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# Using regional forest nutrition data to inform urban tree management in the northeastern United States

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ABSTRACT

Managing tree health in urban environments is complicated due to the disconnect that exists between novel environmental conditions created by urbanization and those under which tree species evolved. Soils influence tree health and growth, but optimal nutrient and pH recommendations are often informed by agricultural and horticultural norms which do not typically include norms for forest tree species. At the Arnold Arboretum in Boston, Massachusetts, USA, we investigated the relationships between tree health, foliar chemistry, and soil chemistry for three native forest tree species (*Acer saccharum*, *Quercus alba*, and *Tsuga canadensis*) located throughout the arboretum. We compared these ranges and relationships to data collected from trees of the same species growing in forested areas throughout the northeastern United States. For all species, the distributions of most foliar nutrient concentrations were similar in the arboretum and across the region. However, foliar potassium (K) concentrations were lower at the arboretum than in reference datasets. Soil pH was higher at the arboretum than most forest soils in the region, potentially a result of liming and irrigation with city water. Concentrations of soil and foliar magnesium were also high at the arboretum. Potassium deficiency could result from the blocking of K uptake by magnesium or limited K availability due to forest floor loss. In addition, there is some evidence that manganese is at low to deficient levels. These results show the value of comparing chemical conditions between urban tree populations with trees in natural forests in nearby rural settings to identify potential areas of concern and inform soil management strategies.

## 1. Introduction

Urbanization changes the environment in ways that alter temperature, precipitation patterns, atmospheric chemistry, and soil physical and chemical properties (Seto et al., 2013). While these dynamics are not unique to urban systems, they often co-occur and can be exacerbated in cities, consequently leading to changes in tree physiological function (Calfapietra et al., 2015). Trees growing in urban environments face a unique combination of stressful conditions that, taken together, are not found outside cities. Several of these altered environmental conditions include increased heat stress and drought (Gillner et al., 2014), soil compaction due to construction (Day and Bassuk, 1994) or pedestrian trampling (Komatsu et al., 2007)), reduced leaf litter and altered litter decomposition (Kostel-Hughes et al., 1998). Tree growth and productivity across varied urban site types is critical for the continued provision of important ecosystem services that enhance the lives of urban residents (Livesley et al., 2016). While there is a body of research on the stressful growing conditions of urban trees, less work has been done to link individual tree species physiological responses to these altered urban environmental conditions (Calfapietra et al., 2015).

Urban soil nutritional status has the potential to have both acute and chronic effects on tree health and growth. Although changes in soil chemistry correspond to urbanization gradients in many cities, the nature of the response varies depending on spatial patterns of urban development, soil parent material, and pollution sources in each city (Pouyat et al., 2008). These factors interact to affect physical and chemical properties of urban soils, which are not uniform across a city, but vary according to past and present land use and underlying

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environmental gradients (Scharenbroch et al., 2005; Groffman et al., 2006; Pouyat et al., 2007). As a result, the status of urban soils and associated nutrient availability is dynamic, complex, and difficult to predict.

In urban arboreta, individual trees are intensively managed to maintain their health and survival. Arboreta are living museums, and specimens often carry with them significant historical, scientific, or ornamental value. In addition to their valuable collections, urban arboreta, like many other urban greenspaces, are catalysts for environmental education, sites for research on urban environmental impacts on trees, and a component of urban green space that is important to human health and wellbeing (Cavender and Donnelly, 2019). Trees in urban arboreta face environmental conditions similar to those found in other urban green spaces, such as public parks or institutional grounds (Percival and Hitchmough, 1995). A detailed understanding of tree health and environmental conditions in urban arboreta can therefore provide actionable information for arboreta managers while having implications for trees cultivated in urban green spaces in general.

Arborists manage individual trees or shrubs, which includes managing soil health and nutrients (Scharenbroch et al., 2014). When addressing tree health issues in urban arboreta, traditional management strategies tend to be reactive, such as irrigating in dry periods and raising soil pH to values between 5.5 and 8 to increase nutrient availability for plants. Nutrient availability is often assessed by sending soil samples to agriculture extension laboratories. As a result, management recommendations are typically agricultural or production-oriented, tailored broadly towards coniferous or deciduous trees. Key soil physical and chemical properties that relate to urban tree growth have been identified in the midwestern United States (Scharenbroch and Catania, 2012), but to our knowledge, little work has been done on species-specific physiological performance of trees in response to urban soil environments, specifically in park-like environments. Just as we find in rural systems, each species is likely to respond differently to the environment to which they are exposed (Vaz Monteiro et al., 2017).

For tree species found in forests in the ecoregion surrounding urban centers, we can compare knowledge gained from studying the rural forest chemical environment and its relationship with tree health and productivity to those found in urban settings. Making these comparisons and thereby employing an "ecosystem approach" (Close et al., 1996) may help diagnose tree health issues and identify differences in growing conditions, such as soil quality, that may warrant further investigation as potential causes of stress. In addition to traditional visual inspections of tree health, an efficient way to assess incipient tree stress in urban environments is through chlorophyll fluorescence measurements. Chlorophyll fluorescence can easily be measured using a handheld meter, and the resulting parameters are promising indicators of early stress, providing an estimate of photosynthetic capacity and efficiency (Percival, 2005; Pregitzer et al., 2016). Regional datasets from rural forests that include visual tree health indicators, foliar nutrient concentrations, and soil element concentrations can be used to establish ranges of key parameters for each species.

In this study, we compare tree health metrics and soil and foliar element concentrations associated with trees in an urban arboretum in Boston, Massachusetts, USA to those of the same species found in forested areas of the northeastern USA in order to assess tree health and identify potential stress from imbalanced nutrition. We hypothesize that with this comparison we can illuminate areas of elemental imbalance that affect tree health and productivity in an urban arboretum. This species-level approach may inform future management options and strategies and could provide a basis for revising traditional soil management recommendations for urban landscape applications.

## 2. Materials and methods

### 2.1. Site description

Foliar and soil samples were collected in August 2017 at the Arnold Arboretum of Harvard University in Boston, Massachusetts, USA (42.3074°N, 71.1208°W), a 281-acre public arboretum within the temperate deciduous forest biome. Soils are Inceptisols, with several of the major soil series being Hinckley, Newport, and Paxton. These are primarily very deep, well to excessively drained sandy loams and silt loams. Prior to becoming an arboretum in 1872, most of this landscape was farmland (Hay, 1994). Consequently, many of the soils in this area have an Ap horizon: an artifact of past plowing. Organic matter, as loss on ignition, averaged 19.4% (± 6% SD) in composited Oa and A horizons of soil across the landscape and averaged 9.6% (± 3% SD) in upper B horizons.

Several areas of the landscape, referred to as the "natural areas", have been left relatively unmanaged since the Arboretum's founding, but the rest of the landscape has been cultivated, regularly mowed since at least the 1950s, and more intensively managed around each tree. Intensive management activities in the cultivated areas includes annual mulching of individual trees, air-spading of high-priority trees to reduce soil compaction in the rooting zone, and broad scale irrigation with municipal water during droughts.

### 2.2. Recent soil management history

During the last two decades, concerns about maintenance of tree health across the landscape prompted the arboretum staff to investigate by collecting soil samples from across the arboretum for analysis at the University of Massachusetts Soil & Plant Nutrient Testing Laboratory (through UMass Amherst Extension), with a full arboretum-scale collection of soil samples completed in 2015. Their goal was to learn more about soil quality in the arboretum and determine if there were any nutrient deficiencies that could be corrected at a landscape scale, potentially improving tree health. Samples were taken using soil probes to a depth of up to 20 cm and were not separated by soil horizon. Soil pH from these samples ranged from 4.07 to 6.19 with a mean of 5.33. Fertilizer recommendations were made based on soil test results which indicated that soil pH was below an "optimal range" (pH $< 5.5$) based on standard horticultural recommendations for 65% of soil samples.

As a result, much of the arboretum was treated with calcitic lime at a rate of 1 ton (2000 lbs) per acre once or twice between 2015 and 2016, with target soil pH levels of 6 (in line with recommendations from the University of Massachusetts) and 5.5 for the predominantly conifer collections. In addition, areas of the landscape with potassium (K) base saturation levels below 2% (the low end of the range typically seen in New England soils; Spargo, 2013) received K fertilizer additions once as potassium sulfate ($K_2SO_4$) in these same years. If Mg base saturation levels were below 10% (the low end of the range typically seen in New England soils; Spargo, 2013), Sul-Po-Mag ($K_2Mg_2O_{12}S_3$) was applied once at a rate of 400 lbs of K per acre. All areas that were treated with K were also treated with lime, as nearly all the cultivated landscape at the arboretum were limed at this time. These fertilizer applications were operational and the result of management decisions made in order to improve the health of the living collections.

Prior to these recent soil amendments, select areas of the arboretum landscape had been treated with lime and fertilizer in the 1990s, to improve the health of the *Juglans* and conifer collections. Prior to the 1990s soil amendments may have occurred but were not recorded.

### 2.3. Sample selection and experimental design

For this study, mature canopy dominant or co-dominant trees were selected from natural areas (areas of the arboretum landscape which have remained forested since the establishment of the arboretum and

**Table 1**
Mean, standard error, and range of soil variables measured at the Arnold Arboretum ("Arnold") and as part of other, past studies conducted in the northeastern USA ("Reference"). Values are expressed as "Mean ± Standard Error (Minimum–Maximum)." Nutrient concentrations are expressed in cmol(+) $kg^{-1}$.

| | | *A. saccharum* | | *Q. alba* | | *T. canadensis* | |
|---|---|---|---|---|---|---|---|
| Variable | Horizon | Arnold (n = 30) | Reference (n = 56) | Arnold (n = 30) | Reference (n = 89) | Arnold (n = 30) | Reference (n = 33) |
| pH | A | 5.29 ± 0.16 (4.00–7.03) | 3.46 ± 0.08 (2.68–5.67) | 4.99 ± 0.16 (3.76–6.71) | 3.59 ± 0.06 (2.28–5.00) | 4.44 ± 0.13 (3.63–6.50) | 3.08 ± 0.10 (2.46–5.96) |
| | B | 5.04 ± 0.11 (4.29–6.85) | 3.82 ± 0.07 (3.29–6.40) | 4.87 ± 0.10 (3.84–6.27) | Not measured | 4.52 ± 0.09 (3.89–6.16) | 3.40 ± 0.10 (2.79–5.93) |
| K | A | 0.36 ± 0.02 (0.19−0.61) | 0.36 ± 0.02 (0.14−0.59) | 0.34 ± 0.02 (0.19−0.54) | 0.26 ± 0.01 (0.09−0.87) | 0.35 ± 0..03 (0.13−0.98) | 0.70 ± 0.06 (0.06–1.33) |
| | B | 0.18 ± 0.02 (0.08−0.48) | 0.12 ± 0.01 (0.04−0.27) | 0.17 ± 0.02 (0.08−0.40) | Not measured | 0.15 ± 0.01 (0.07−0.42) | 0.09 ± 0.01 (0.01−0.19) |
| Ca | A | 7.42 ± 0.78 (1.52–17.4) | 8.21 ± 2.23 (0.52–98.5) | 6.44 ± 0.81 (0.45–16.5) | 2.05 ± 0.40 (0.03–22.5) | 5.61 ± 0.87 (0.63–19.4) | 6.44 ± 0.81 (0.02–17.8) |
| | B | 2.41 ± 0.44 (0.36–8.96) | 2.41 ± 1.12 (0.05–56.8) | 2.18 ± 0.40 (0.16–6.94) | Not measured | 1.53 ± 0.40 (0.20–11.5) | 0.60 ± 0.45 (0.01–15.1) |
| Mg | A | 1.36 ± 0.15 (0.46–3.87) | 1.01 ± 0.22 (0.09–11.2) | 1.54 ± 0.19 (0.42–4.33) | 0.51 ± 0.06 (0.08–2.72) | 1.43 ± 0.19 (0.58–6.26) | 2.05 ± 0.25 (0.02–7.43) |
| | B | 0.50 ± 0.09 (0.13–2.15) | 0.37 ± 0.20 (0.02–11.0) | 0.65 ± 0.13 (0.11–3.02) | Not measured | 0.43 ± 0.10 (0.11–3.29) | 0.22 ± 0.15 (0.01–4.71) |
| Al | A | 1.74 ± 0.17 (0.18–3.78) | 3.10 ± 0.35 (0.06–10.5) | 2.03 ± 0.15 (0.74–3.55) | 4.20 ± 0.27 (0.35–12.7) | 2.17 ± 0.14 (0..87−4.49) | 2.74 ± 0.94 (0.05–29.5) |
| | B | 2.96 ± 0.21 (0.16–4.56) | 7.12 ± 0.55 (0.01–19.2) | 3.43 ± 0.16 (1.41–4.92) | Not measured | 3.76 ± 0.21 (1.75–6.57) | 5.41 ± 0.54 (0.06–12.3) |
| Mn | A | 0.05 ± 0.01 (0.01−0.19) | 0.44 ± 0.05 (0.04–1.64) | 0.05 ± 0.01 (0.001−0.30) | 0.07 ± 0.01 (0.004−0.39) | 0.06 ±0.01 (0.02−0.24) | 0.60 ± 0.11 (0.04–2.34) |
| | B | 0.02 ± 0.002 (0.005−0.05) | 0.04 ± 0.01 (0.003−0.23) | 0.01 ± 0.0001 (0.003−0.03) | Not measured | 0.02 ± 0.002 (0.004−0.04) | 0.06 ± 0.03 (0.01−0.77) |
| LOI (%) | A | 14.5 ± 1.07 (4.69–27.5) | 26.0 ± 1.87 (9.91–84.6) | 18.3 ± 1.30 (7.94–36.6) | 11.9 ± 0.53 (5.04–34.6) | 25.3 ± 1.41 (9.15–39.1) | 67.7 ± 3.76 (8.22–95.4) |
| | B | 8.00 ± 0.49 (2.83–15.5) | 7.11 ± 0.37 (2.67–14.7) | 10.0 ± 0.55 (6.11–19.6) | Not measured | 10.7 ± 0.56 (6.47–17.2) | 7.20 ± 0.69 (1.15–17.1) |
| Exchangeable acidity | A | 13.9 ± 1.36 (2.12–25.7) | Not measured | 16.3 ±1.32 (2.50–25.7) | Not measured | 21.4 ± 1.05 (4.69–25.7) | Not measured |
| | B | 14.6 ± 0.97 (1.86–25.7) | Not measured | 16.6 ± 0.85 (5.20–25.7) | Not measured | 19.6 ± 0.75 (6.61–24.5) | Not measured |

have not, to our knowledge, ever been limed or fertilized), from cultivated areas (areas of the arboretum that have been regularly mowed and more intensively managed around each tree) to which K had not been added (most were recently limed), and from cultivated areas where K fertilizer was added (in addition to lime). We selected three tree species – *Acer saccharum* (Marsh.), *Quercus alba* (L.), and *Tsuga canadensis* (L.) Carrière – due to their widespread presence throughout the arboretum landscape. These species were also selected because we had existing foliar and soil chemistry data for these species from forests in the northeastern USA. We randomly selected 30 mature trees per species, with 10 trees of each species in the natural areas, 10 trees in cultivated areas with recent K addition, and 10 trees in cultivated areas without K addition, in order to represent trees exposed to the full range of management and landscapes in the arboretum. We allowed cultivars in our sample and avoided grafted trees.

All trees studied were greater than 24 cm in diameter at breast height (DBH) with crowns in the open or in a dominant position when in a closed canopy. The mean DBH of arboretum trees sampled was 68 cm (±20 cm SD). While exact ages are unknown, the oldest accession date for *A. saccharum* was 1883, for *Q. alba* was 1882, and for *T. canadensis* was 1947. The natural areas regenerated between 1790 and 1872 (Hay, 1994), meaning that some trees sampled in these areas could have theoretically been over 200 years old. Condition codes ascribed to these trees ranged from "Fair" to "Excellent", with no "Poor" trees included; excluding "Poor" trees enabled us to exclude trees in our study that were intensively suffering from pests, disease, or other damage, though we note that nutrient stress may lead to increased susceptibility to pest and disease (Bal et al., 2015), and thereby it was not feasible to completely exclude trees without evidence of minor pest and disease presence. Only two *A. saccharum* trees had somewhat substantial defoliation at the time of sampling, and all *T. canadensis* trees in this study, and in the arboretum as a whole, had been regularly treated for *Adelges tsugae* (hemlock woolly adelgid) with imidacloprid and then horticultural oil since the 1990s.

### 2.4. Tree health and foliar sampling

In August 2017, we visited each of the 90 trees once and performed a tree health assessment using methods adopted from Pontius and Hallett (2014). Ocular estimates of leaf discoloration, fine twig dieback and crown vigor were made from the ground for each tree. Crown transparency was assessed using a digital camera (Pontius and Hallett, 2014). Foliage was sampled from at least three separate sun exposed portions of the canopy using an arborist throw bag and slingshot. Chlorophyll fluorescence measurements were made on five leaves per tree using the Handy PEA (Plant Efficiency Analyzer) chlorophyll fluorescence meter (Hansatech Instruments Ltd., England United Kingdom; Pontius and Hallett, 2014). Leaves were dark adapted for 30 min prior to measurement. We used Performance Index ($PI_{ABS}$) and $F_V/F_M$ for our analyses. $PI_{ABS}$ is a measure of how efficiently a leaf can use light for photosynthesis (Hermans et al., 2003) and $F_V/F_M$ is a measure of the efficiency in photosystem II (Hong and Xu, 1999).

To compare health between trees, a comprehensive tree stress index was created by standardizing each health assessment variable using z-scores (Green, 1979). Researchers used a tree health database containing 2689 *A. saccharum*, 76 *Q. alba*, and 1554 *T. canadensis* trees, from the reference forest datasets, to obtain the mean and standard deviation for each variable by species. A z-score was calculated for each variable and tree in the study. The z-scores for each variable were averaged for each tree to create an overall, species-specific stress index. Lower values represent healthier trees. This procedure is a refinement of methods outlined in Pontius and Hallett (2014).

At least 15 of the sampled leaves per tree were taken back to the lab ground, oven-dried, digested using a microwave-assisted acid digestion

**Table 2**
Mean, standard error, and range of foliar elements measured at the Arnold Arboretum ("Arnold") and as part of other, past studies conducted in the northeast ("Reference"). This dataset includes trees for which only foliar chemistry was measured. Values are expressed as "Mean ± Standard Error (Minimum - Maximum)" and are expressed in mg $kg^{-1}$, except for nitrogen, which is expressed as a percentage.

| Element | *A. saccharum* Arnold ($n = 28$) | Reference ($n = 778$) | *Q. alba* Arnold ($n = 30$) | Reference ($n = 107$) | *T. canadensis* Arnold ($n = 29$) | Reference ($n = 607$) |
|---|---|---|---|---|---|---|
| Al | 30.3 ± 1.6 (15.0–45.7) | 27.6 ± 0.67 (1.61–379) | 42.9 ± 1.8 (22.8–63.1) | 31.3 ± 0.9 (10.5–179) | 505 ± 23.0 (299–766) | 317 ± 5.21 (87.3–1,004) |
| Ca | 12,171 ±727 (5,154–20,187) | 7448 ± 147 (1,335–32,181) | 6251 ± 301 (2,761–9,738) | 7108 ± 160 (2,771–16,000) | 4835 ± 199 (3,202–7,820) | 5335 ± 76.8 (1,058–15,503) |
| Mg | 2022 ±115 (872–3,193) | 1144 ± 17.6 (361–3,805) | 1341 ± 52.2 (757–2,013) | 1269 ± 27.8 (575–2,310) | 1747 ± 66.7 (1,129–2,501) | 1213 ± 14.5 (444–2,960) |
| Mn | 619 ± 90.7 (66.8–1,822) | 1373 ± 31.7 (111.5–6,424) | 468 ± 79.2 (39.4–2,075) | 849 ± 53.8 (30.9–2,683) | 678 ± 91.6 (78.4–1,808) | 1019 ± 25.2 (118–3,874) |
| N | 2.1 ± 0.07 (1.3–2.9) | 1.9 ± 0.009 (0.9–2.9) | 2.5 ± 0.06 (1.8–3.1) | 2.3 ± 0.04 (0.8–3.3) | 1.4 ± 0.03 (1.1–1.8) | 1.4 ± 0.008 (0.8–2.1) |
| P | 1579 ± 104 (938–2,995) | 1300 ± 17.6 (505.3–5,693) | 1641± 34.1 (1,298–2,056) | 1440 ± 28.7 (630–2,400) | 1627 ± 60.6 (980–2,450) | 1420 ± 16.9 (464–2,930) |
| K | 5520 ± 186 (3,812–7,850) | 7883 ± 54.0 (2,735–17,716) | 6443 ± 191 (4,202–8,276) | 8474 ± 211 (5,102–15,702) | 4444 ± 219 (2,175–7,596) | 6519 ± 42 (3,474–9,576) |

procedure (USEPA Method 3052), and analyzed for aluminum (Al), calcium (Ca), potassium (K), magnesium (Mg), manganese (Mn), and phosphorus (P) by ICP spectroscopy. Foliar nitrogen (N) was determined by combustion with a PerkinElmer 2400 series II CHNS/O analyzer (PerkinElmer, Waltham, MA). All foliar characteristics measured in this study were compared to publicly available data from a foliar database containing similar metrics for thousands of trees across the northeastern USA (NERC) and from Sonti et al. (2020a).

### 2.5. Soil sampling

The Oa/A and upper B horizons (hereafter horizons 1 and 2) were sampled in August 2017 using a stony soil auger beneath each of the 90 trees in this study. In order to obtain a representative soil sample from within the dripline of each tree, four soil cores were taken in each of the cardinal directions from the trunk of the tree (Sonti et al., 2019) to a depth of up to 20 cm; two samples were taken at the edge of the canopy and the other two mid canopy. The cores were composited by horizon, air dried, and sieved through a 2-mm sieve. Oa/A horizons at the Arnold Arboretum average 10.4 cm (± 3.4 SD).

Soil samples were analyzed by the University of Massachusetts Amherst, Soil & Plant Nutrient Testing Laboratory. Soil pH was measured using a 1:1 ratio of soil to water (Eckert and Sims, 2011), and the salt-extractable element concentrations were measured using a modified Morgan extraction, 1.25 M ammonium acetate extraction buffered at pH 4.8 (Wolf and Beegle, 2011). Soil organic matter was determined by loss on ignition (Schulte and Hoskins, 2011). Exchangeable acidity was calculated using the Modified Mehlich Buffer pH values in the following equation modified by John Spargo from Hoskins and Erich (2008):

$$Exchangeable\ Acidity = 83.511 - (12.838 \times Buffer\ pH) \quad (1)$$

The constant 83.511 was modified from 83.0 and 12.838 from 12.83, presumably to adjust for local conditions (Tracy Allen, pers. comm., 23 Dec 2019).

Cation exchange capacity was calculated using the following equation

$$\frac{K}{391} + \frac{Mg}{122} + \frac{Ca}{200} + Exchangeable\ Acidity \quad (2)$$

where K, Mg, and Ca represent concentrations of those elements in cmol (+) $kg^{-1}$ (Ross and Kettering, 2011).

### 2.6. Reference forest data

We assembled a reference dataset consisting of trees from forested areas of the northeastern USA. Variables, for each species in this study, included tree health (i.e., chlorophyll fluorescence, visual tree health metrics), foliar nutrient concentration, and/or soil nutrient concentration data. Our reference dataset for *A. saccharum* consisted of data collected between 1995 and 1998 across Pennsylvania, New York, Vermont and New Hampshire (Hallett et al., 2006; Horsley et al., 2008). The reference dataset for *T. canadensis* consisted of data collected in 2001 in Connecticut, Massachusetts, New Hampshire, New Jersey, New York, and Pennsylvania (Pontius et al., 2006). Our reference dataset for *Q. alba* consisted of data collected in forested areas across urban to rural gradients in New York, Pennsylvania, and Maryland in summer 2015 (Sonti et al., 2020a). Not all parameters were available for each tree species or reference dataset, which explains differences in sample sizes across species and between soil and foliar data (Tables 1,2).

This reference data set provides information about the expected range of each variable for each species. Knowing the expected range of a variable allows us to see if samples from the arboretum are at the high or low end of that range. Broad scale geographic sampling of a single species has been used for *A. saccharum* (Bal et al., 2015; Hallett et al., 2006), *Q. alba* (Sonti et al., 2020b), and *T. canadensis* (Pontius et al., 2006).

## 3. Results

### 3.1. Tree health

*Acer saccharum* trees at the arboretum were more stressed than 60 % of the trees in the reference dataset (Fig. 1). Arboretum *T.canadensis* trees were also generally less healthy than many of the trees in the reference dataset (Fig. 1). *Q.alba* spanned the range of stress index values observed in the reference dataset (Fig. 1).

Chlorophyll fluorescence parameters $F_V/F_M$ and Performance Index ($PI_{ABS}$) were compared between arboretum and reference trees for *Q. alba* and *T. canadensis*, but not *A. saccharum*. $F_V/F_M$ measured in trees at the arboretum spanned the range of values measured in the reference trees for *Q. alba*, but were towards the higher end for *T. canadensis*, which corresponds with healthier trees and higher photosynthetic efficiency (Fig. 2). These trends were also reflected in $PI_{ABS}$ values (Fig. 2).

### 3.2. Soil quality

In general, soils at the arboretum had higher pH, high levels of Mg, and low levels of Al compared to soils collected from the reference forests (Table 1, Figs. 3 and 4). Soil pH in the natural areas at the arboretum was lower than in the cultivated areas (Fig. 3). Arboretum soils spanned a wide range of values for Ca but were all above the 10th percentile for *A. saccharum* and above the 20th percentile for *Q. alba*. Ca concentrations in the natural areas at the arboretum tended to be lower than they were in cultivated areas of the arboretum (Fig. 4).

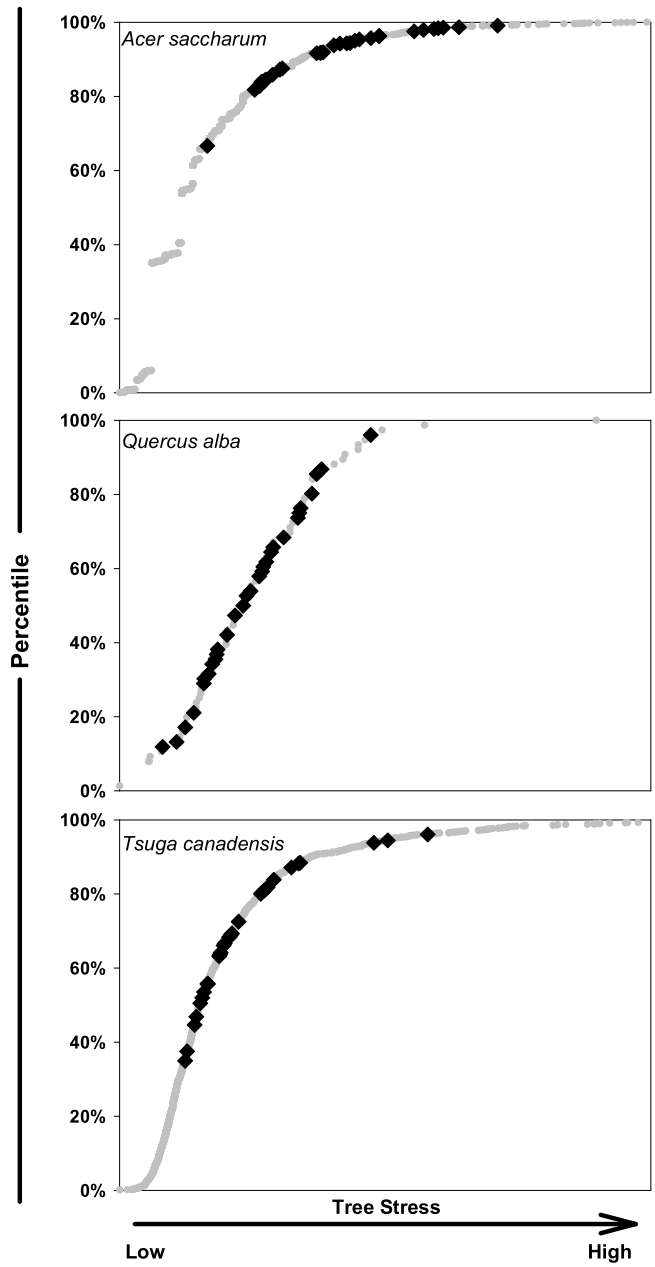


**Fig. 1.** Cumulative frequency distribution for tree stress for three native tree species (*A. saccharum*, *Q. alba*, and *T. canadensis*). Grey circles are rural reference trees. Black diamonds are trees at the Arnold Arboretum.

### 3.3. Foliar and soil nutrition

For all three species, foliar K concentrations were typically below the 50th percentile as compared to trees in the reference forests. In addition, trees in the natural areas of the arboretum usually had lower foliar K concentrations than those found in cultivated areas of the arboretum. (Table 2, Fig. 5). In all three species, though, there appeared to be no relationship between K concentrations in soil (both horizons 1 and 2) and foliage (Fig. 6). Across all species, average foliar Mn was higher in reference trees than in trees at the arboretum (Table 2). Among the trees at the arboretum, the trees in the natural areas had higher Mn concentrations (Fig. 5). For *A. saccharum*, concentrations of Mn in both foliage and soil were low compared to the reference dataset (Figs. 5,7).

Foliar Mg concentrations in *A. saccharum* and *T. canadensis* trees at the arboretum were at the upper end of the range of values measured for reference trees (Fig. 5). In *A. saccharum*, these high values corresponded with relatively high Mg in both soil horizons (Fig. 8). In *T. canadensis*, these high foliar Mg values corresponded with relatively high concentrations of Mg in the upper B soil horizons (Fig. 8). Similarly, foliar Ca concentrations in *A. saccharum* at the arboretum were at the higher end of values measured in the reference trees, which corresponded with relatively high levels of Ca in soil horizon 1 as well (Fig. 9). This trend was not observed in *T. canadensis* or *Q. alba*.

For *A. saccharum*, concentrations of Al in both foliage and soil were low compared to the reference forests (Fig. 10). By contrast, for *Q. alba*, concentrations of Al in foliage were higher compared to the reference forests (Fig. 10).

## 4. Discussion

We used regional, species-level datasets of soil and foliar chemistry to assess three common tree species growing in the Arnold Arboretum in Boston, Massachusetts. This ecosystem approach (Close et al., 1996) differs from traditional methods that apply conventional generalizations reactive to decline symptoms, instead encouraging managers to consider their trees within a regional context. In this analysis, we documented high soil pH levels and high concentrations of soil Ca and Mg, which correlated with high concentrations of Ca and Mg in foliage. We also documented low concentrations of foliar K and Mn across all species, and high tree stress indices among *A. saccharum* and *T. canadensis* compared to reference forest datasets. These comparisons among arboretum and reference forest datasets contextualize trees and nutrient recommendations provided by extension laboratories within a regional context, informing future investigations of tree health and subsequent management decisions.

Tree health and productivity are linked to soil nutrient imbalances (Waring, 1987; Bal et al., 2015), making soils an important consideration in urban tree health programs (Scharenbroch and Catania, 2012), such as the one at the Arnold Arboretum. Our comparison of arboretum soils to soils in the reference dataset showed how arboretum soils differed from regional forest soils. While these differences in soil chemistry do not confirm causes of tree decline, they provide a starting point for investigations into nutrient imbalances that may affect tree health.

Higher soil pH in the arboretum than in regional forests is likely due to management efforts such as recent liming and irrigation with high pH Boston city water. City water in Boston, sourced from the Wachusett Reservoir, has nearly twice the concentrations of Ca, Mg, and K as compared to water sourced elsewhere in Massachusetts (e.g., Ca concentrations of 4 mg $L^{-1}$ in Boston compared to 2 mg $L^{-1}$ elsewhere in Massachusetts) and is additionally treated to increase alkalinity (MWRA, 2016). Lower pH in the "natural areas" (which were not limed and irrigated) compared to the cultivated areas provides further evidence that these horticultural treatments likely caused an increase in soil pH. Increases in pH from horticultural treatment can limit Al activity, and thereby toxicity, in soil and increase nutrient availability in a general sense, with a pH range of 5.5–8 considered optimal for most nutrients (Scharenbroch et al., 2014). In soils supporting forest trees in the northeastern USA, however, increases in pH can also lead to imbalances among base-cation nutrient concentrations in soil, which could adversely affect tree health.

Soil test results yielded recommendations focused on increasing the pH and nutrient status of arboretum soils. These recommendations are often heavily influenced by a diagram showing the relationship between

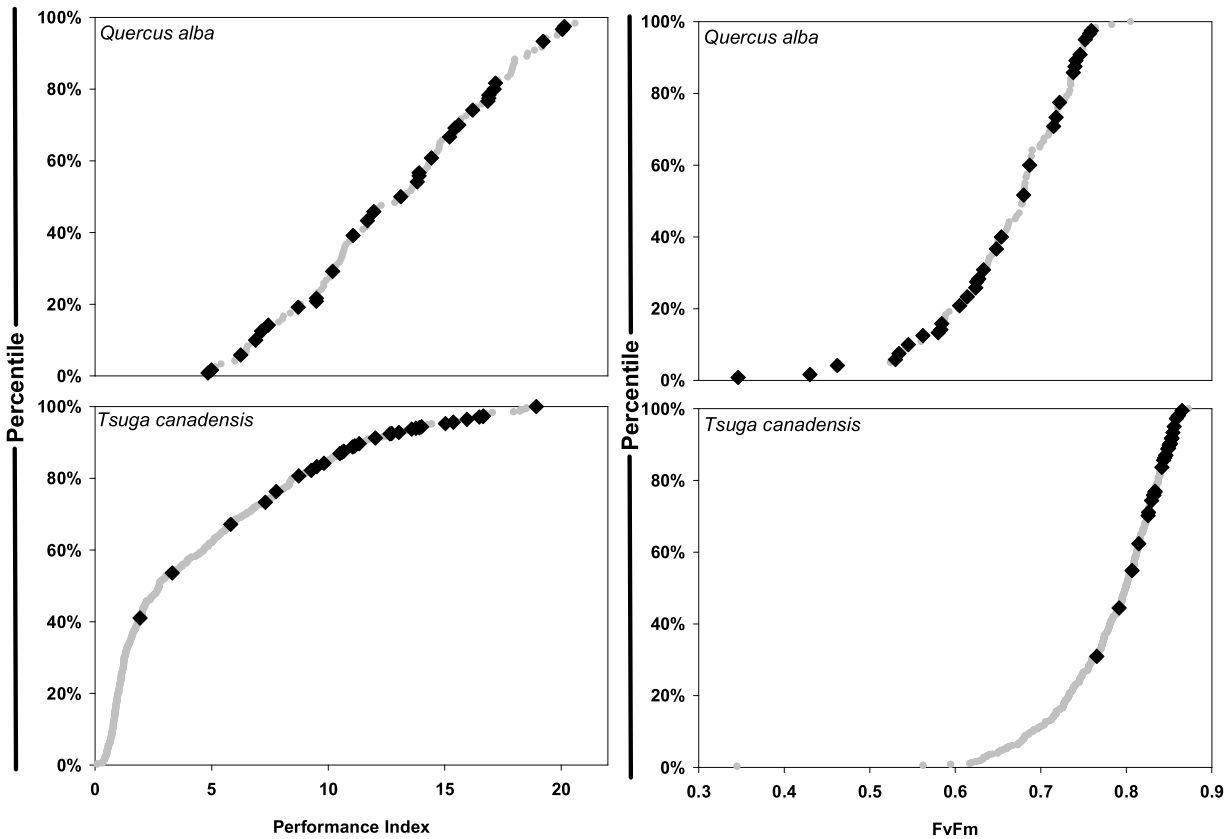


**Fig. 2.** Performance index and $F_V/F_M$ for *Q. alba*(top) and *T. canadensis* (bottom). Reference data for comparison were not available for *A. saccharum*. Grey circles are rural reference trees. Black diamonds are trees at the Arnold Arboretum.

soil pH and optimal availability of plant nutrients which first appeared in the peer reviewed literature in Truog (1947) as a general relationship in soils, but based primarily on research of agricultural, row-crop soils. The region of general optimal nutrient availability is concentrated around a soil pH of 7, and fertilizer recommendations are designed to optimize yield in agricultural systems (McGrath et al., 2014). However, in many cases, these agricultural recommendations also provide the basis for best management practices for urban trees (Scharenbroch et al., 2014).

In the northeastern USA, productive and healthy forests are found growing in soils with a pH of less than 7 (Fig. 3); in fact, forest soil pH greater than 5 is rare; acidic soil pH is typical in humid temperate climates. Tree species in these forests are adapted to acid soils and in fact may do better in soils with a pH that is far less than recommendations based on optimal plant nutrient availability suggest. Relying solely on the theoretical relationship between nutrient availability and pH, therefore, can be misleading. Diagnosing tree health problems related to nutrient supply should involve an understanding of plant-available elements in the soil coupled with foliar chemistry. Foliar chemistry can indicate of how much of a given element the tree is able to access and take up. This is complicated by the fact that different tree species can have vastly different foliar element concentrations, even when growing next to each other. However, optimal ranges of foliar nutrients are available for some species, such as *A. saccharum* (Hallett et al., 2006); these ranges can be used to help managers diagnose deficiencies. In urban areas, foliar analyses might even be more straightforward to use to diagnose nutrient deficiencies than soil analyses (Kopinga and van den Burg, 1995).

For all three species in this study, low concentrations of foliar K, an essential macronutrient required for plant growth (Lawton and Cook, 1954), and high concentrations of foliar Mg relative to those found in the reference datasets, suggests a possible nutrient imbalance at the arboretum, resulting in a possible K deficiency. For *A. saccharum*, K deficiency is indicated by a range of foliar K between 4500 and 5900 ppm (Bernier and Brazeau, 1988); two thirds of the arboretum *A. saccharum* trees sampled had foliar K levels within this range (Fig. 5). Potassium uptake may be limited by high levels of plant-available Mg, either due to dolomitic bedrock, or due to high levels of Mg fertilization. In Quebec, K deficiency was identified in *A. saccharum* growing in soils with high Mg saturation (Ouimet and Camiré, 1995), and in Pennsylvania, K levels in *A. saccharum* foliage was reduced by high levels of lime application (Long et al., 1997). In addition, liming Norway spruce (*Picea abies*(L.) Karst.) stands resulted in induced K deficiency due to an antagonism of Ca and K in root uptake (Ingerslev and Hallbacken, 1999; Weis et al., 2009). Past lime applications, naturally high Mg levels in soil, or both, may have therefore contributed to the lower levels of K in *A. saccharum* foliage at the arboretum.

We did not find significant differences in K concentrations in arboretum soils that had and had not been fertilized; this lack of correlation has been observed before (White and Leaf, 1964). One potential explanation for low K retention following fertilizer application, as well as low availability of K overall, could be the relatively restricted expression of O horizons in soils at the arboretum. Most of the cultivated landscape consisted of a ground cover, such as grass, rooted in an A horizon (typically Ap). In the natural areas, which have more of an O horizon, these horizons tended to be relatively thin due in part to agricultural

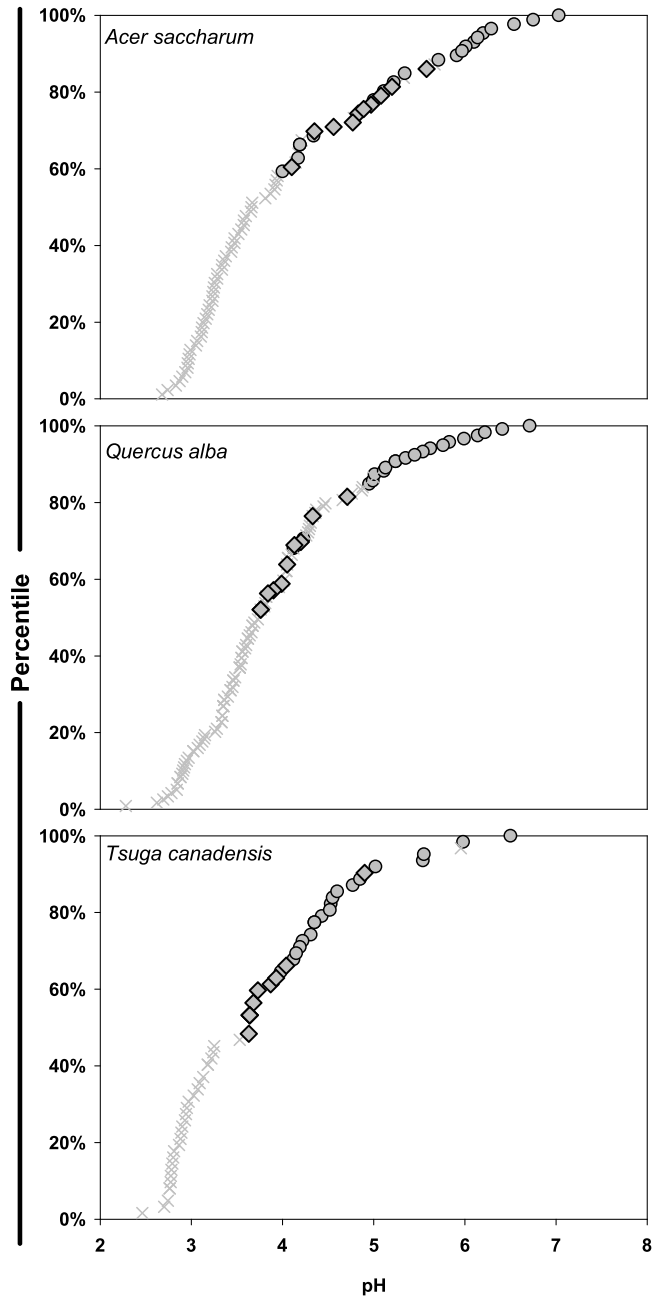


**Fig. 3.** Cumulative frequency distribution of soil A horizon pH. Circles and diamonds are trees at the Arnold Arboretum. Diamonds are trees located in the natural areas of the arboretum. Xs represent trees in the reference forests.

land-use history and a recent increase in invasive earthworm abundance in this region (Nuzzo et al., 2009).

Forest-floor organic horizons may play a key role in maintenance of K availability relative to the availability of other base-cation nutrients. Potassium-bearing minerals generally decompose more slowly than Ca- and Mg-bearing minerals, limiting the supply of K from soil-forming weathering processes (e.g., Hyman et al., 1998). The forest floor is therefore relatively more important in recycling K from leaf litter than it is for Ca or Mg. Potassium in litter is soluble (Schreeg et al., 2013) and has a much smaller residence time during decomposition than other nutrients (Dincher et al., 2019). Furthermore, K ions with a single positive charge and large ionic radius are poor competitors for soil exchange sites where smaller cations with higher charge (e.g., Ca, Mg, Al) have an advantage. Therefore, soluble K amendments not immediately taken up by plants are more likely to leach off site.

Improving organic matter retention on site by retaining litter or adding compost may increase cation exchange capacity and help soils in urban systems that have similar land-use histories and similar stressors retain more soil K. In 2018, the Arnold Arboretum began retaining leaf litter in more locations to produce "forest floor" environments and incorporated leaves collected from highly manicured areas into their composting system (Arnold Arboretum, 2018). Our measurements can serve as a baseline for future comparisons to help managers assess whether these efforts to were effective.

Another element that consistently differed between the arboretum and reference datasets was Mn, which was lower on average in foliage at the arboretum. This corresponded with low soil Mn concentrations beneath *A. saccharum* trees, but not necessarily *T. canadensis* or *Q. alba*. While Mn is a micronutrient and at high concentrations may be toxic (Hallett et al., 2006), it is possible for plants to be Mn deficient as well (Hacskaylo et al., 1969). Manganese deficiency in *A. saccharum* has previously been documented in urban soils with pH values ranging from 7.29 to 8 (Close et al., 1996; Kielbaso and Ottman, 1976). Unlike other nutrients, which are more available at moderate pH levels, Mn availability is highest at low pH.

Nutrient imbalances may predispose tree species, in particular *A. saccharum*, to stress (Bal et al., 2015). In this study, *A. saccharum* trees in the arboretum were more stressed than *A. saccharum* trees found in regional forests. While this observation is not enough to conclude that nutrient imbalances at the arboretum increased stress in *A. saccharum*, it is important to consider that imbalances in Ca, Mg, Mn, and Al in the northeastern USA have previously been linked to *A. saccharum* decline, manifesting as predisposition to mortality after defoliation, pest and disease incidence, and drought stress (Hallett et al., 2006; Long et al., 2009). *Tsuga canadensis* also exhibited greater stress than other *T. canadensis* trees in the region. Unlike regional trees, however, these trees were treated for the nonnative *Adelges tsugae* (hemlock woolly adelgid, or HWA) currently threatening trees in the eastern United States (Ellison et al., 2005). This means that signs of decline in *T. canadensis* are likely not due to pest and disease. While some evidence of pests and pathogens were found on foliage from *A. saccharum* and *Q. alba*, trees from both species in this study did not show signs of extensive infestation or defoliation. This suggests that pests and disease did not strongly influence the data collected in this study.

While pests and disease may not have been confounding, we acknowledge that other stressors not measured may be inciting factors resulting in poor health. There are many stressors in urban environments, including elevated temperature (Wang et al., 2017), atmospheric pollution (Calfapietra et al., 2015; Rao et al., 2014), and increased soil compaction due to machinery and visitor traffic (Nawaz et al., 2013). Adding any of these factors to future comparisons would better characterize differences between urban and natural sites and inform management. We only focus on soil chemistry in our study, for example, but physical properties of soil, such as bulk density and texture, greatly influence nutrient availability as well, complicating interpretations of nutrient availability from soil chemistry tests alone. For this reason, foliar chemical analyses are sometimes seen as more straightforward to interpret in the context of urban tree nutrient deficiencies than soil chemical analyses (Kopinga and van den Burg, 1995), but both foliar and soil analyses impart important information on tree health that can facilitate management decisions.

Unlike *A. saccharum* and *T. canadensis*, *Q. alba* spanned the range of values observed for stress and chlorophyll fluorescence parameters.

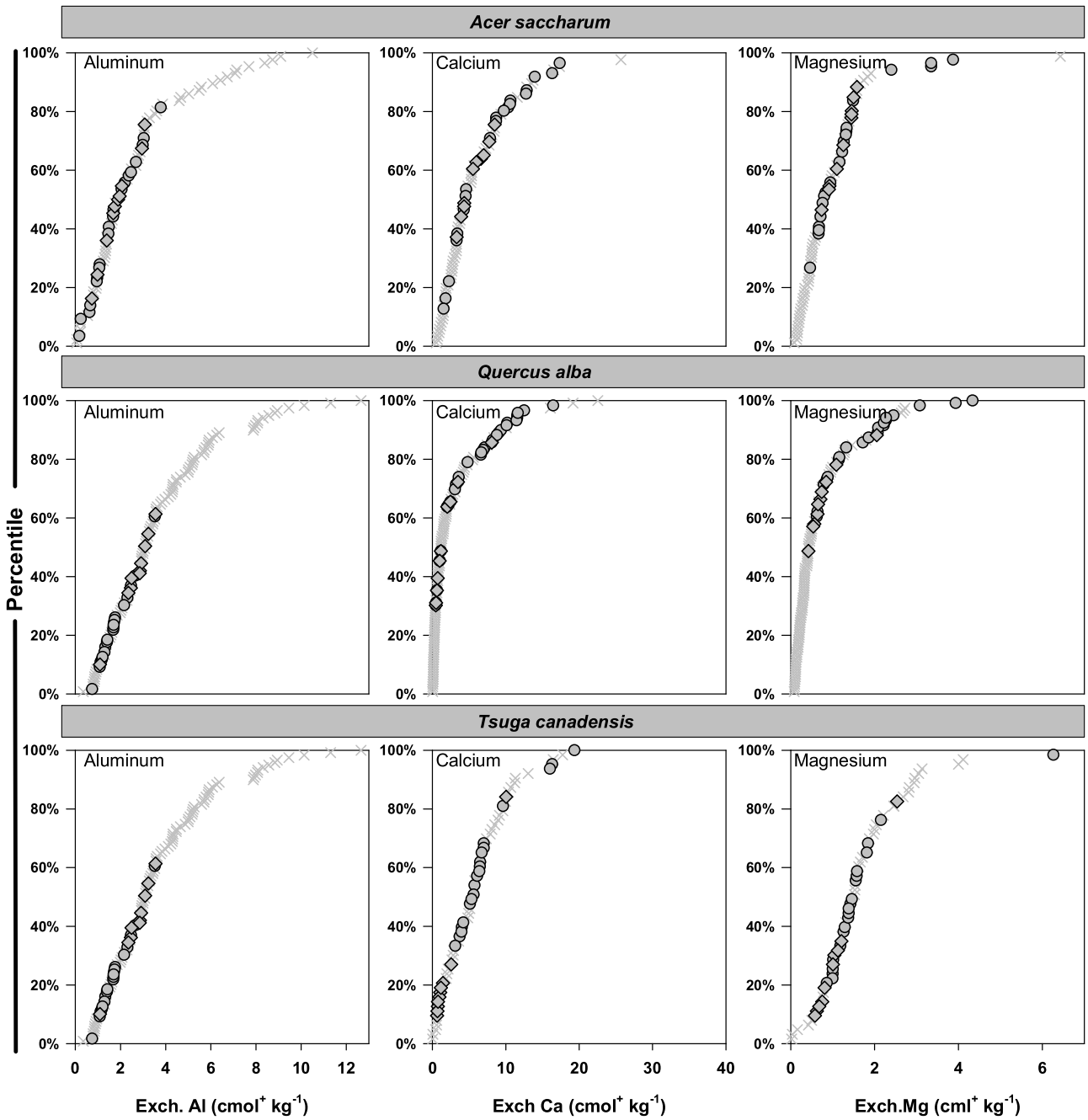


**Fig. 4.** Plant available elements in the soil A horizon. Circles and diamonds are trees at the Arnold Arboretum. Diamonds are trees located in the natural areas of the arboretum. Xs represent trees in the reference forests.

Differences among species' responses may be related to the reference forest datasets used in the analysis. More so than for *A. saccharum* and *T. canadensis*, the *Q. alba* reference forests varied more strongly along an urban-to-rural gradient, and so are more likely to include trees in conditions similar to the arboretum's natural areas. It is therefore crucial, when interpreting comparisons with reference forest data, to know the conditions under which the foliage and soil were measured. This often limits the scope of analysis to within species.

Soil characteristics and foliar nutrient data for many forest tree species currently exist in open-source databases. Foliar chemistry data from many species in the northeastern USA and southeastern Canada are available online through the Northeastern Ecosystem Research Cooperative (NERC, 2019), for example, and accompanying soil chemistry data exist for many datasets in this database. Managers may consider accessing these data and comparing them to data from their landscapes to situate their observations into a regional context and employ more of an ecosystem approach.

To expand on this resource, we recommend gathering data on more species found in urban environments that may not be present in existing databases, and compiling these species-level data from regional reference areas to serve as baselines for tree health and nutrition assessments in urban areas moving forward. In doing so, it will be important to

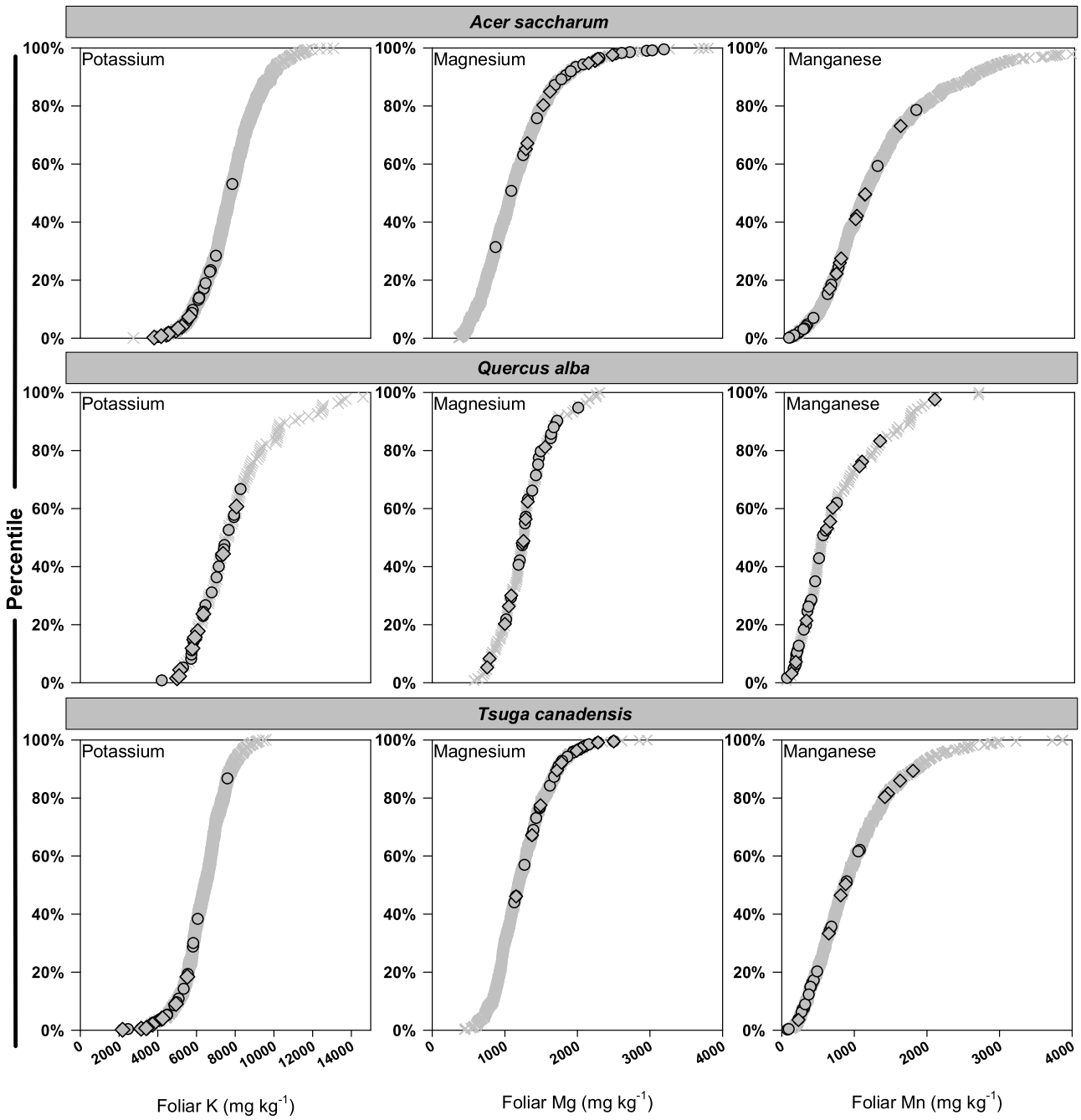


**Fig. 5.** Foliar element concentrations. Circles and diamonds represent trees at the Arnold Arboretum. Diamonds represent trees located in the natural areas of the arboretum. Xs represent trees in the reference forests.

determine thresholds of concern for both foliar and soil element concentrations. In our study, comparisons were possible because laboratory methods were identical; when gathering additional data for these types of comparisons, it is important to compare values obtained from comparable laboratory methods as well. Developing this resource further would enable more evidence-based approaches to land management that would go beyond conventional methods and, as ecological forestry approaches silviculture by mimicking natural stand development (Franklin et al., 2002), would encourage an approach to urban arboriculture that could be more strongly informed by comparisons to how trees grow in forests.

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**CRediT authorship contribution statement**

**Jenna M. Zukswert:** Conceptualization, Methodology, Investigation, Formal analysis, Project administration, Data curation. **Richard**

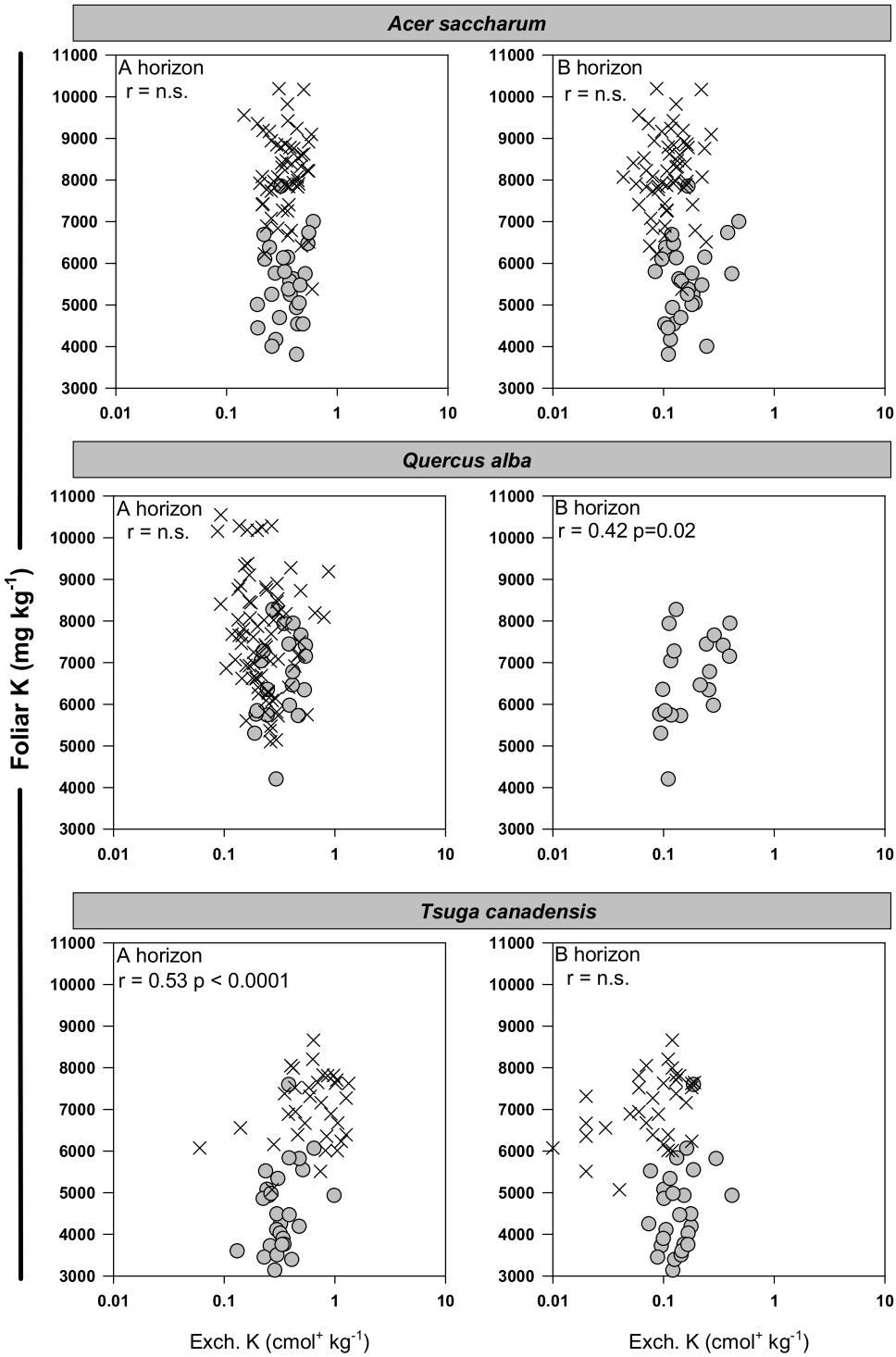


**Fig. 6.** Foliar K versus plant-available K in soil. Circles represent Arnold Arboretum trees and Xs represent trees from reference forests. Note: the X axes are on a log scale.

**Hallett:** Conceptualization, Methodology, Investigation, Formal analysis, Resources, Data curation, Visualization. **Scott W. Bailey:** Conceptualization, Methodology, Investigation, Formal analysis, Resources, Data curation. **Nancy F. Sonti:** Investigation, Data curation.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jenna Zukswert was employed by the Arnold Arboretum from June 2016 through November 2017. This was one of her Living Collection Fellowship projects. We suspect that any bias from this former employment would be minor.

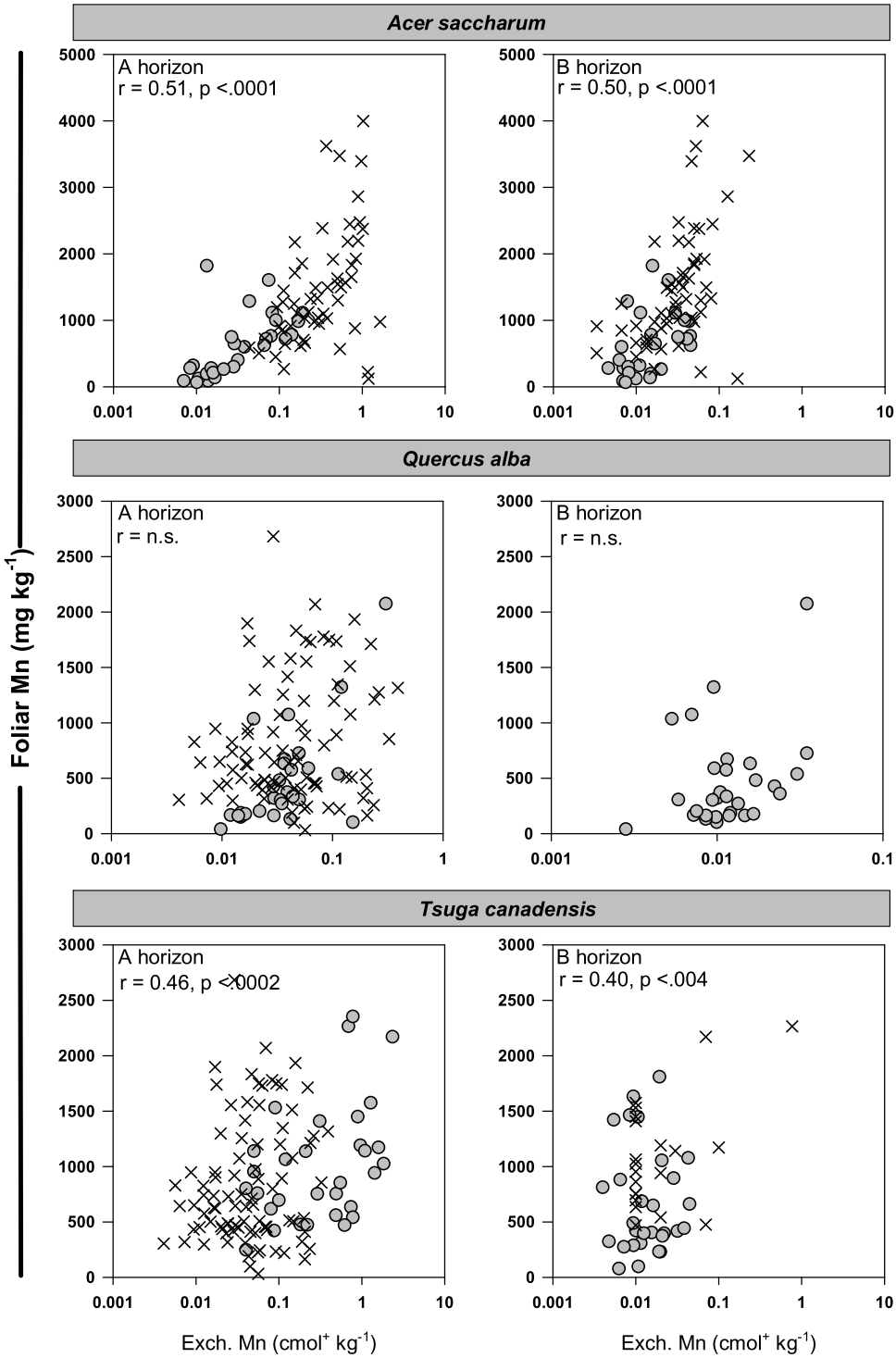


**Fig. 7.** Foliar Mn versus plant-available Mn in soil. Circles represent trees from the Arnold Arboretum and Xs represent trees from the reference forests. Note: the X axes are on a log scale.

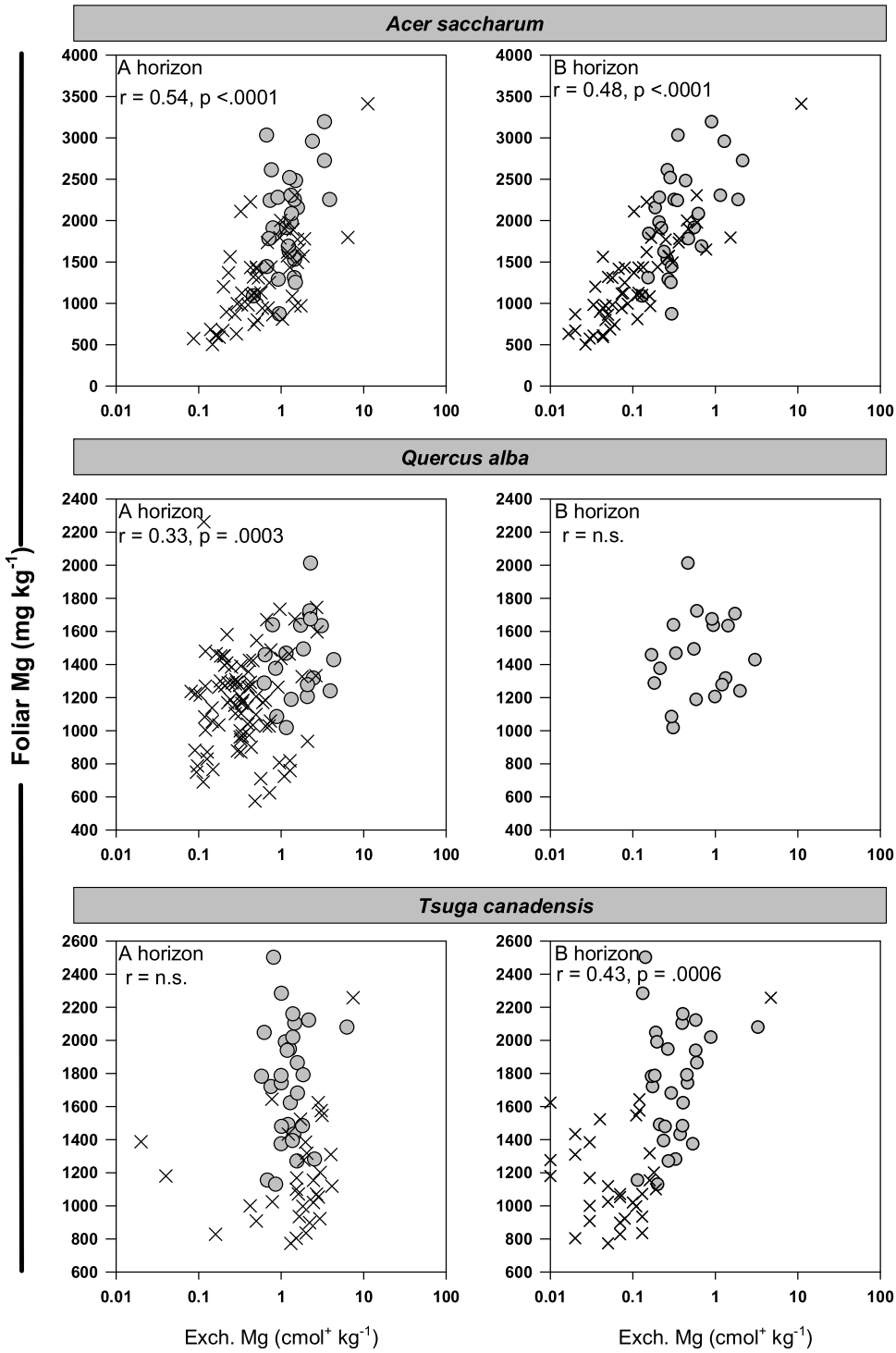


**Fig. 8.** Foliar Mg versus plant-available Mg in soil. Circles represent trees from the Arnold Arboretum and Xs represent trees from reference forests. Note: the X axes are on a log scale.

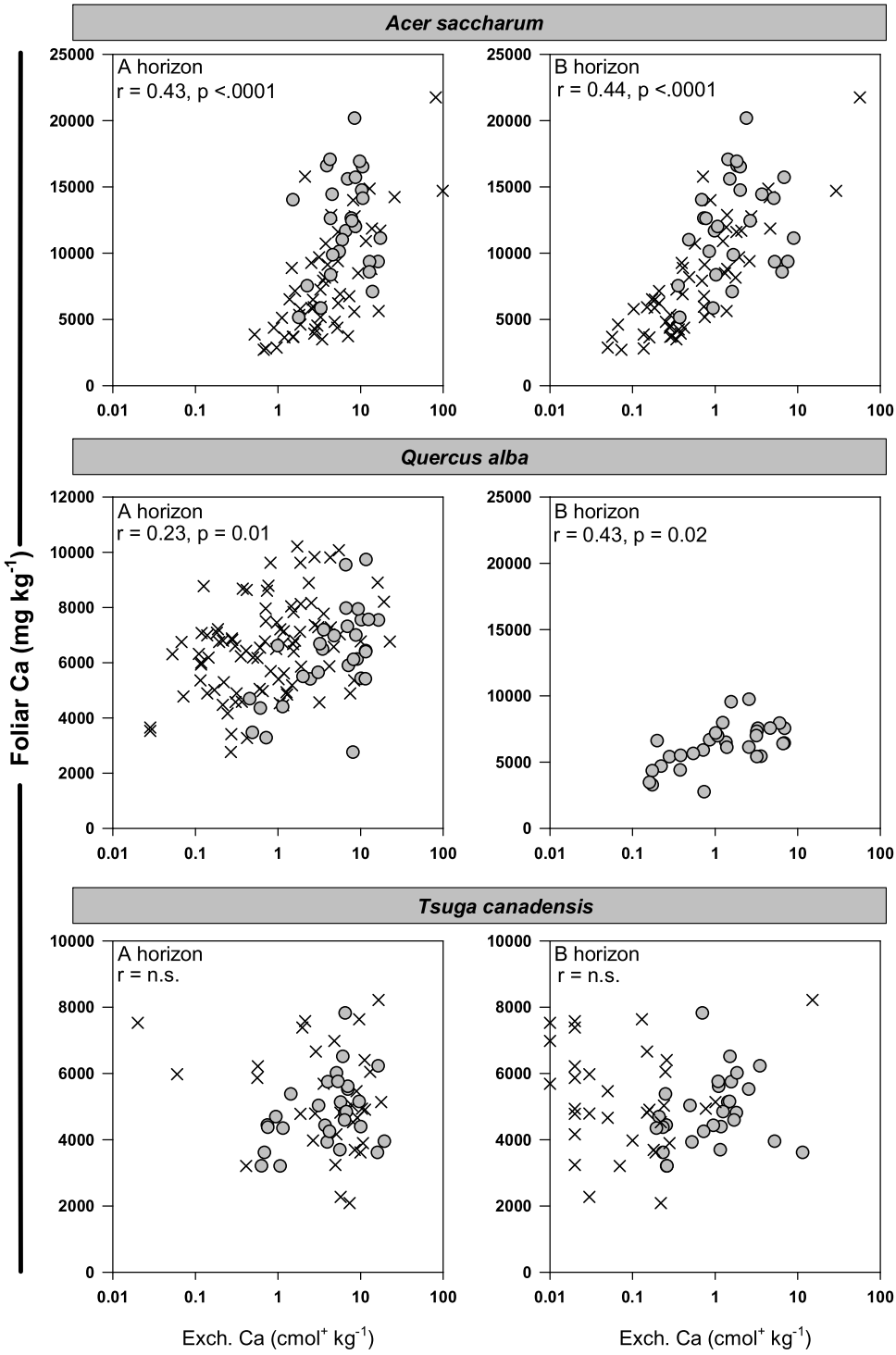


**Fig. 9.** Foliar Ca vs plant-available Ca in soil. Circles represent trees from the Arnold Arboretum. Xs represent trees from reference forests. Note: the X axes are on a log scale.

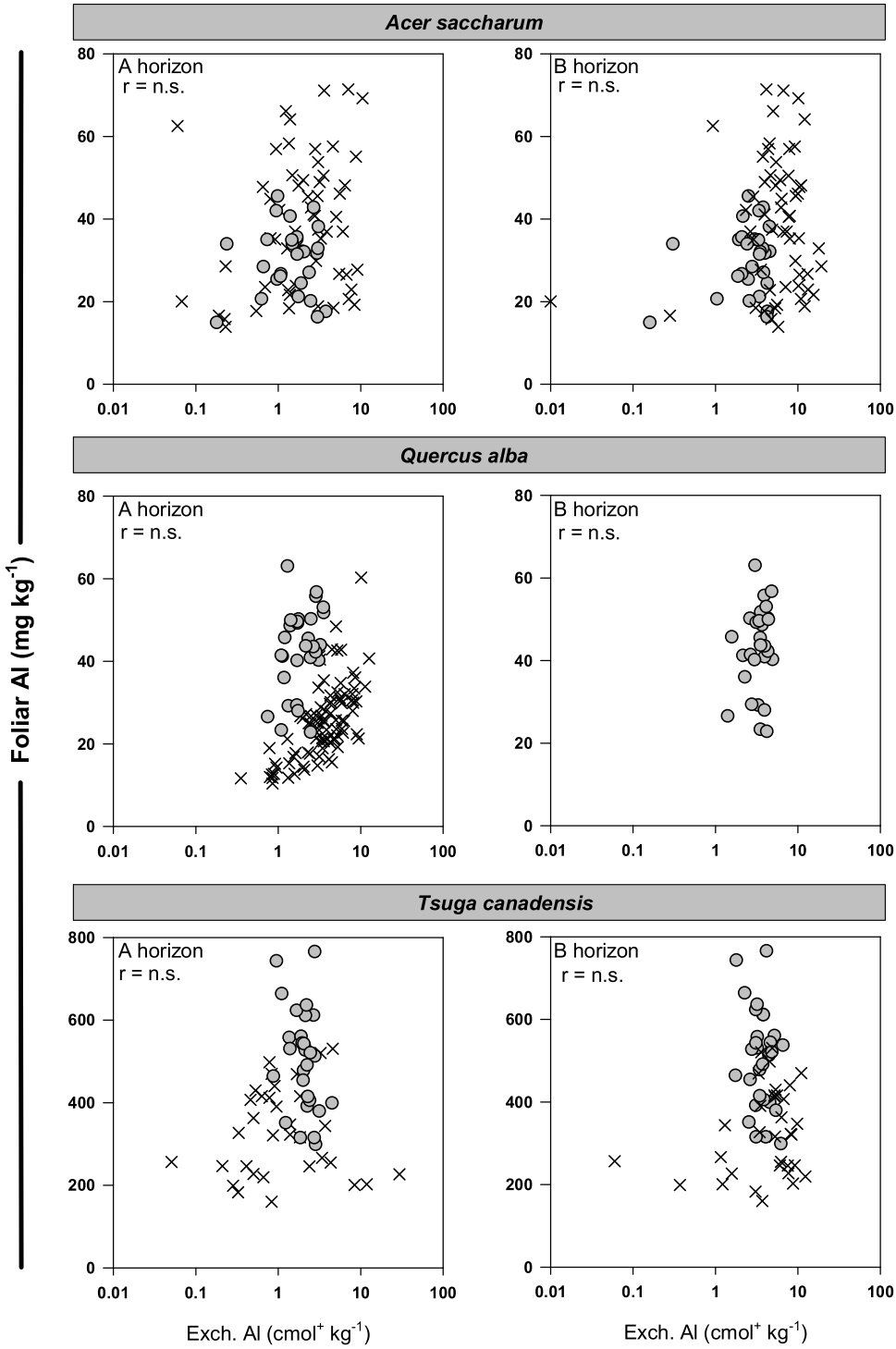


**Fig. 10.** Foliar Al vs. plant-available Al in soil. Circles represent trees from the Arnold.

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