.02)	1.07 (0.04)
SiM	0.14 (0.01)	0.97 (0.09)	1.82 (0.08)	1.94 (0.05)	2.02 (0.06)	2.16 (0.12)	0.26 (0.03)	1.27 (0.08)	2.02 (0.14)	2.37 (0.03)	2.55 (0.02)	2.69 (0.08)
SuM	0.01 (0.03)	0.16 (0.02)	0.44 (0.06)	0.72 (0.08)	0.80 (0.10)	0.84 (0.11)	0.08 (0.01)	0.25 (0.02)	0.66 (0.05)	0.93 (0.09)	1.08 (0.14)	1.12 (0.14)
CP	0.001 (0.0004)	0.003 (0.002)	0.02 (0.005)	0.03 (0.01)	0.07 (0.02)	0.11 (0.02)	0.08 (0.003)	0.08 (0.003)	0.12 (0.01)	0.19 (0.02)	0.25 (0.05)	0.33 (0.04)
LL	0.01 (0.001)	0.08 (0.01)	0.18 (0.03)	0.28 (0.04)	0.36 (0.07)	0.42 (0.08)	0.07 (0.01)	0.16 (0.01)	0.31 (0.03)	0.42 (0.06)	0.55 (0.07)	0.64 (0.09)
LP	0.01 (0.001)	0.03 (0.01)	0.10 (0.04)	0.17 (0.07)	0.27 (0.09)	0.36 (0.10)	0.06 (0.01)	0.11 (0.02)	0.19 (0.03)	0.32 (0.08)	0.44 (0.11)	0.58 (0.13)
HB	0.0001 (0.00002)	0.0004 (0.0001)	0.001 (0.0002)	0.001 (0.0003)	0.002 (0.0001)	0.03 (0.01)	0.07 (0.01)	0.08 (0.01)	0.09 (0.01)	0.09 (0.01	0.12 (0.01)	0.23 (0.03)

Appendix Table 2: Distance Matrix of maximal DRP release for each species.

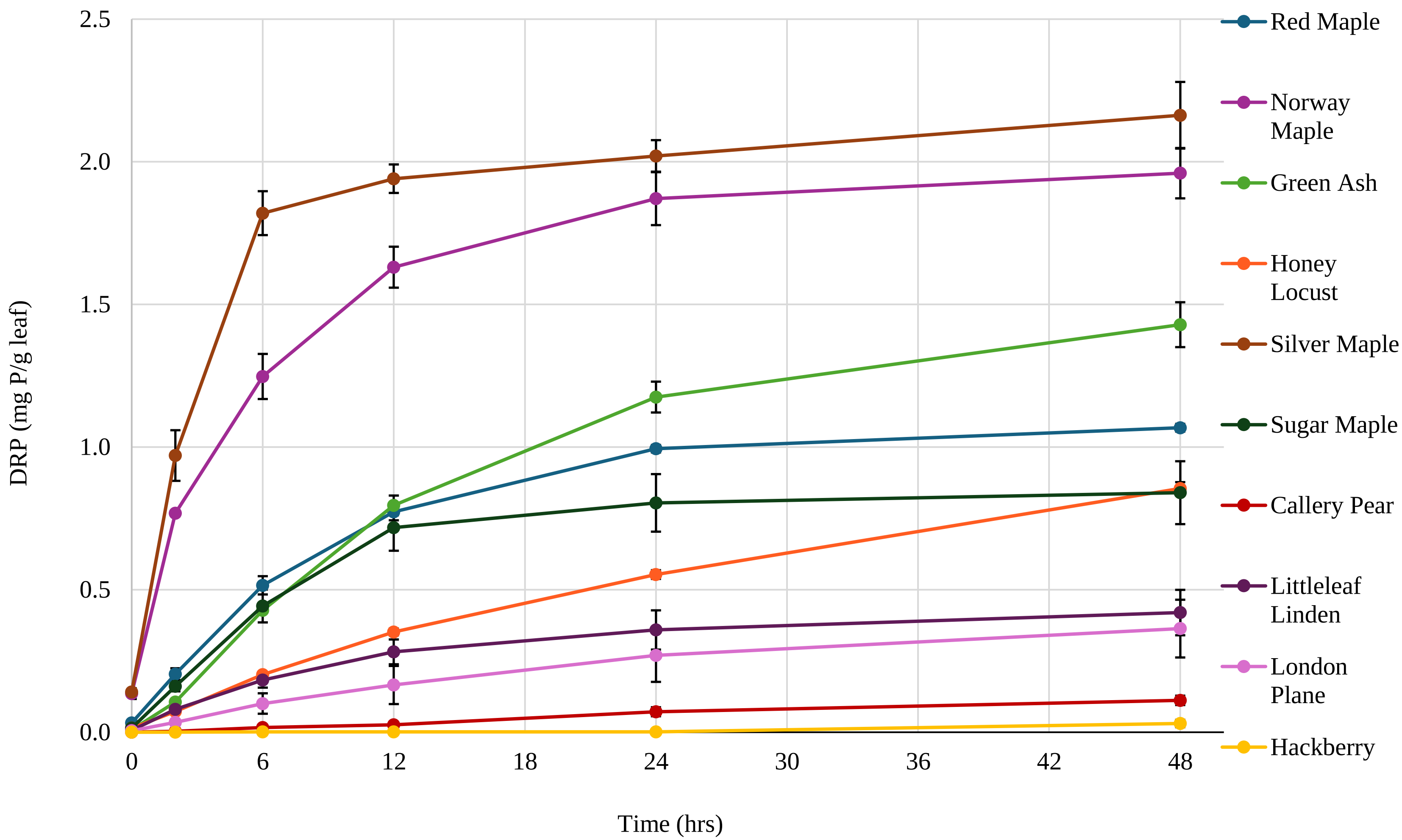
	Silver Maple	Norway Maple	Green Ash	Red Maple	Honey Locust	Sugar Maple	Littleleaf Linden	London Plane	Callery Pear
Norway Maple	0.72								
Green Ash	1.27	0.73							
Red Maple	2.82	2.11	1.68						
Honey Locust	2.78	2.10	1.55	0.40					
Sugar Maple	1.79	1.61	1.04	2.29	2.00				
Littleleaf Linden	2.49	2.09	1.37	1.83	1.46	0.88			
London Plane	2.45	2.20	1.54	2.34	1.99	0.66	0.54		
Callery Pear	3.58	2.97	2.31	1.30	1.01	2.36	1.53	2.03	
Hackberry	3.75	3.13	2.28	1.41	1.14	2.52	1.69	2.19	0.17

Numbers in the distance matrix represent the "distance" between two values of maximal release. The greater the number, the farther two values are from each other. Clusters highlighted in the table are highlighted in their associated cluster color in the distance matrix.

Appendix Table 3: Results of multiple linear regression analysis

Residuals				
Min	**1Q**	**Median**	**3Q**	**Max**
-0.14333	-0.02667	-0.01167	0.01583	0.15667
Coefficients				
	Estimate	**Std. Error**	**t-value**	***p*-value**
(Intercept)	8.1425741	0.8671652	9.390	1.36e-05 ***
Latitude	-0.1053555	0.0103956	-10.135	7.68e-06 ***
MAT	-0.1541193	0.0174394	-8.837	2.12e-05 ***
MAP	-0.0013242	0.0005838	-2.268	0.053 *
Residual SE	0.0911 on 8 degrees of freedom (DoF)			
Multiple R^2	0.9628			
Adjusted R^2	0.9489			
F-statistic	69.05 on 3 and 8 DoF, p = 4.634e-06 ***			

Significance codes: 0 to 0.001 ‘***’ highly significant, 0.001 to 0.01 ‘**’ moderately significant, 0.01 to 0.05 ‘*’ significant, 0.05 to 0.1 ‘,’ insignificant, 0.1 to 1 ‘ ‘ highly insignificant.



Appendix Figure 1: Cumulative DRP over time for all species. Error bars represent one standard error.