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Soil chemical properties in forest patches across multiple spatiotemporal scales in mid-Atlantic U.S. metropolitan areas

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Abstract
Temperate deciduous forests in the United States are in the most densely populated states across the northern and mid-Atlantic east coast. Land development and associated human activities have resulted in small forests that are susceptible to various anthropogenic influences across multiple spatiotemporal scales. The objective of this study was to assess soil chemistry in forest patches of various sizes embedded within an urban development gradient. We established 36 forest sites along the U.S. east coast in northern Delaware and southeastern Pennsylvania, and assessed soil chemical properties across metro (city size), landscape (surrounding urban density), patch (forest patch size/shape, non-native plant invasion), and temporal (time since forest canopy closure) scales. At the metro and landscape scale, we found significantly greater soil Cu, Zn, and S concentrations in forest patches with greater surrounding urban density. At the forest patch scale, soil pH and Ca increased with greater abundance of non-native invasive plants within the forest, whereas soil organic matter decreased with plant invasion. However, increased soil pH and Ca with decreasing SOM may also be a result of land use legacies since we found younger forests had significantly more plant invasion. Forest patch size and shape were primarily related to urban density, where smaller forests with greater edge to interior ratios had greater soil Cu and Zn concentrations. These findings support the importance of considering forest patch structure (size and shape), site legacies, proximity to urban land uses, and duration of intact canopy in understanding patterns and processes in forest soils.

Keywords Temperate deciduous forests · Urban soils · Spatiotemporal scales · Urban forests

Introduction

Across China, Europe, and North America, the temperate deciduous forest biome contains the most densely populated regions (United Nations 2013). In the United States, population growth and urban sprawl resulted in 20% of the total population residing in temperate deciduous forests along the east coast (US Census Bureau 2010). Additionally, these forested areas have undergone tremendous changes since the colonization by Europeans began in the sixteenth century (Oswald et al. 2020). As a result, few original forests remained post-European colonization in the northeastern United States. After centuries of continued deforestation, afforestation began with widespread agricultural land abandonment in the late 1800s, which resulted in an increase in forest cover throughout the region (Flinn and Vellend 2005). Much of this forest cover, however, remains separated due to the patchwork of land abandonment that has occurred in addition to the expansion of urban and suburban areas throughout the region. The resultant forest now consists of mostly small patches that are embedded within or near developed landscapes (Haddad et al. 2015).

Small temperate deciduous forests embedded across human modified landscapes are susceptible to adjacent anthropogenic activities, and subsequently are influenced by the surrounding landscape context (e.g., agriculture, urban). How this patchwork of forests with various land use histories is impacted by adjacent land use and their associated environmental changes has important implications on forest soil health (Pouyat and Trammell 2019). Research has shown that microenvironments near forest edges exhibit distinct growing conditions that result in changes in tree productivity, carbon sequestration, and N dynamics (Smith et al. 2018).

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Additionally, these "edge effects" appear to vary by adjacent land use, across biomes, and different land use histories (Harper et al. 2005; Mitchell et al. 2015). Likewise, various urban measures of the surrounding matrix within which a forest patch is embedded has been shown to correlate with soil chemical (trace metals), physical (temperature), and biological (earthworm abundance and composition) characteristics in the New York City and Baltimore metropolitan areas (Szlavecz et al. 2006; Pouyat et al. 2008, 2010). This research suggests that in temperate deciduous forest patches soil characteristics should vary at multiple spatiotemporal scales within or near urban metropolitan areas. Moreover, understanding the potential controls on soil chemical properties in these forests is vital for predicting their future responses to anthropogenic caused environmental changes.

While the individual effects of forest fragmentation and urban land use on invasive plant and animal species has been well described (e.g., Ries et al. 2004; McKinney 2002; and many others), the potential for their interactive effects and subsequent influence on soil properties have received little or no attention. For example, invasive plant species have been shown to significantly alter soil C and N dynamics in deciduous forests located within or near an urban area (e.g., Trammell et al. 2012; Ehrenfeld 2010), while similarly forest patches within an agricultural context may not be exposed to these invasive species, but rather have impacts from edge effects and other environmental factors (Pouyat and Trammell 2019). In addition to differences in context, invasive plant and soil biota that may co-inhabit landscapes modified by urban land uses can exhibit positive feedbacks that support the other's continued presence in these landscapes, such as the non-native buckthorn tree (*Rhamnus cathartica*) and invasive earthworm species that have invaded woodlands in the Chicago metropolitan area (Heneghan et al. 2006). Few studies, however, have simultaneously analyzed the contribution of land use context, invasive species, and forest patch structure in determining soil properties in forests.

The aforementioned research suggests that impacts of fragmenting forests on soil characteristics and their respective community composition should vary significantly from place to place depending on the size and shape of the patch and where it is situated in the landscape, along with its spatial relationship with urban and suburban areas (Pouyat and Trammell 2019). These potential impacts include edge effects at the patch scale (e.g., light penetration and atmospheric deposition; Weathers et al. 2001), matrix effects at the landscape scale (e.g., road emissions and seed dispersal by vehicles; Forman et al. 2003, Rentch et al. 2005), and long range environmental effects at the metro or regional scale (e.g., urban heat island, N deposition, plant and soil animal species introductions; Bonan 2002, Oke 1973, Lovett et al. 2000, McKinney 2002). Other factors include site history (Roman et al. 2018; Zitter and Turner 2018) and the native soil parent material (Pouyat et al. 2009) or biome type (Smith et al. 2018).

The FRAME study, a long-term urban forest network, represents a unique opportunity to address these factors at multiple scales. Across northern Delaware and southeastern Pennsylvania, we measured soil chemical properties (pH, organic matter, and concentrations of P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, S, and Al) within 36 forests that varied in their land use context, forest patch size and shape, soil type, abundance of non-native invasive plants, and time since forest canopy closure (Fig. 1). The overarching goal of this study was to assess soil chemical properties across a range of spatiotemporal scales (Table 1). Specifically, we analyzed soil characteristics at the patch scale (i.e., forest patch size and shape; abundance of non-native invasive plants), landscape scale (i.e., gradient of urban density surrounding forest patch), metro scale (i.e., two metropolitan areas of differing population densities), and across a temporal scale (i.e., forests with varying time since canopy closure). We addressed the following questions: 1) How do soil chemical characteristics in temperate deciduous forests of different patch structure and landscape context vary across spatiotemporal scales in an urban corridor?, 2) How are potential drivers (e.g., urban intensity and forest patch size) of soil chemical properties correlated?, and 3) What are the relationships between non-native plant invasion and soil chemical properties across patch, landscape, and metro scales and do these relationships change over time?

We expected differences in soil chemistry at the metro (between metro regions) and landscape (urban density gradient) scales. Specifically, we expected soil nutrients (e.g., P, K) and metals (e.g., Zn, Cu) to be greater in the larger city (many pollutant sources) than the smaller city (fewer pollutant sources) and to increase positively with urban density surrounding the forest patch due to nutrient and metal inputs resulting from the combination of metropolitan scale deposition patterns and local deposition from road edges (e.g., Trammell et al. 2011). At the patch scale, we expect pH and Ca to increase positively with non-native plant invasion due to previous research demonstrating pH and Ca shifts associated with invasive plants in forests (e.g., Leicht-Young et al. 2009; Huebner et al. 2014).

We expect our potential drivers of soil chemistry across spatial scales to directly correlate, such as a positive correlation between forest patch size and edge to interior ratios and between forest patch size and urban density (i.e., smaller forests embedded within increasing developed areas due to pressures for various land uses [e.g., commercial, residential]). Our previous research demonstrated no relationship between the urban density surrounding the forest patches and the degree of non-native plant invasion within these forests, and a positive relationship between non-native plant invasion and the time since the forest canopy closed (Trammell et al.

Table 1 In 36 forest sites, soil chemical properties were assessed across a range of spatiotemporal scales. Three spatial scales were classified to assess (1) regional (metro – city size), (2) local (landscape – % impervious surface area [ISA] surrounding each forest patch [Urban Density Gradient]), and (3) within site (patch – abundance of non-native invasive plants [Invasion Gradient], forest patch size, forest patch edge to interior ratio [E:I]) influences on soil chemistry. To assess how age of the forest patch relates to soil chemistry, we determined the time since forest canopy closure using aerial imagery (range = 20 to more than 90 years of canopy closure)

Scale Type	Scale	Characteristic of Spatiotemporal Scale	Metric used in this study
Spatial	Metro	• Regional deposition inputs to forest patches	Newark, DE Philadelphia, PA
	Landscape	• Local-scale influence of urban density surrounding forest patches	Urban density gradient (ISA)
	Patch	• Non-native plant invasion within forest patch • Forest patch size and shape	# Invasive plants Hectares, E:I
Temporal	Time	• Time since forest canopy closure	Years since canopy closure

2020). Therefore, we expect soil chemical properties to respond differentially to urbanization and plant invasion. Since we expect forest patches surrounded by higher urban density to be smaller, deposition inputs from urban activities should increase soil nutrients and metals in smaller forests. Finally, adjacent land uses and time since canopy closure should relate to non-native plant invasion, and thus, greater patch edge to interior ratios (E:I) and younger forests should have greater pH and Ca due to greater non-native plant invasion in these forests.

Methods

Study area

Our forest research sites are part of a long-term urban forest ecology study, the FRAME (FoRests Among Managed Ecosystems, http://sites.udel.edu/frame/), established in 2009 by researchers at the USDA Forest Service and University of Delaware. Coastal Plain and Piedmont hardwood forests were selected using a Generalized Random Tesselation Stratified (GRTS) design, a method well suited to designing long-term monitoring programs for patchy site types such as urban forests (Comiskey et al. 2009; Lookingbill et al. 2012). The GRTS approach was useful for choosing sites in densely populated areas with a range of ownership types, as it allowed sites to be excluded if owned by private individuals rather than universities, cities, or states. All forest sites are separated by roads and at least 250 m apart, except for two forests that are 150 m apart yet are separated by a four-lane divided highway. Within each forest, we randomly positioned a 25 m × 25 m grid along the edge of the forest to capture potential edge effects. Using a stratified random approach along every other line on the grid, we established ten to fifteen grid points for long-term observation in each forest patch ensuring sampling locations were at least 50-m from each other. The FRAME traverses an urbanization gradient extending from Newark, DE (population = 31,454, density = 1403 people km^{-2}) to Philadelphia, PA (population = 1,526,006 people, density = 4405 people km^{-2}; US Census Bureau 2010), to enable our long-term study to address questions related a wide range of urbanization impacts across spatial scales.

Soil Sample collection and analyses

Soils were collected during peak growing season across all forests (n = 36 forests). At each sampling location (n = 10 to 15 points) within each forest, loose litter was removed from the soil surface prior to soil collection. Each soil sample consisted of two pooled soil cores (2-cm diameter) from the top 12–15 cm of mineral soil. These soil samples were measured for pH, soil organic matter (SOM), and nutrient concentrations in the University of Delaware Soil Testing Lab (https://www.udel.edu/academics/colleges/canr/cooperative-extension/environmental-stewardship/soil-testing/). Soil pH was measured using a 1:1 soil (15 g) to deionized water (15 ml) mixture after mixing for 30 min. Soil organic matter content was measured using the loss-on-ignition method at 500 °C for six hours. Soil nutrient concentrations were extracted using the Mehlich-III method and analyzed for plant available elements (P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, S, and Al). Depending on concentrations, Al, Zn, and Cu may be toxic for plant growth. Furthermore, the Mehlich-III extraction solution is not as stringent as other soil extraction methods; thus, elemental concentrations reported here may be lower than in other urban forest studies (e.g., Pouyat and McDonnell 1991).

Spatial scales

In order to identify spatial scales of influence on soil physical and chemical properties, we categorized the forests based on city size (metro scale), level of urban density (landscape scale), forest size and edge to interior ratio (patch scale), and non-native invasive plant abundance (patch scale). We conducted spatial analysis on each forest and the surrounding landscape content using Geographic Information Systems (ArcGIS). We assessed various landscape metrics (e.g.,

Fig. 1 Map showing location of forests (black circles) across northern DE and southeastern PA, with a closer view of forests within A) Philadelphia, PA and B) Newark, DE

impervious surface, population density) that determine the level of urban density surrounding each forest site. Buffer areas of four spatial scales (i.e., 100-m, 250-m, 500-m, and 1000-m) were used to determine whether urbanization context surrounding each forest site was scale sensitive. Spatial data layers for impervious surface and land cover data were provided by the National Land Cover Database (Homer et al. 2015). Population density was determined from the year 2010 census tract data provided by US Census Bureau TIGER/Line shapefiles (US Census Bureau 2010). We conducted a multivariate principle component analysis (PCA) of all landscape metrics. The first principle component (PCA1) explained 45% of the variation and was most strongly correlated with % developed land, % impervious surface area, and population density. All of the variables had significant, positive loadings on PCA1. We utilized the most important variable explaining variation in the PCA (% impervious surface area [ISA] within 1000-m buffer of the forest) to assess the landscape scale influence of urban density surrounding the forests (hereafter *Urban Gradient*). To assess metro scale influences on soil characteristics, we compared the Newark, DE urban forests ($n = 15$ forests) that overlapped with the Philadelphia, PA urban forests ($n = 6$ forests) along PCA1.

At the scale of the forest (patch), the size of the forest as well as the shape or configuration of the forest can influence the magnitude of urban influences on soil characteristics (Table 2). Using GIS, we measured the size of each forest patch (ha) as well as the ratio of the perimeter to area of the forest (edge:interior; E:I). In addition to these characteristics of the forest patch structure, we quantified the impact of non-native plant invasion within the forest as a patch scale influence on soil characteristics. Within each forest, we conducted a complete inventory of all understory woody stems (i.e., saplings, shrubs and vines) with a height ≥ 1 m within a 2.5-m radius circular plot around the sampling locations. For our urban forest network, plants that did not occur in the lower 48 states prior to 1600 CE are considered non-native, and plants that are widely established and have potential to cause ecological harm are defined as invasive (Delaware Invasive Species Council [DISC] 2019). The majority of all non-native stems inventoried in our forests were reported invasive in the mid-Atlantic region of the United States (i.e., 98% of all non-native stems; National Invasive Species Information Center [NISIC] 2019). We calculated the mean non-native stem density per sampling location (20 m^2) within each forest to assess the patch scale influence of plant invasion on soil chemistry (hereafter *Invasion Gradient*). Finally, to determine whether parent material was related to the soil chemical properties, we characterized the soil parent material across our 36 forests using the Natural Resources Conservation Service (NRCS) soil survey maps overlaid on our forest plots in ArcGIS data (NRCS Soil Survey Staff 2020).

Temporal scale

In order to determine the influence of time (temporal scale) on soil characteristics within urban forests, we used aerial images from multiple years over the last century (e.g., 1937, 1954, 1961, 1971, 1992, 2002, 2014) obtained from the Delaware and Pennsylvania Geological Survey (Delaware Geological Survey 2018; Pennsylvania Geological Survey 2018). To establish time points for full canopy closure, each image was evaluated visually for full forest canopy closure for each image time point by a single observer to minimize error in image interpretation. The year the forest canopy closed (temporal scale) was designated based on the image year when full canopy was observed for the entire extent of the forest site area (Table 2). We realize forest canopy closure occurs at some point prior to the image date observed; however, to minimize any potential errors in estimation of time since canopy closure, we used the image-date as the year for data analysis. Higher temporal resolution of forest images would increase our predictive ability.

Statistical analysis

All data analyses were conducted in R (Version 3.3.3; R Core Team 2019). All tests for significance are reported at the $\alpha = 0.05$ critical value, and in a few case the $\alpha = 0.10$ critical values are reported to identify potential trends in the data.

Table 2 Statistics of variation (i.e., minimum and maximum) and central tendency (i.e., mean ± 1 SE) for forest patch metrics (size, shape complexity, and age) across the 36 forest study sites. Data are shown for rural forests, Newark-DE forests, Philadelphia-PA forests, and all forests combined. The size of the forest (ha) represents the entire forest patch area. Forest shape complexity is characterized by the edge to interior ratio (E:I) for the entire forest patch area. Using aerial imagery, forest age is estimated as the time since forest canopy closure

	Forest Size (ha)			Forest Edge:Interior			Forest Age		
	Min	Mean (SE)	Max	Min	Mean (SE)	Max	Min	Mean	Max
Rural (n=15)	9.3	77.6 (20.02)	150.9	0.0075	0.0144 (0.0037)	0.0232	1937	1961	2000
Newark (n=15)	4.4	74.1 (19.12)	249.1	0.0075	0.0168 (0.0043)	0.0332	1937	1970	1992
Philadelphia (n=6)	12.7	43.4 (17.71)	80.9	0.0099	0.0167 (0.0068)	0.0246	1928	1979	2000
All Forests (n=36)	4.4	70.4 (11.73)	249.1	0.0075	0.0158 (0.0026)	0.0332	1928	1968	2000

We conducted univariate statistical analyses to determine the individual influence of various spatial and temporal scale metrics on soil characteristics across the 36 forest sites. To assess the difference in soil characteristics between a large (Philadelphia) and a small (Newark) city, we used non-parametric Kruskal-Wallis rank sum test since the data did not meet the assumptions of normality or homoscedasticity. To assess the individual influence of spatial and temporal scales on urban forest soils, we conducted bivariate linear regression between each soil chemical characteristic (i.e., pH, SOM, nutrient concentrations and ratios) and the landscape- (i.e., urban intensity surrounding each forest patch), patch- (i.e., forest patch structure: shape complexity [edge:interior] and patch size; non-native plant invasion), and temporal-scale metrics (i.e., year forest canopy closed). Finally, to verify whether soil parent material had any influence on each soil chemical characteristic, we used non-parametric Kruskal-Wallis rank sum test, due to unequal sample sizes and assumptions of normality and homoscedasticity were not met, followed by the post hoc Dunn test using the FSA package (i.e., pairwise multiple comparisons of mean ranks; Olge et al. 2019).

To determine correlations between our predictor variables (i.e., spatiotemporal scales), we conducted Pearson correlation analysis. We used the rcorr function in the Hmisc package (Harrell et al. 2019) to determine the correlation matrix for the landscape (urban: ISA), patch (forest structure: size, E:I; non-native plant invasion), and temporal (year since forest canopy closure) scales. In addition, we tested whether our predictor variables varied with soil parent material using the non-parametric Kruskal-Wallis rank sum test.

We conducted principle components analysis (PCA) to determined multivariate patterns in soil characteristics across the 36 forest sites using the prcomp function in R. The soil characteristics used in this analysis were soil pH, SOM, nutrient concentrations (P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, S, Al), and nutrient ratios (Ca:Mg, Ca:Al, Mg:Al). We separated forest sites based on the urban density surrounding each forest patch using ISA (described in *Spatial Scales* above), and categorized forests as Newark urban forests (n = 15), Philadelphia urban forests (n = 6), and rural forests (n = 15). Individual forests sites and differences in Newark urban forests, Philadelphia urban forests, and rural forests were evaluated using the fviz_pca_ind function, and the significant soil characteristics contributing to each dimension were evaluated using the fviz_pca_var function in the ggfortify package (Horikoshi and Tang 2016; Tang et al. 2016). The fviz_add function in ggfortify was used to determine potential predictors of patterns in soil characteristics across the forests (i.e., urban gradient, forest patch size, forest patch shape [edge:interior], non-native plant invasion, and year forest canopy closed). Finally, differences in parent material were evaluated using the fviz_pca_ind function in ggfortify.

Results

Univariate relationships in soil characteristics

At the metro scale, we found significant differences in soil characteristics between Newark and Philadelphia forests. In Philadelphia, forests soils had significantly greater soil K (143.9 ± 17.50 mg kg^{-1}) and B (1.5 ± 0.11 mg kg^{-1}) concentrations than in Newark forest soils (K: 100.9 ± 8.78 mg kg^{-1}, B: 0.6 ± 0.05 mg kg^{-1}; $p = 0.04$ and $p < 0.001$, respectively). Alternatively, Newark forest soils had significantly greater Fe (304.1 ± 28.12 mg kg^{-1}) and S (25.0 ± 1.19 mg kg^{-1}) concentrations than in Philadelphia forest soils (Fe: 198.7 ± 29.73 mg kg^{-1}, S: 14.3 ± 1.60 mg kg^{-1}, $p = 0.05$ and $p < 0.001$, respectively). Across a gradient of urban density surrounding each forest, we found significant differences in five soil characteristics (Fig. 2). Soil Zn ($r^2 = 0.41$, $p < 0.001$), Cu ($r^2 = 0.36$, $p < 0.001$), and S ($r^2 = 0.12$, $p = 0.04$) significantly increased with greater urban density surrounding each forest, and there was a trend for greater soil Fe ($r^2 = 0.08$, $p = 0.10$), whereas soil K ($r^2 = 0.13$, $p = 0.03$) significantly decreased with greater urban density surrounding each forest (Fig. 2).

At the patch scale, we found soil characteristics were influenced by forest patch structure (e.g., forest size and shape) and by non-native plant invasion. Soil pH ($r^2 = 0.13$, $p = 0.03$), Ca ($r^2 = 0.23$, $p = 0.003$), B ($r^2 = 0.11$, $p = 0.05$), Ca:Al ($r^2 = 0.12$, $p = 0.04$), and Ca:Mg ($r^2 = 0.27$, $p = 0.001$) significantly increased with increasing non-native plant invasion, whereas soil organic matter ($r^2 = 0.13$, $p = 0.03$) and S ($r^2 = 0.19$, $p = 0.008$) significantly decreased with more non-native plant invasion (Fig. 3). We found soil Zn ($r^2 = 0.26$, $p = 0.002$) and Cu ($r^2 = 0.19$, $p = 0.008$) significantly increased with increasing edge to interior ratios (SM Fig. 1), whereas soil Zn ($r^2 = 0.20$, $p = 0.007$) and Cu ($r^2 = 0.26$, $p = 0.001$) significantly decreased with increasing forest size (SM Fig. 2).

We characterized 12 parent material (PM) types across our forests based upon major PM source (e.g., eolian sand, residuum, alluvium) and type (e.g., schist, mica). Two soil chemical elements had significant differences across soil PM, soil K ($p = 0.02$) and S ($p = 0.004$). Post hoc analysis revealed soil K concentrations in soils with residuum weathered from mica schist PM (164.4 mg kg^{-1}) were significantly greater than in soils with silty eolian deposits over fluviomarine sediments PM (78.9 mg kg^{-1}; $p = 0.05$). Alternatively, soils with silty eolian deposits over fluviomarine sediments PM had significantly greater S concentrations (29.0 mg kg^{-1}) than soils with either residuum weathered from mica schist (15.1 mg kg^{-1};

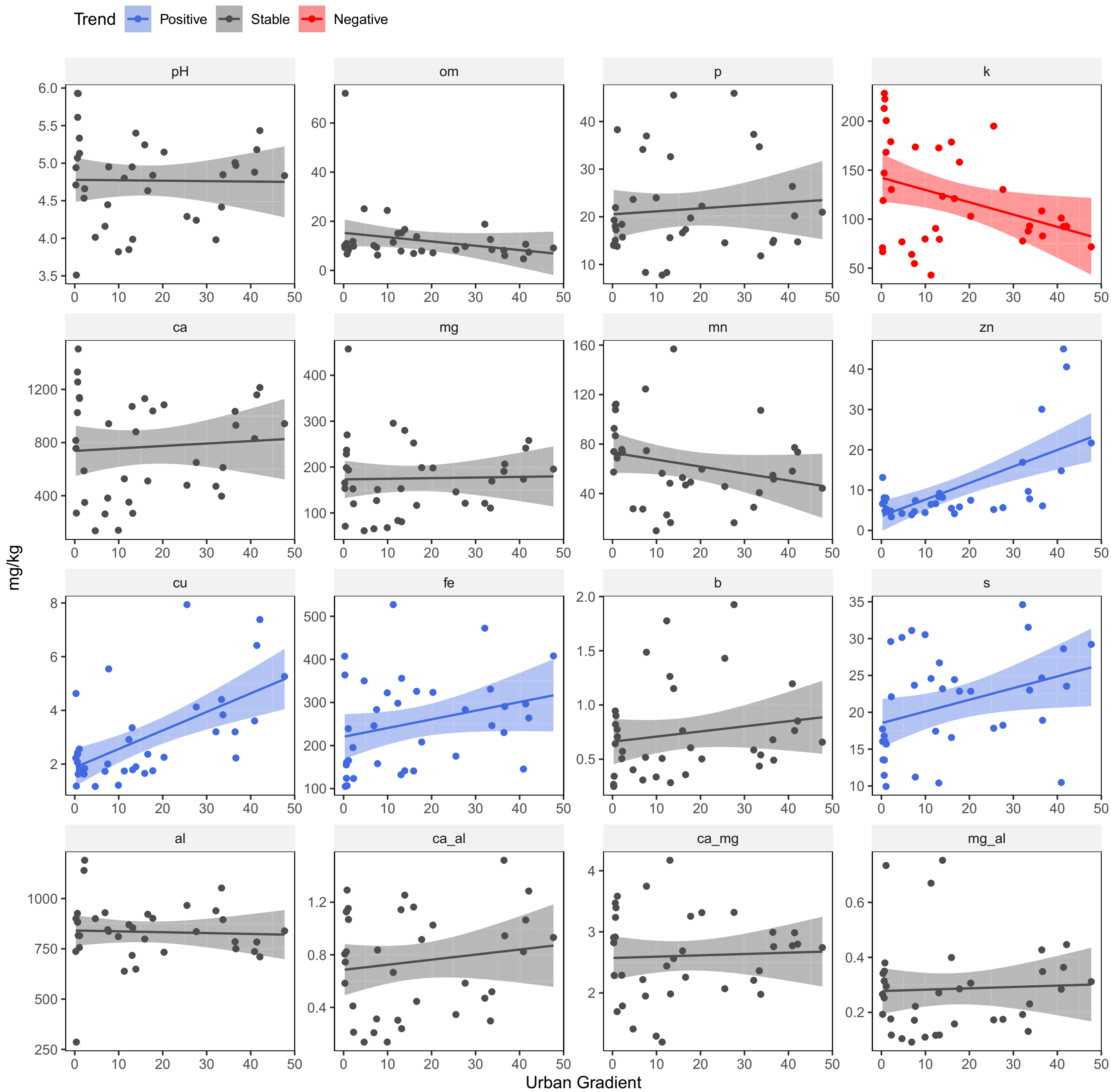

Fig. 2 Landscape scale: across 36 forest sites, relationship between soil pH, organic matter (%), nutrient concentrations (P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, S, and Al; mg kg^{-1}), nutrient ratios (Ca:Al, Ca:Mg, and Mg:Al) and the urban gradient (% impervious surface surrounding each forest plot). Significant positive relationships are shown in blue, negative relationships are shown in red, and no relationship is shown in gray

$p = 0.02$) or alluvium from igneous/metamorphic rock (16.1 mg kg^{-1}; $p = 0.02$) parent material.

We found soil characteristics had significant relationships with the temporal component of the forest (i.e., time since forest canopy closure). Soil Ca ($r^2 = 0.25$, $p = 0.002$), Cu ($r^2 = 0.14$, $p = 0.03$), Ca:Al ($r^2 = 0.12$, $p = 0.04$), and Ca:Mg ($r^2 = 0.25$, $p = 0.002$) significantly increased with more recent forest canopy closure, and there was a trend for greater soil pH ($r^2 = 0.09$, $p = 0.08$), P ($r^2 = 0.08$, $p = 0.09$), and K ($r^2 = 0.10$, $p = 0.06$) in these younger forests (Fig. 4). Soil organic matter increased in forests with longer canopy closure ($r^2 = 0.14$, $p = 0.02$).

Correlations between predictor variables

At the landscape scale, we found that urban density (impervious surface area within 1000 m) surrounding the forest patches was positively correlated with the forest edge to

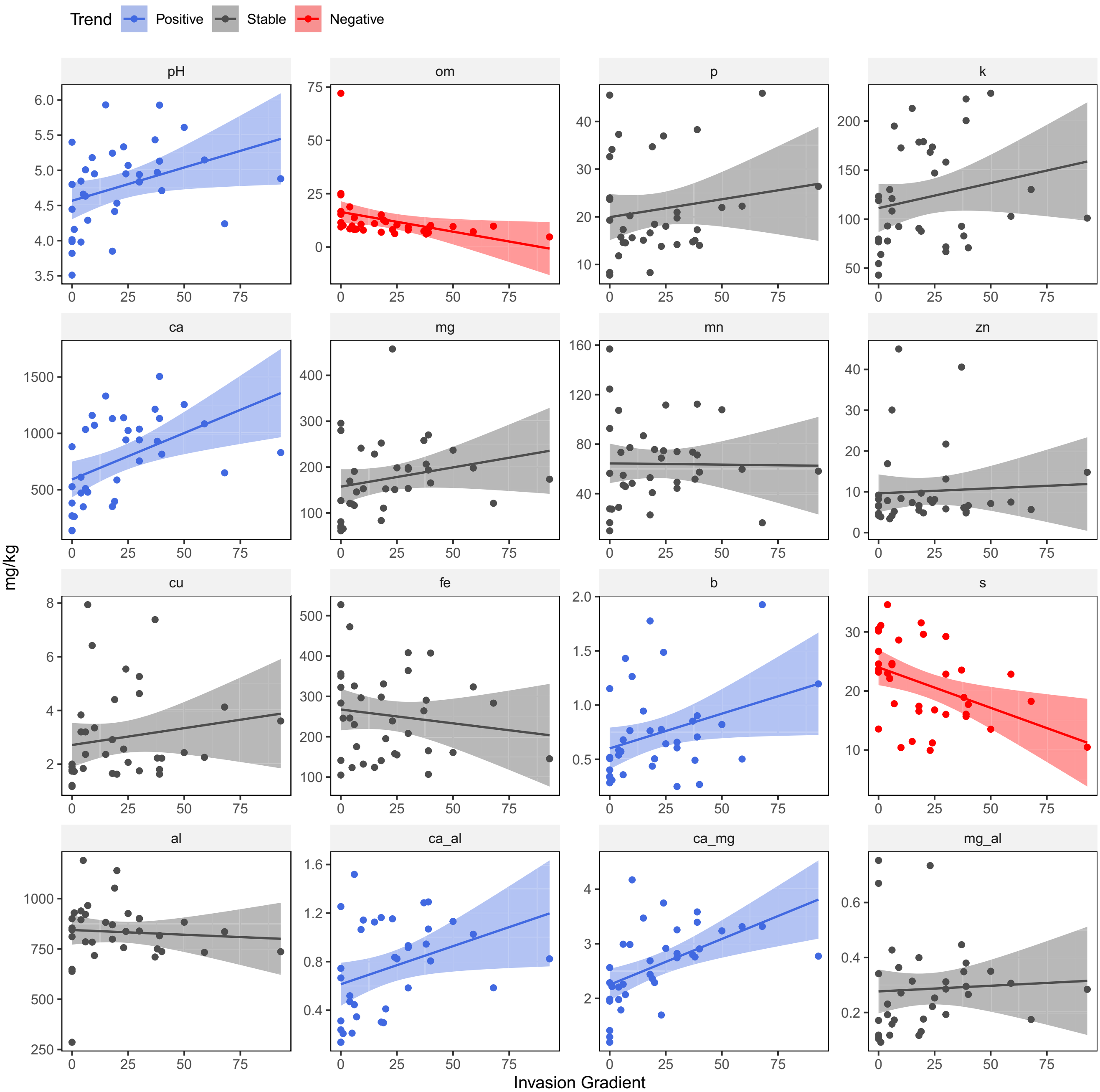

Fig. 3 Patch scale: across 36 forest sites, relationship between soil pH, organic matter (%), nutrient concentrations (P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, S, and Al; mg kg^{-1}), nutrient ratios (Ca:Al, Ca:Mg, and Mg:Al) and the invasion gradient (mean # non-native invasive stems $forest^{-1}$). Significant positive relationships are shown in blue, negative relationships are shown in red, and no relationship is shown in gray

interior ratio (R = 0.50, p = 0.002) and negatively correlated with the forest patch size (R = −0.38, p = 0.024). At the patch scale, forest patch size and E:I are negatively correlated (R = −0.68, $p < 0.0001$). Non-native plant invasion was not related to urban density or forest size ($p > 0.05$). The year the forest canopy closed was positively related to the E:I of forest patches (R = 0.34, p = 0.04), and there was a positive trend between non-native plant invasion and the E:I of forests (R = 0.30, p = 0.08). Finally, we found no significant differences in the predictor variables (i.e., urban density gradient, invasion gradient, forest patch size, forest patch E:I, and time since forest canopy closure) across soil parent material type (p > 0.05).

Multivariate analysis of soil characteristics

Principal component analysis was used to characterize complex patterns in soil characteristics and spatial and temporal

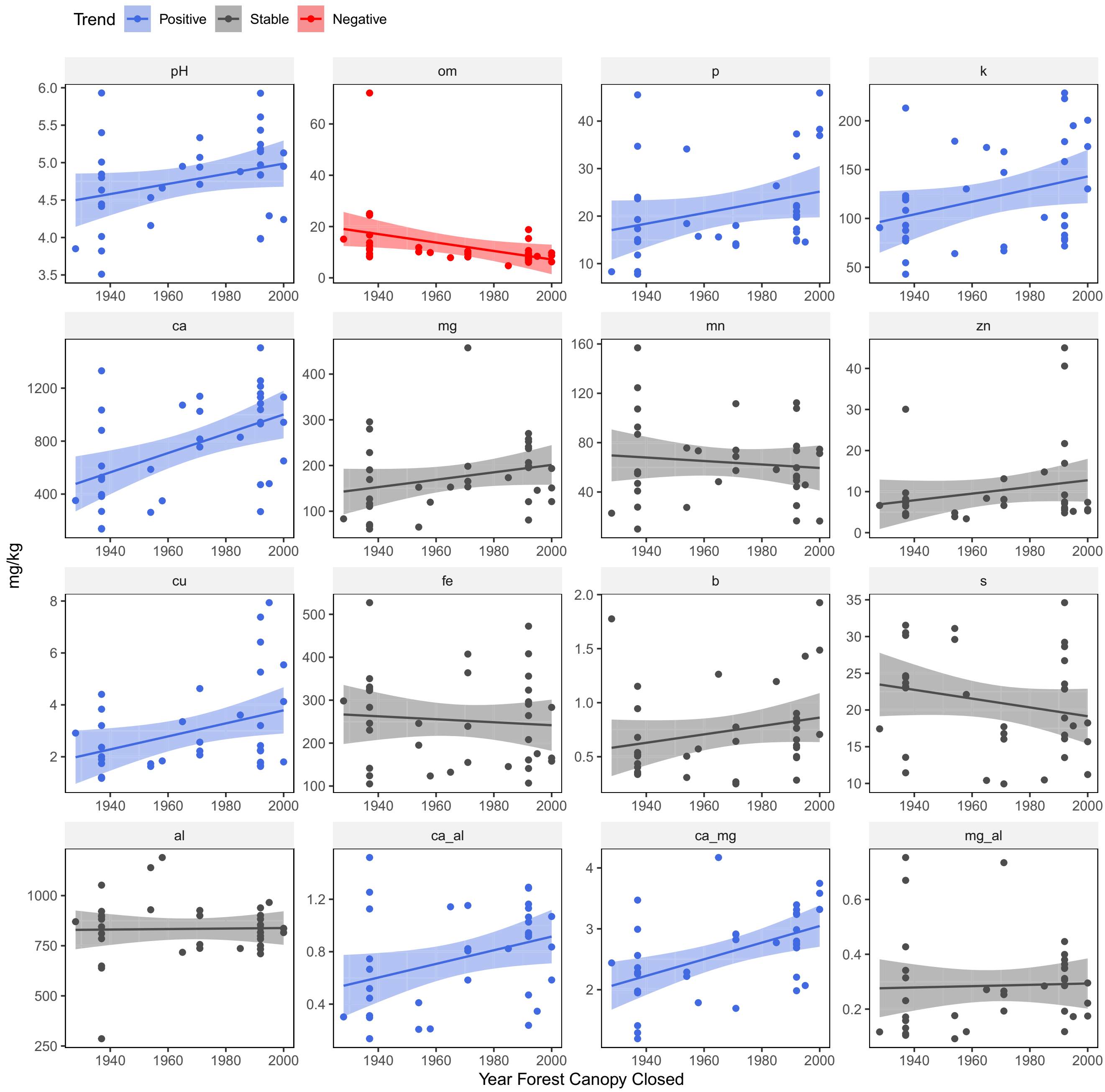

Fig. 4 Temporal scale: across 36 forest sites, relationship between soil pH, organic matter (%), nutrient concentrations (P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, S, and Al; mg kg^{-1}), nutrient ratios (Ca:Al, Ca:Mg, and Mg:Al) and the year the forest canopy closed (historical aerial imagery analysis). Significant positive relationships are shown in blue, negative relationships are shown in red, and no relationship is shown in gray

scale metrics across all forest sites. The first four axes explained 76.3% of the variation in these forest soils. The first principle component (Dim1) explained 38.1% of the total variation in soil characteristics (Fig. 5a). The variables most strongly loaded on Dim1 were pH, Ca (mg kg^{-1}), and Ca:Al, and all of the variables had significant negative loadings on Dim1 (Fig. 5b). The second principle component (Dim2) explained 14.8% of the total variation and the soil characteristics most strongly loaded on Dim2 were SOM content and P, which all had significant negative loadings (Fig. 5b). Alternatively, soil Fe had a significant positive loading on Dim2. While soil characteristics in Newark and Philadelphia forests did not separate from rural forests across Dim1 or Dim2, Newark forests separated along Dim2 from Philadelphia forests where Fe concentrations are higher (Fig. 5c). Forest soils with greater pH, Ca, and Ca:Al had greater non-native plant invasion and more recent forest canopy closure (i.e., left side of Dim1), whereas forest soils with greater Fe concentrations (i.e.,top of Dim2) had greater E:I of forest patches, smaller forest patches, and greater urban density

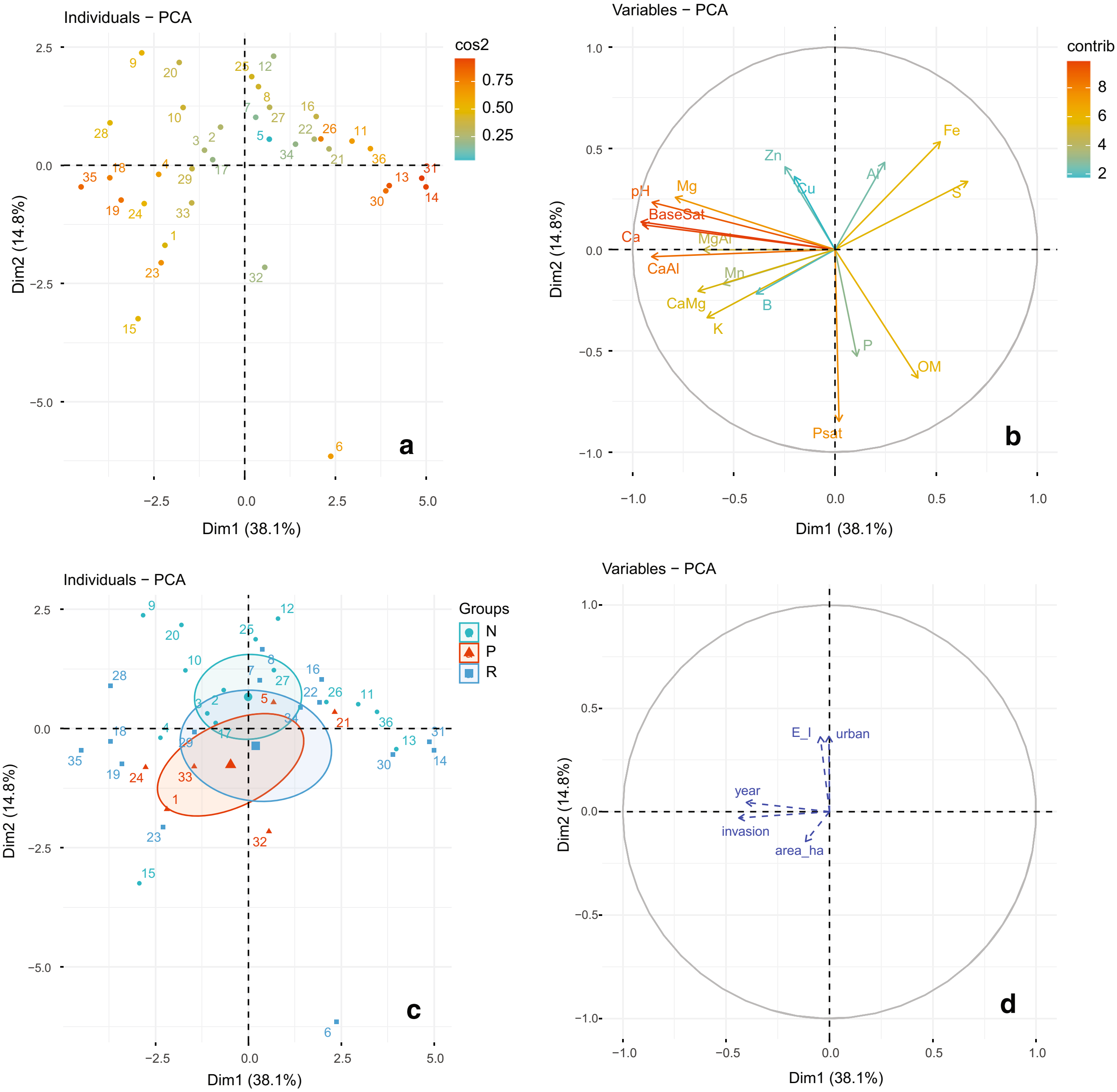

Fig. 5 Principle components 1 vs. 2 of soil characteristics across 36 forest sites. Each point represents one forest site (**a**) which are color coded based on correlations with principle components. The (**b**) soil variables that most strongly loaded with principle component 1 (Dimension 1) were pH (−), Ca (−), base saturation (−), and Ca:Al (−), and all had significant negative loadings, and soil variables most strongly loaded on Dim2 were SOM (−), P (−), P saturation (−), and Fe (+). The city scale differences in soil characteristics are shown (**c**) are represented by Newark (green), Philadelphia (red), and neither city (R – rural, blue). The landscape, patch, and temporal scale predictors (**d**) overlaid on Dim1 and Dim2 are shown

surrounding the forest (Fig. 5d). Across all forest sites, we found no separation along Dim1 or Dim2 based upon soil parent material (SM Fig. 3).

Across all forest sites, the third (Dim3) and fourth (Dim4) principle component explained an additional 12.7% and 10.7% of the variation in soil characteristics, respectively (Fig. 6a). The variables most strongly loaded on Dim3 were soil Al, negatively loaded (i.e., left side), and Mg:Al, positively loaded (i.e., right side; Fig. 6b). The variables significantly loaded on Dim4, soil Cu and Zn, were both negatively loaded (i.e., greater concentrations on bottom of Dim4; Fig. 6b). Soil characteristics associated with Dim3 and Dim4 separated across Newark urban forests, Philadelphia urban forests, and rural forests (Fig. 6c). Specifically, Philadelphia urban forests separated from rural forests and Newark

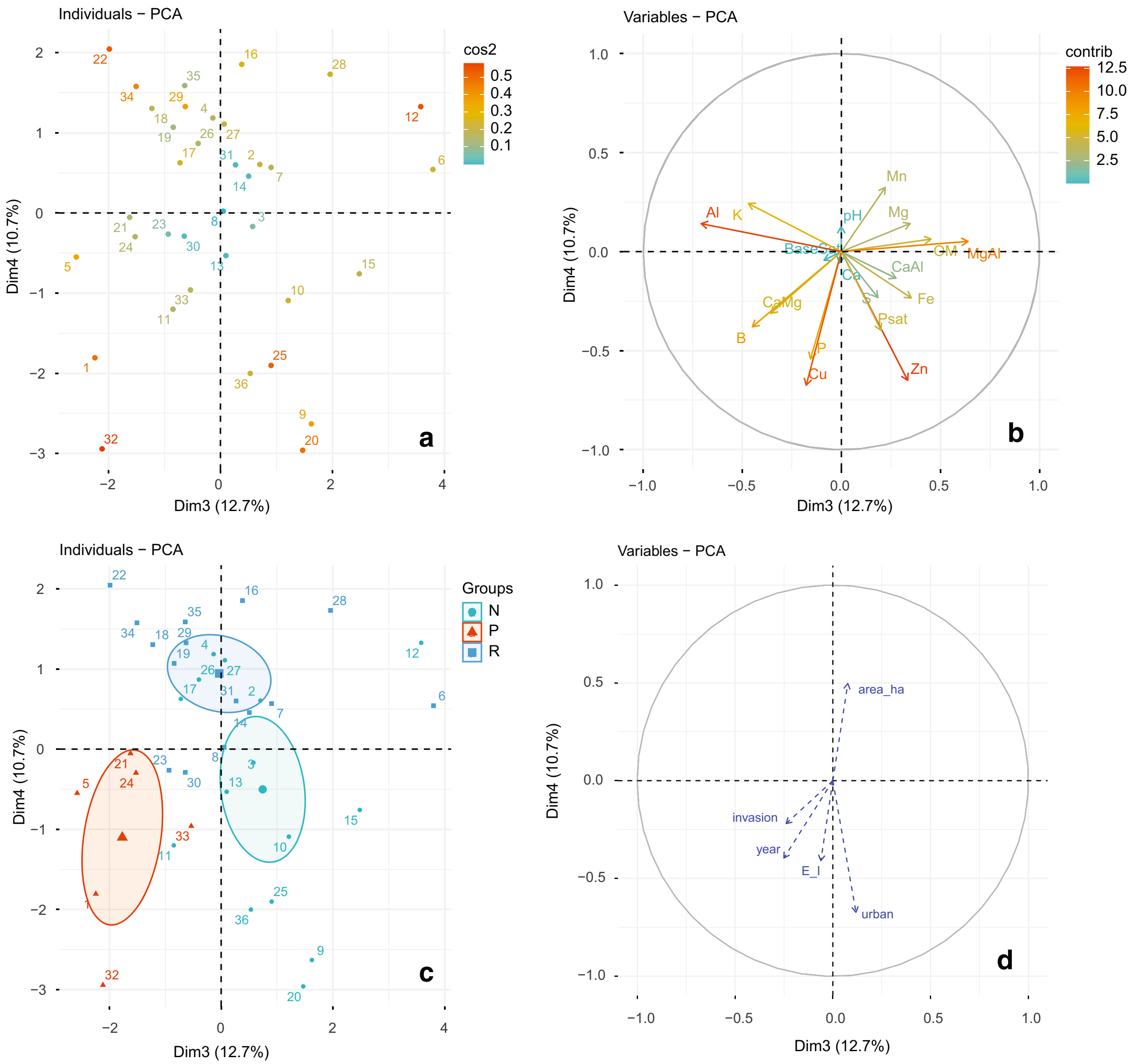

Fig. 6 Principle components 3 vs. 4 of soil characteristics across 36 forest sites. Each point represents one forest site (**a**) which are color coded based on correlations with principle components. The (**b**) soil variables that most strongly loaded with principle component 3 (Dimension 3) were Al (−) and Mg:Al (+), and soil variables most strongly loaded on Dim 4 were Cu (−) and Zn (−). The city scale differences in soil characteristics are shown (**c**) are represented by Newark (green), Philadelphia (red), and neither city (R – rural, blue). The landscape, patch, and temporal scale predictors (**d**) overlaid on Dim3 and Dim4 are shown

urban forests along Dim3, where Al concentrations were greater (i.e., left side of Dim3). Rural forests separated from Newark and Philadelphia forests along Dim4, where Cu and Zn concentrations were lower (i.e., top of Dim4). Furthermore, forest soils with greater Cu and Zn concentrations had greater urban density surrounding the forest and were in smaller forest patches with greater E:I (Fig. 6d). Finally, we found no separation along Dim3 or Dim4 based upon soil parent material (SM Fig. 3).

Discussion

In this study, we explored how soil chemical properties varied across multiple spatiotemporal scales in temperate deciduous forests of different patch sizes and situated within varying urban land use density. Forest patches embedded across landscapes with high urban density in northern DE and southeastern PA had greater soil metal concentrations (e.g., Cu, Zn) than forests situated within lower urban density. Similarly, smaller forests and forests with high E:I were associated with high Cu and Zn concentrations. Alternatively, forest patches with greater soil pH and Ca concentrations were associated with non-native plant invasion, which related to the time since canopy closure. Univariate and multivariate analyses across spatiotemporal scales provide insight on the potential controls on soil chemical properties in forests embedded across developed landscapes along the east coast of the United States.

Soil chemical properties at metro and landscape scales

At the metro and landscape scale, we found that Zn and Cu concentrations were greater in both Newark and Philadelphia urban forests compared to the rural forests (Fig. 6c, d). This supports our expectation of greater metal concentrations in urban forest soils from deposition inputs at a metro scale. Similar results were found in a comparison of three cities of various population densities and development patterns (Pouyat et al. 2008). At the landscape scale, Zn and Cu increased linearly with increasing impervious surface surrounding the forest patch (i.e., urban density gradient; Fig. 2), supporting our prediction that roadside inputs would increase metals in urban soils. Zn and Cu are associated with roadside environments since vehicles are sources for these metals (e.g., brake linings, tire wear, oil, grease, hydraulic fluids; Forman et al. 2003; Yesilonis et al. 2008). We found a trend for Fe concentrations to increase along the urban gradient (Fig. 2), and this was primarily due to Fe concentrations in Newark forest soils, which had significantly greater soil Fe concentrations than Philadelphia forests. Similarly, S concentrations increased along the urban gradient due to greater concentrations in Newark than Philadelphia forest soils. These findings demonstrate that while urban development is related to increases in some nutrient and metal elements, not all cities will demonstrate the same elemental increases and that regional patterns of deposition, site legacies, and/or soil mineralogy are important for determining soil chemical properties.

Across local to regional scales, we recognize that soil parent material can drive differences observed in soil chemical properties and can be especially important for specific elements (e.g., Fe and/or Mn; Pouyat et al. 2009). Our forest sites are spread across two metropolitan areas with differing soil parent material across some forests. However, differences in soil elemental concentrations across these forest patches are not related to broad scale variation in soil parent material across these sites (SM Fig. 3). This suggests differences observed in soil chemistry, specifically Zn, Cu, and Fe, across the urban gradient and between Newark and Philadelphia forests are driven by urbanization activities that increase soil nutrient and metal concentrations (e.g., Pouyat et al. 2008).

Multiple human activities associated with cities and towns, like industrial processes and mobile/stationary emissions, result in the accumulation and deposition of elements to the soil surface, which can lead to metal contamination (Wong et al. 2006). Toxicity levels for metal elements depends on a variety of factors including the organism exposed (e.g., plant vs soil biota) and soil physio-chemical properties that determine mobility and bioavailability of metals (e.g., pH). While we found greater soil Zn and Cu in our forest soils along with urbanization, the potential for toxic effects of these elements on plant growth and vigor in these forests is low. The maximum concentration for Zn (45.0 mg kg^{-1}) and Cu (7.9 mg kg^{-1}) across our forest soils was lower than Ecological Soil Screening Levels for plants developed by the U.S. Environmental Protection Agency (EPA 2007) and lower than potential impacts on soil biota (Bååth 1989). While our extraction method may underestimate metal concentrations for these elements relative to the EPA standard method, there is some question as to the validity of these limits due to the lack of studies that have empirically tested biological endpoints for most contaminants (Efroymson et al. 1997). Current thresholds for soil contamination suggest the urban forest soils in our study are likely to support healthy plant growth or provide the nutrients necessary for plants to acclimate to urban environmental conditions (McDermot et al. 2020).

An unexpected and interesting result from our study was the negative relationship between soil K concentrations and the urban gradient, yet Philadelphia forest soils had significantly greater K concentrations than Newark forest soils. The Newark and Philadelphia urban forests overlap with respect to the urban gradient, such that the range in % impervious surface area surrounding Philadelphia forests (8 to 41%) is comparable to Newark forests (11 to 48%). Therefore, our findings suggest that regional deposition and/or site history may be important in determining soil K concentrations across Philadelphia forests. Alternatively, soil parent material may be an important determinant of differences in soil K between Philadelphia and Newark forests. While most of the soil parent material types had no significant relationships with any spatial scale (e.g., urban gradient, invasion; SM Fig. 3) or soil chemical properties, the parent material with the greatest soil K concentrations were found in most of the Philadelphia forests, whereas the parent material with significantly lower K was found in half of the Newark forests. The findings from our study suggest soil parent material may be responsible for the differences in K concentrations between Philadelphia and Newark forests.

Soil chemical properties at the patch-scale

At the patch scale, we found non-native plant invasion strongly related to multiple soil chemical properties within our forests (Figs. 3 and 5). Soil Ca concentrations and pH increased as the number of non-native invasive plants within the forest increased. The pattern of increasing soil Ca and pH with plant invasion has been shown across plant growth forms (e.g., grass: Blank 2008; liana: Leicht-Young et al. 2009; shrub: Gavilán et al. 2016) and ecosystem types (e.g., grasslands: Blank 2008; forests: Howard et al. 2004). Whether this pattern is a result of non-native invasive plants colonizing soils with greater Ca concentrations or invasive plants increasing soil Ca has not been experimentally determined, to our knowledge. However, a subsampling effort within our forests suggests invasive plants contribute to greater soil Ca concentrations in our forests since we found increased soil Ca concentrations underneath the most dominant non-native invasive plant in these forests (multiflora rose, *Rosa multiflora*; Trammell et al. 2020) compared adjacent soil not underneath multiflora rose (D'Amico et al. unpublished data). Furthermore, we found, in a separate analysis of variation in soil characteristics within our forest patches, that variation in soil Ca concentrations significantly decreased with increasing plant invasion within the forest, which further indicates these invasive plants may contribute to altered soil Ca cycling in forests. The pattern of increasing Ca:Al and Ca:Mg ratios with invasion follows increasing Ca concentrations since Al and Mg concentrations had no relationship with plant invasion, which highlights the potential for plant invasion to alter soil biogeochemical cycles (Ehrenfeld 2010).

Non-native plant invasion within the forests was also related to decreasing soil organic matter (SOM) and S concentrations, which is an unexpected, yet not surprising, result from this study (Fig. 3). Organic matter inputs to forest soil has been shown to decrease significantly in invaded forests simultaneously with faster decay rates of invasive plant litter (Trammell et al. 2012), which results in a severely reduced leaf litter layer in invaded forests. Across our forest sites, we found a significant negative relationship between non-native plant invasion and leaf litter volume ($R = 0.64$, $p < 0.0001$), which implies less organic matter accumulation in these invaded soils due to faster organic matter decay rates and/or lower foliar biomass inputs to soil. Since sulfur is a major organic constituent in soils, it is possible that S concentrations would follow SOM in relation to plant invasion. However, a likely explanation for a decrease in soil S concentrations with increasing plant invasion would be differences in soil parent material. In some of the most invaded forests, the soils were over parent materials with the lowest S concentrations, whereas the least invaded forests had soils over parent material with the highest S concentrations. Therefore, parent material differences may explain decreasing S concentrations with increasing plant invasion. The potential impact of reduced SOM and sulfur on native tree or shrub growth in invaded forests and subsequent impacts on forest community composition is a potential direction for future research.

Forest patch structure, size and shape, is an important determinant of soil chemistry within small forests across developed landscapes. Across all our forest sites, smaller more complexly shaped forest patches (i.e., greater E:I) are associated with more urban development surrounding the forest patch. While this pattern is not surprising due to competing needs for urban land use (e.g., residential vs commercial) that leads to development pressure within urban areas, our study documents the relationship between urbanization and forest structure across the mid-Atlantic United States. Furthermore, the only soil chemical property associated with forest size and edge to interior ratios were soil elements associated with increased urbanization, i.e., Cu and Zn concentrations (SM Figs. 1 and 2), specifically, smaller forests with greater edges had elevated concentrations of soil Cu and Zn, which could be used as indicators of enhanced urban regional and local deposition inputs (e.g., Weathers et al. 2000). Since forest patch structure and urban development correlated in our study, an interesting future research direction would be to decipher forest size and shape determinants on soil chemical properties in urban and non-urban settings. It is reasonable to predict that in cities smaller forests with greater edges would accumulate local and regional deposition inputs at a faster rate than larger forests within an urban setting. Deposition influences on forest edges will depend on adjacent land use and land cover as well as prevailing wind directions. While the influence of forest size and location across an urban matrix has been assessed for offsetting urban heat island effects (e.g., Forman 2014), we know of no studies that have examined how forest patch structure relates to nutrient and/or metal deposition in urban environments.

Soil chemical properties across a temporal scale

We previously reported the significant correlation between time since forest canopy closure and abundance of non-native plants in our forests, such that newer forests are more invaded ($R = 0.58$, $p < 0.001$; Trammell et al. 2020). The dominant relationships between our temporal scale and soil chemistry (Fig. 4) reflected patterns between soil chemistry and our invasion gradient (i.e., soil pH, Ca, Ca:Al, Ca:Mg, SOM) indicating the importance of plant invasion with respect to soil acidity, Ca, and organic matter. Alternatively, new forests have had less time to accumulate organic matter in the soil and may reflect legacies associated with previous agricultural land management practices that reduce SOM (e.g., harvesting) or increase soil Ca (e.g., liming). Furthermore, we found a trend for higher P and K concentrations in forests with more recent canopy closure supporting the concept that legacies from fertilizer additions may be influencing these nutrient elements in younger forests. While the design of this forest study cannot separate the effects of plant invasion and duration of canopy closure on soil properties, observations and empirical evidence of differences in soil nutrient concentrations (i.e., Ca, N; unpublished data) and nutrient processes (i.e., N mineralization; unpublished data) in soils directly underneath invasive plants and adjacent to invasive plants suggests plant invasion does have an effect on soil biogeochemical cycling as supported by other research (e.g., Ehrenfeld 2010). We recognize the need to study the effects of land use legacies and plant invasion separately on forest soil properties and processes. However, whether a study design separating forest age and plant invasion is possible remains to be determined.

The temporal scale across our forests had no relationship with urban development surrounding the forest patches, yet related to one aspect of forest patch structure (i.e., edge to interior ratio). Younger forests that have higher edge to interior ratios also had greater soil Cu concentrations suggesting this soil element responds to local deposition inputs to forests with greater edge area. However, soil Zn did not relate to time since canopy closure indicating this soil element responded differentially to time since canopy closure and forest patch edge to interior ratios. While this research highlights the importance of considering site legacies and duration of intact canopy in understanding patterns and processes in forest soils, future work is needed to differentiate the relative influence of these spatiotemporal scales on forests embedded across developed landscapes.

Conclusion

Our study is the first to assess urban soil properties across multiple spatiotemporal scales and simultaneously analyze how urbanization and non-native plant invasion relate to urban soil chemistry. We found metal elements associated with industry and mobile/stationary emissions (i.e., Cu, Zn) were elevated along the urban density gradient and a nutrient potentially associated with land-use legacies (i.e., Ca) was elevated along the invasion gradient. In addition, we examined how forest patch structure relates to urbanization and plant invasion. The temporal scale was significantly related to plant invasion, and soil chemical properties mimicked soil patterns associated with plant invasion, while forest patch size and E:I reflected the elevated soil elements observed with increasing urban density. These findings are important in determining how forest patch structure relates to human activities that drive changes in soil chemistry.

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Data availability Data are available on the FRAME website https://sites.udel.edu/frame/published-data/

Compliance with ethical standards

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