



Legacies of Nutrient Accumulation and Depletion in Residential Ecosystems

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ABSTRACT

In residential ecosystems, land management can help regulate climate and improve water quality by promoting the accumulation of nutrients in the soil. We tested how varying intensity of residential land use and management altered nutrient (Ca, K, Mg, P, S) pools. We studied soils and vegetation across twelve land use-intensity gradients (yards-perennial old fields-forests) established 15–227 y. ago in the native ecosystems of temperate forests. We found that yard soils were enriched with nutrients relative to fields and forests, regardless of recent yard management intensity. Yard soils from 0- to 40-cm depth contained an average 72–93% more Ca, 11–22% more Mg and 18–50% more P than fields and forests. In the upper 20 cm of soil, where land-use effects were pronounced, 200-year-old yards contained 24% more soil P than one

decade-old yards. Yards where managers exported grass clippings for forty years contained less soil K and Mg than yards managed similarly for ten years. Yard soil cation exchange capacity and C were not correlated, suggesting the importance of inorganic mechanisms of nutrient accumulation. With more intense land use, across yards-fields-forests and within yards, soil S and C tightly covaried indicating these nutrients may limit or stimulate organic nutrient cycling. Our research suggests residential land management can contribute to nutrient legacies that support resilient responses to global change.

Key words: Land use; Residential ecosystems; Soil; Nutrient cycling; Base cations; Organic macronutrients; Lawn management.

HIGHLIGHTS

- Yard soils contained 1.2–2.8 times more Ca and P than field and forest soils.
- Old yard soils were Ca and K depleted but P enriched relative to young yards.
- Soil S and C tightly covaried suggesting their biogeochemical cycles were coupled.

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INTRODUCTION

Land-use legacies have influenced ecosystem nutrient dynamics for centuries (Ziter and others 2017; Roman and others 2018; Ziter and others 2018). Nutrient cycles are well studied across wildlands yet remain a research frontier in residential ecosystems (Groffman and others 2014, 2017). The establishment and management of residential ecosystems can affect nutrient accumulation or depletion by altering inputs (for example, fertilization), cycling rates (for example, changes in vegetation composition) and outputs (for example, biomass export) (Fissore and others 2011; Olofsson and others 2016; Hobbie and others 2017). Revealing how residential land use and management influence nutrient cycling is necessary for resilient responses to global change (Ellis 2015; Steffen and others 2015; Elmqvist and others 2019).

Residential ecosystems, defined by human residents, houses and related uses, are a testing ground for theories and mechanisms developed in wildlands (Lundholm 2015; Groffman and others 2017). In residential ecosystems, adjacent lands that shared legacies prior to their present use can control for prior activities that might have altered ecosystem properties (Peach and others 2019). By using this spatiotemporal model, we can understand how residential land use alters nutrient dynamics. Wildlands theory predicts that over a timescale of decades to centuries ecosystems accumulate nutrients as biomass aggrades (Vitousek and others 1975; Peltzer and others 2010; Lajtha 2020). Despite these predictions, it is unclear how nutrient cycles have responded in residential ecosystems (Carpenter and others 2015; Groffman and others 2016).

Biogeochemical elemental cycling could be impacted by vegetation changes in residential ecosystems (Jobbágy and others 2004; Trammell and others 2017). Around houses, in yards and fields, the dense roots of perennial grasses access a large volume of surface mineral soil horizons, actively cycling nutrients to their aboveground biomass where nutrients are concentrated (Beard and others 1994). Managers regularly cut grasses and often remove clippings, causing a physical export of nutrients. Organic matter exports over time could decrease soil cation exchange capacity (CEC) diminishing inorganic nutrient storage and promoting net leaching and depletion of the base cations Ca, Mg, and K. Nutrient exports could eventually limit productivity and nutrient accumulation. By contrast, in unharvested forests,

nutrients accumulate above- and belowground as they cycle and exports are primarily controlled by leaching.

Biogeochemical cycling of nutrients may respond to fertilization from residential land use and management. Yards and fields, of high nutrient demands relative to native ecosystems, are fertilized unintentionally in land use (for example, pet waste) and intentionally in management (for example, liming). Counterintuitively, fertilization could lead to nutrient depletion. For example, Ca fertilization can boost plant productivity (Reid and others 2014; Alves and others 2019), but more available Ca could stimulate decomposition of existing soil organic matter (SOM) (Marinos and others 2018; Keel and others 2019). Loss of SOM and its derived CEC reduces the likelihood of base cation accumulation and soil nutrient availability. This could result in less available Ca that can hinder the accumulation of P sorbed or precipitated with Ca (Murphy and others 2010). Fertilization in residential ecosystems could influence biogeochemical processes that potentially lead to nutrient depletion.

Alternatively, fertilization could promote nutrient accumulation through efficient bottom-up biogeochemical elemental cycling (Rao and others 2014; Decina and others 2018, 2020; Nelson and others 2018; Schulte-Uebbing and others 2018). Carbon that accumulates in response to nutrient inputs can interact with pedogenic Fe and Al, generating stable organo-mineral complexes that can increase CEC, with exceptional sorption of P as phosphates (Kallenbach and others 2016; Liang and others 2017; Porrás and others 2017; Li and others 2019; Sokol and others 2019). This process can self-perpetuate with Ca and Mg creating stable complexes of microbial C and secondary oxide minerals (Kramer and others 2018; Rowley and others 2018). Fertilization in residential ecosystems may contribute to productive and efficient biogeochemical cycles, wherein nutrients accumulate in a positive feedback.

We tested competing hypotheses about how residential ecosystem land use and management could influence biogeochemical processes that lead to soil nutrient accumulation or depletion. We first hypothesized that soil nutrient depletion would coincide with legacies of soil C loss since residential development (Peach and others 2019) (Figure 1). We expected organic macronutrient (C, P, S) dynamics to be related (Buchkowski and others 2019), with the loss of SOM and its CEC contributing to base cation (K, Ca, Mg) depletion. Managers who export plant biomass, such as grass

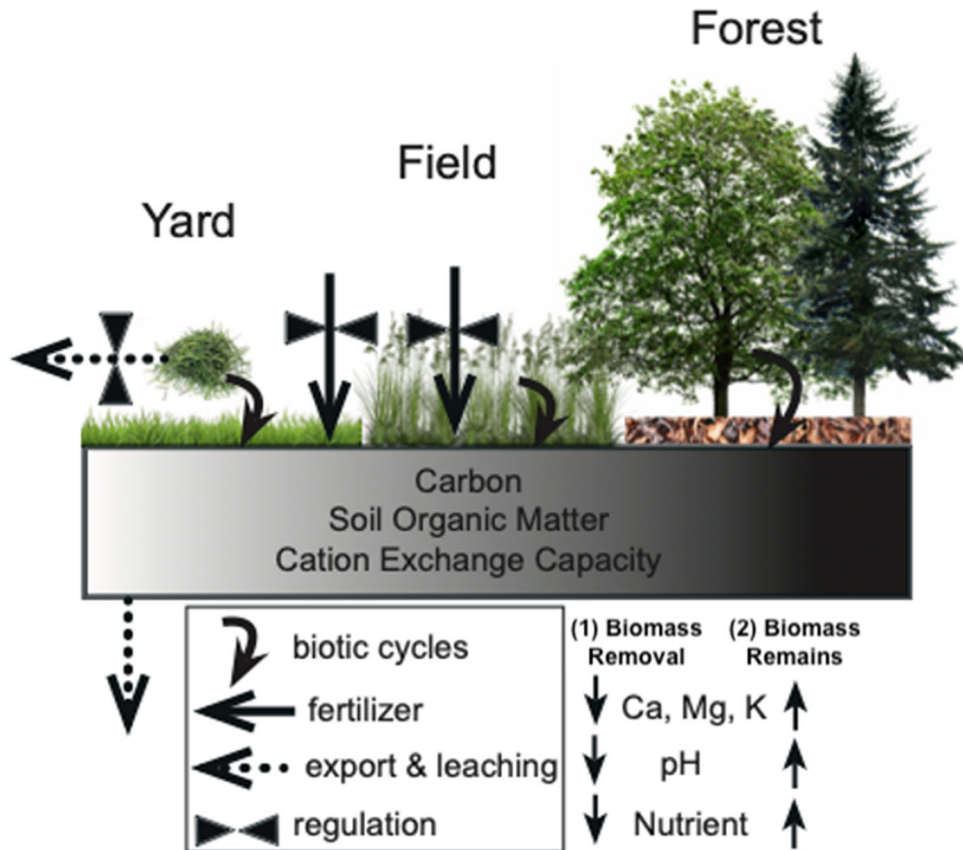


Figure 1. From left to right, soil organic matter (SOM; white to black gradient box) and its cation exchange capacity (CEC) increase. There are management- and land-use-related nutrient inputs in yards and fields. We hypothesized that (1) managers who remove biomass decrease SOM, CEC and drive nutrient depletion. Acidic fertilizer inputs and loss of base cations (Ca, Mg, K) decrease soil pH, which may further deplete base cations. Managers who leave biomass (2) could promote the accumulation of SOM, CEC, and base cations.

clippings, contribute to nutrient loss. Soils with fewer base cations have less capacity to buffer pH and are susceptible to acidification. Thus, we expected organic macronutrients, CEC and base cations to be depleted from yard soils.

Alternatively, we hypothesized that more intense residential land use and management would result in base cation dynamics uncorrelated with soil CEC. For example, fertilization with K, Ca, or Mg could enlarge their soil pools, even in C-depleted soils of low CEC. Base cation inputs can increase soil pH, decreasing the dissolution and precipitation of secondary Fe and Al minerals that can increase CEC and accumulation of organic macronutrients. These processes could decouple the biogeochemical cycling of base cations from CEC. To test our competing hypotheses, we examined a residential ecosystem land-use-intensity gradient from yard to adjacent field to adjacent forest, in residential ecosystems established decades

to centuries ago. We asked (1) Have soil nutrient pools changed across land-use intensities since residential ecosystem establishment? (2) Are soil C, pH, CEC, or Fe and Al related to nutrient differences across land-use intensities? (3) Over decades of recent yard management does export of plant biomass drive nutrient depletion?

METHODS

Site Selection

We selected residential ecosystems in the Upper Connecticut River Valley, Vermont and New Hampshire, USA, a developed cool moist temperate mixed forest (mean annual 7.8 °C, 992 mm precipitation) (Arguez and others 2010, NOAA Climate Normals). We studied large residential ecosystems (> 0.4 ha parcels) developed 15–227 years ago. We selected parcels in spatial clusters that shared similar parent material from

glaciofluvial deposits, subsequent soil forming processes and land-use legacies. We sampled yards ($n = 20$ total) adjacent to fields ($n = 13$) and secondary forests ($n = 12$) in these clusters ($n = 12$). Each cluster included one or more yards, one or more fields (one cluster with two fields, hence $n = 13$ fields) and one forest, within a parcel owned and managed by residents for at least ten years. Based on land-user interviews and land-use history research (see Peach and others 2019), uncultivated old fields, composed of perennial grasses and forbs, were mown annually to biannually and received nutrient inputs since residential development (that is, lime, wood ash, or manure every ~ 10 – 30 y). We selected fields for our sample that shared similar land management history and served as a lower-use intensity comparison with yards. Forests were unmanaged or experienced low-intensity thinning cuts since development.

Following in-person interviews, we sorted participating residents into two analytic groups of intensive (IM) or non-intensive (NIM) yard management over 10–48 years of consistent, recent management (Peach and others 2019). Over the past one to five decades, residents either hired commercial yard managers, who mowed weekly over a five-month growing season and removed grass clippings (IM; $n = 9$), or mowed themselves less often (bimonthly to monthly) and left clippings on the yard (NIM; $n = 11$). Across all yards, regardless of management intensity group, fertilizer applications of lime (Ca), dolomitic lime (Ca, Mg) and wood ash (Ca, Mg, K) were common both before and during the tenure of present-day residents. As reported by residents, NPK applications by commercial managers or homeowners were less common. Based on our interviews and land-use history research, we assumed relatively similar yard fertilizer inputs across space and time following development. In recent decades, commercially managed yards may have received more fertilizer inputs, but this was not reported to us by residents. In young yards across management intensity groups, there was evidence of excavation-related deep soil redistribution to the surface and loam import in development.

Our interviews and archival research supported the assumption that yards received nutrient inputs in excess of fields and land uses shared similar pre-residential development land-use legacies within land-use clusters. The residential ecosystems we sampled had similar parent material, reflected by soil maps and soil textures (Peach and others 2019). This, in addition to the relatively homoge-

neous pre-development land-use history across the study region, indicated that yards likely had similar nutrient pools at the time of residential development. Our statistical analyses account for possible site-scale differences in yard nutrient pools at the time of development. Further description of our site selection, sampling, soil C and N analysis and pool estimation methods can be found in Peach and others (2019). In the next sections, we briefly describe our sampling and detail our nutrient analyses.

Sampling and Laboratory Processing

We sampled soils and vegetation during the spring and summer of 2016 and 2017. We selected plots randomly within each land use, avoiding below-ground infrastructure. Plots in yards represented grass-dominated lawn use and cover. We collected three surface vegetation and Oi/Oe horizon samples per plot within the area of a soil core (7.3 cm dia.). We collected three soil cores from random locations within a plot (16 m dia.) from the 0- to 10- and 10- to 20-cm-depth increments and auger extracted soil from 20 to 40 cm. We estimated the auger-extracted volume by back-filling with sand.

We air-dried vegetation samples under standard laboratory conditions, weighed them, homogenized them and ground a 15.0 g subsample. We oven-dried 1.0 g plant and soil aliquots prior to C and N analysis with a Costech ECS 4010 Elemental Analyzer (Costech Analytical Technologies Inc., Valencia, CA). We weighed soil samples when field moist and air dried. We sieved soils to separate roots and rocks from the less-than-2 mm fraction and weighed these fractions. For the calculation of soil bulk density, we oven-dried a 15.0 g subsample at 105 °C for 48 h and weighed it. We corrected for rock volume in the bulk density calculation using the average particle density of 2.65 g cm^{-3} . We measured soil texture of a 30.0 g subsample by the hydrometer method (Bouyoucos 1962). We measured soil pH in a slurry of 6.0 g soil to 12 mL reverse osmosis deionized water. We homogenized and composited soil and vegetation samples by plot and depth increment and used a 3.0 g subsample for nutrient analysis.

Plant and Soil Nutrient Analysis

We quantified soil and plant nutrient concentrations (Al, Ca, Fe, Mg, K, Na, P, S and Zn) using a “pseudo-total” extraction method adapted from USEPA method 3050. This method is often referred to as a pseudo-total digestion due to the inability to dissolve silicates and other refractory compounds;

these refractory compounds are dominant in soils and may be present in plants. However, pseudo-total extraction offers a more robust investigation since our study focuses on nutrients over multiple decades and cation exchangeable concentrations often fluctuate through time depending on current soil conditions (Eh, pH, ionic strength, and so on). We henceforth refer to pseudo-total concentrations as total concentrations used in our calculation of plant and soil nutrient pools.

We oven-dried 2.0 g of air-dried soil and plant material overnight at 105 °C. We then combusted the sample at 480 °C for 8 h to remove organic matter and cooled it in a desiccator. We extracted the combusted soil and plant material in 10 mL of 1:1 trace-metal grade nitric acid in a crucible on a hot plate maintaining a gentle reflux for 30 min. We filtered samples (Whatman 41; > 20 µm particulate removed) into acid-washed 60 mL LDPE bottles and diluted digests with reverse osmosis deionized water to a weight of 62.5 g (~ 50 mL) to obtain a weight/weight digestion factor.

We analyzed the diluted samples for Al, Ca, Fe, Mg, K, Na, P, S and Zn via inductively coupled plasma-optical emission spectrometry (Agilent 5110, Agilent Technologies, Santa Clara, CA, USA). Every 25 samples included a process blank, a duplicate and a standard reference material (SRM). For every 25 samples, we used the SRMs of Montana Soil 2711 for mineral soil samples (National Institute of Standards and Technology, Gaithersburg, MD, USA) and Pine Needles for plant tissue samples (High-Purity Standards, North Charleston, SC, USA). Preparation blanks had elemental concentrations below detection limits. %Relative standard deviations (RSDs) averaged across eight soil duplicates were Al (13%), Ca (9%), Fe (13%), K (13%), Mg (23%), Na (21%), P (4%), S (9%) and Zn (13%). RSDs among Montana soil SRMs were an average 8%. RSDs among plant material duplicates and Pine Needle SRMs were less than 5% aside from Fe (17%) in SRMs. Total concentration recoveries for Montana soil SRM ranged from 60–95% for all nutrients, aside from Fe (50%) and Na (118%). Montana Soil SRM was not certified for S. Relatively low RSDs among soil S duplicates indicated our S measurement was consistent. S magnitudes we report likely underestimate S. Total recoveries for Pine Needles SRM were Al (97%), Ca (108%), Fe (46%), Mg (112%), K (113%), Na (85%), P (127%), S (29%) and Zn (97%). As expected, low recoveries were likely due to the failure to digest silicate and other residual compounds including Fe and S colloids. High recoveries in the Pine Needles SRM likely resulted

from the calibration curve required for the range of sample concentrations across land uses and possible Cu interference with P.

We calculated soil CEC, across depth increments and land uses, by dividing base cation concentrations (ppm) by their centimoles of positive charge per kilogram soil dry weight ($\text{cmol}^+ \text{kg}^{-1}$) constants for Ca (200), Mg (120), K (390) and Na (230). We estimated exchangeable acidity (acid cations) as follows:

$$\text{acid cations} = 12 \times (7 - \text{pH})$$

We summed acid and base cations to result in soil CEC.

We estimated nutrient pools in forest woody biomass and foliage to compare whole ecosystem aboveground nutrient pools across land uses. We measured nutrients in the organic horizon (Oi/Oe) and surface vegetation. To this pool we added the mean Ca, K and Mg contained in mixed deciduous forest bolewood and foliage (mass of nutrient per area) estimated by Richardson and others (2016). We sourced mixed deciduous forest P concentration data for our study region from Likens and others (1970). We used tree biomass ha^{-1} values from Richardson and others (2016) to calculate forest P pools in wood and foliage, then added to our estimate of P pools in the Oi/Oe horizon and surface vegetation.

To estimate the cumulative nutrient exported in lawn clippings over time from IM yards, we first calculated the mass of nutrients in yard plants (predominately grass, but including forbs) on an areal basis (g m^{-2}) by multiplying the composited sample concentration ($\text{g nutrient g dry biomass}^{-1}$) by the average dry biomass (g) per three sampled areas within a yard extrapolated to one m^2 . We multiplied the mass of yard plant nutrients per m^2 by two-thirds, the assumed fraction of grass leaves clipped based on our homeowner interviews, then multiplied by 20 weeks in a five-month growing season, by 10 years of consistent management. We assumed plant nutrient concentrations and biomass at the time of mowing were stable over time. We report the average nutrient exported in clippings across all IM yards.

Statistical Analyses

We fit generalized linear mixed-effects models (GLMMs) in R's *lme4* package (Bates and others 2015) to determine (1) whether land-use type (yard, field, forest) explained residential ecosystem nutrient dynamics, to test (2) the effect of yard management on soil nutrient pools and to test (3)

how relationships among soil nutrients, C, CEC, and pH varied across land-use types. We began with a full model that tested the interactions of (1) land use with time since development, (2) yard management intensity with duration of recent management and (3) a soil property (for example, pH, CEC) with land-use type. We treated time since development and duration of recent yard management as continuous variables. In soil-related full models, we coded depth as a covariate. In all models, we treated clusters of land-use types along a site-scale gradient as a random intercept to address the violation of spatial non-independence and to account for site-specific legacies. We fit models by maximum likelihood, dropped non-significant interactions and main effects from full models and compared models with Akaike information criterion (AIC; $\Delta \text{AIC} > 2$ are different) (Burnham and others 2011). We inspected model residuals for homoscedasticity. We used AIC to select the best fitting response distribution (Gaussian, gamma) and link function (identity, log, inverse) among candidates. Where there was a significant main effect, we performed Tukey-adjusted *t*-tests of contrasts (*emmeans* package; Lenth 2018). We back-transformed data prior to averaging for contrasts. Where there was a significant interaction between (1) land-use type and time since development, (2) yard management intensity and duration of management, or (3) a soil property and land-use type, we performed Tukey-adjusted *t*-tests of slope contrasts by yard management intensity group or land-use type. We included time since development in yard management intensity models, which was non-significant in the results we report and addressed issues of crossed treatment effects. We report linear rates of nutrient pool changes, associated with time since development or duration of recent yard management, from back-transformed slopes from the best-fit models among candidates. We report levels of statistical significance ($\alpha = 0.05$) from $p < 0.05$ to $p < 0.0001$. We performed analyses in R, version 3.4.4 (R Core Team 2018).

RESULTS

Soil and Vegetation Nutrient Pools Across Residential Ecosystem Land-Use Intensities

We tested whether soil and vegetation nutrient pools were different across yard-field-forest land-use intensities. Differences in soil nutrient pools and concentrations across land uses mirrored each

other; therefore, we report nutrient pools, which accounts for soil bulk density.

We first report Ca, K, Mg, P and S macronutrient soil pools across yards, fields and forests from 0- to 40-cm depth. Yard soil Ca pools were 72–93% larger than field and forest soil pools (Figure 2A, B $p < 0.01$). Yard soil K pools were 24% larger than fields ($p < 0.01$) and not different than forests ($p = 0.10$). Yard and field soil P pools were 50% and 33% larger, respectively, than forest soil P pools ($p < 0.001$). Differences in soil Mg pools across land uses paralleled soil P. Soil S pools were 30% larger in fields than yards from 0- to 20-cm depth, where this difference was evident (Figure S2, $p = 0.01$).

Comparing macronutrient vegetation pools across the three land uses, we observed different patterns than soil pools. Surface vegetation nutrient pools did not differ significantly among yards and fields. As expected, forest vegetation Ca, P and Mg pools were larger than yard and field vegetation pools (Figure S1, $p < 0.0001$). Forest vegetation contained more K than yard plants, but field and forest vegetation K pools were similar. Yard vegetation S pools were 77% smaller than forests, even when excluding woody biomass (Figure S3, $p < 0.01$).

Lastly, we compared total Al and Fe pools as a proxy to examine differences in secondary Al and Fe oxyhydroxides. We observed significantly different trends in Al and Fe than other nutrients. From 0- to 20-cm depth, where land-use effects were pronounced, yard soils contained 17% more Fe than forest soils (Figure S2, $p = 0.01$) and field soils a non-significant 12% more Fe than forest soils ($p = 0.09$). Soil Al pools did not differ by land use. Even when excluding forest tree biomass, yard and field vegetation Fe and Al pools were 130–135% smaller than the forest Oi/Oe horizon and surface vegetation Fe and Al pools ($p < 0.01$).

Soil Nutrient Fluxes Since Residential Ecosystem Establishment

Across land uses since residential ecosystem establishment soils were depleted by $0.0017 \text{ kg Ca m}^{-2} \text{ y}^{-1}$ from 0- to 20-cm depth. On average, yard soils were Ca rich relative to fields and forests (Figure 2B). But older yards contained less Ca than younger yards (Figure 3). There were non-significant trends in field and forest soil Ca pools. Field soils accumulated K since development ($p < 0.0001$) and old yard soils were K depleted ($p < 0.01$). Across land uses, the magnitude of soil Mg pools was unrelated to time since residential

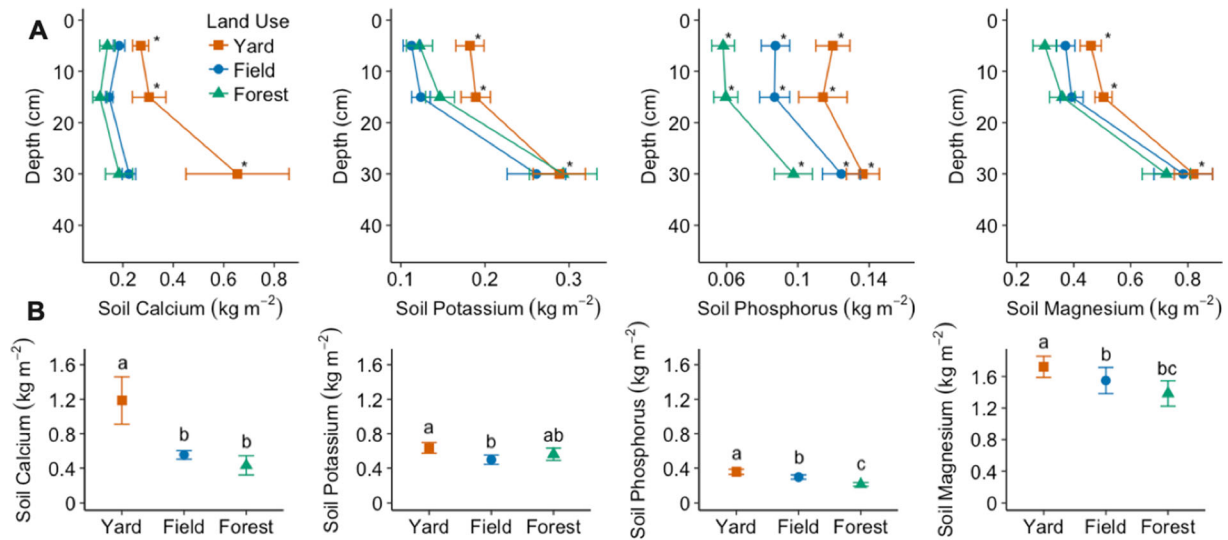


Figure 2. Residential ecosystem land use mean \pm SE soil nutrient pools (**A**) by depth and (**B**) from 0- to 40-cm depth. Asterisks indicate significant differences ($\alpha = 0.05$) across land uses by depth. Lowercase letters indicate significant differences of means by land use.

development. Forest soils lost $0.0002 \text{ kg P m}^{-2} \text{ y}^{-1}$, as yard and field soils accumulated P at an equivalent rate (slope contrast, $p < 0.01$). From 0- to 10-cm soil depth, where land-use effects were more evident, fields accumulated S relative to forests (Figure S4, slope contrasts, $p < 0.05$).

Soil Nutrients, pH and CEC Across Residential Ecosystem Land-Use Intensities

Contrary to our hypothesis, we found that C-depleted yard soils had a CEC similar to forest soils (Figure S6A) and time since development was unrelated to CEC. Carbon-rich forest soils had a CEC 14% greater than fields ($p < 0.01$). But C-depleted yard soils had a CEC 10% greater than field soil CEC ($p < 0.05$).

In support of our leading hypothesis, we found that yard soil pH decreased since residential ecosystem establishment (Figure S7) and as reported in the previous section, older yard soils contained less Ca and K than younger yards. But soil pH was on average greater in yards than forests (Table S1).

In our alternative hypothesis, we expected more intense land use to result in uncorrelated nutrient cycles and soil properties. We found that soil CEC and C, CEC and pH, and Fe-Al and pH, were unrelated in yards but covaried in less intensively used fields and forests (Figure 4A, C, S8A, S8B, slope contrasts, $p < 0.05$). Soil C and Fe-Al were positively correlated ($p < 0.01$), but land use did

not affect their relationship strength. We thus support our alternative hypothesis that yard use would disassociate soil properties that were correlated in less intensively used lands.

Soil C, P and S co-varied significantly on the basis of GLMMs. Soil S concentrations were tightly associated with C concentrations across the three land uses (Figure S5, $p < 0.0001$). In forests, a one mg S kg^{-1} soil increase was associated with an increase of $0.21 \pm 0.016 \text{ g C kg}^{-1}$ soil, an increase greater than in yards or fields (slope contrasts, $p < 0.01$). However, there was a stronger positive correlation between soil S and P in yards than in fields or forests (slope contrast, $p < 0.05$). Soil C had similar relationships with P and S.

Yard Nutrient Cycles in Response to Management

We report soil pool responses to yard management in 0- to 10- and 10- to 20-cm depths where grass roots are concentrated and land-use effects are often conspicuous. Intensively managed (IM; commercially managed, clippings removed, mown weekly in growing season) yard soils were depleted by $0.02 \pm 0.006 \text{ kg K m}^{-2} \text{ y}^{-1}$ and $0.04 \pm 0.02 \text{ kg Mg m}^{-2} \text{ y}^{-1}$ from 0- to 20-cm depth relative to unchanged non-intensively managed (NIM; managed by resident, clippings remain, mown bi-monthly to monthly in growing season) yard soil K and Mg pools (Figure 5A, B, slope contrasts, $p < 0.01$, $p < 0.05$). Recent yard management

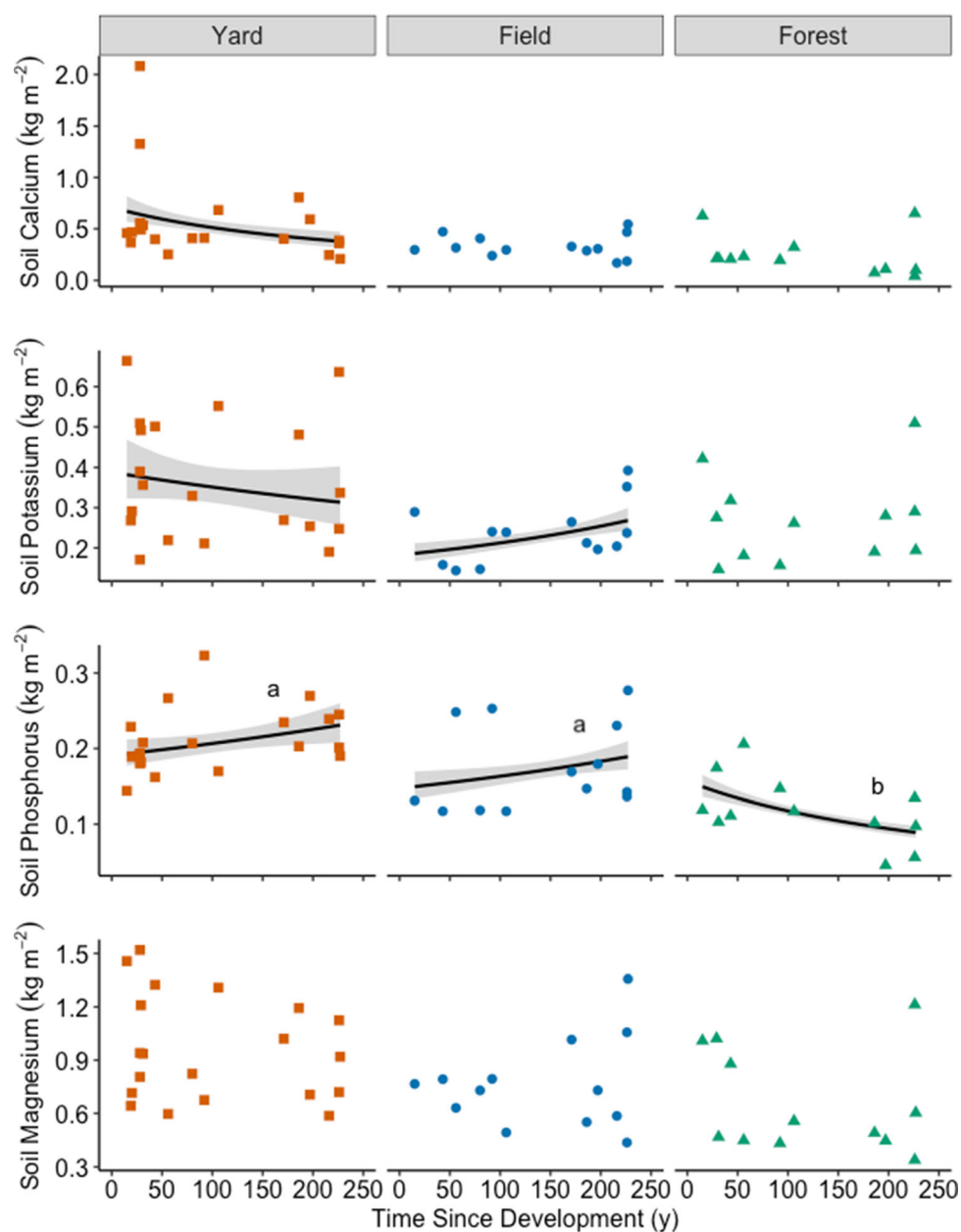


Figure 3. Mean soil nutrient pools from 0- to 20-cm depth in response to residential ecosystem land uses since development. Shaded confidence intervals shown from the best fit models among candidates when a significant effect of time since development ($\alpha = 0.05$). Lowercase letters indicate significantly different slopes.

intensity did not alter soil Ca pools, as all yard soils were on average Ca-enriched.

There was a non-significant trend of IM yard soil CEC decreasing by $1.0 \pm 0.49 \text{ cmol}^+ \text{ kg soil}^{-1} \text{ y}^{-1}$ relative to stable NIM CEC (Figure S6B, slope contrast, $p = 0.08$). IM yard soils accumulated $0.006 \pm 0.003 \text{ kg P m}^{-2} \text{ y}^{-1}$ from 0- to 20-cm depth as NIM yards lost $0.004 \pm 0.001 \text{ kg P m}^{-2} \text{ y}^{-1}$ (slope contrast, $p < 0.01$). IM yards soils accumulated $0.0035 \pm 0.0014 \text{ kg S m}^{-2} \text{ y}^{-1}$ from 0- to 10-cm depth (Figure 5D). IM yard soils were depleted

by $0.034 \pm 0.014 \text{ kg Al m}^{-2} \text{ y}^{-1}$ from 0- to 10-cm depth as NIM soil Al pools remained the same (slope contrast, $p < 0.05$).

As in our soil analyses, we observed identical variations in yard plant nutrient concentrations and pools by management group. Plants in IM yards were on average 46–47% less concentrated with K and S ($p < 0.01$) and 54–66% more concentrated with Fe and Al than NIM yard plants ($p < 0.01$). There was a non-significant trend of higher Mg concentrations in IM yard plants than

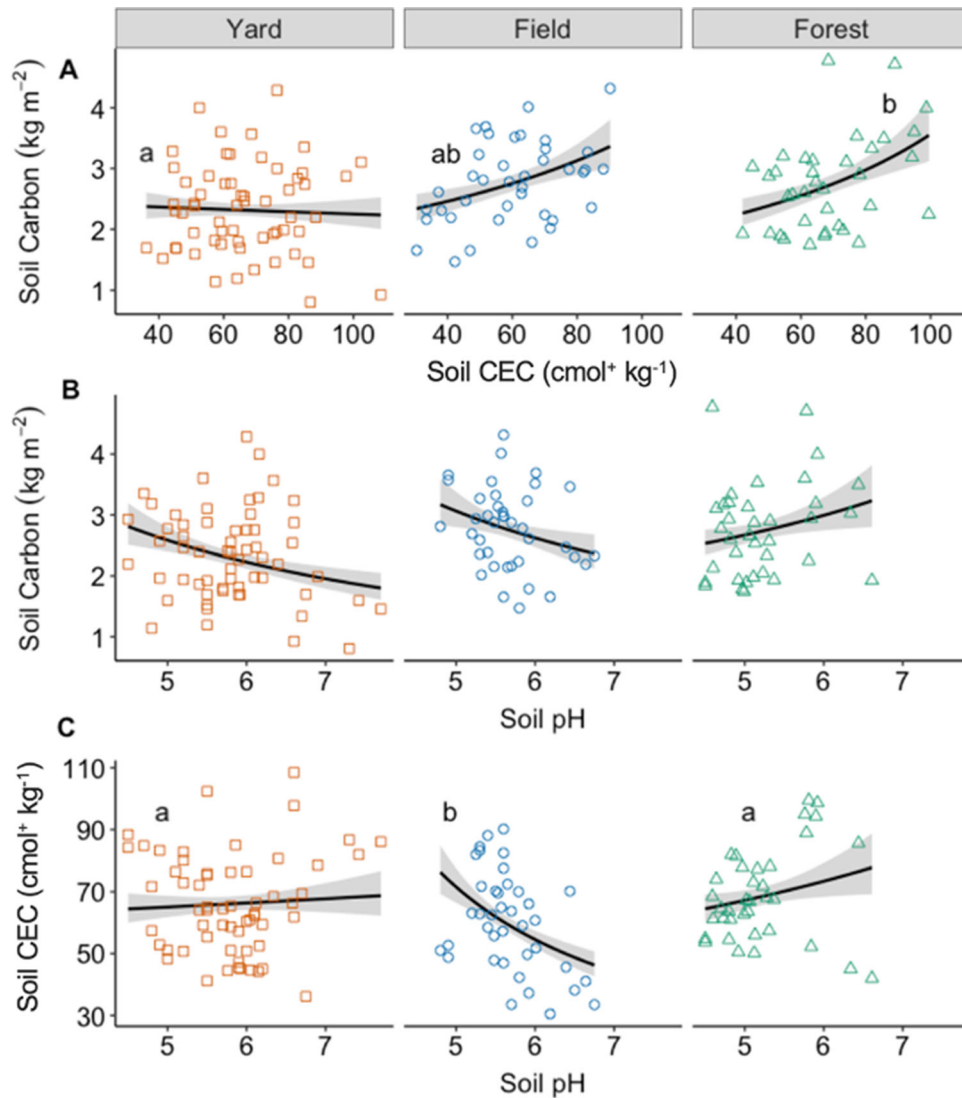


Figure 4. The association of (A) soil cation exchange capacity (CEC) and (B) pH with soil carbon pools and (C) soil pH with CEC, averaged over 0- to 40-cm depths across residential ecosystem land uses. Lowercase letters indicate significantly different slopes ($\alpha = 0.05$). Points represent all depths sampled. Shaded 95% confidence intervals shown.

NIM yard plants ($p = 0.09$). There were no differences in lawn plant Ca or P across management groups. We estimated that in ten years intensive yard management exported 2.9 times more S, 1.7 times more K and 2.4 times more Mg in clippings per unit land area than the average pool of those nutrients from 0- to 40-cm soil depth (Table S2).

DISCUSSION

Alteration of Nutrient Cycles as Land Use Intensified in Residential Ecosystems

Residential ecosystem land use and management, over decades and centuries, has altered the cycling of Ca, K, Mg, P and S, with distinct differences

among managed yards, adjacent minimally managed fields and adjacent unmanaged forests. Our results show that soil nutrient pools were larger in yards than fields or forests, irrespective of recent yard management intensity. This suggests that yards were likely enriched with nutrients by unintentional (that is, land conversion and subsequent use) and intentional (that is, fertilization by managers) human activities. But, in support of our leading hypothesis that C-depleted soils would contain fewer base cations, we found that C-poor old yard soils contained less Ca and K than decades-old yards.

After centuries of use and management, old yard soils had either lost some capacity for nutrient

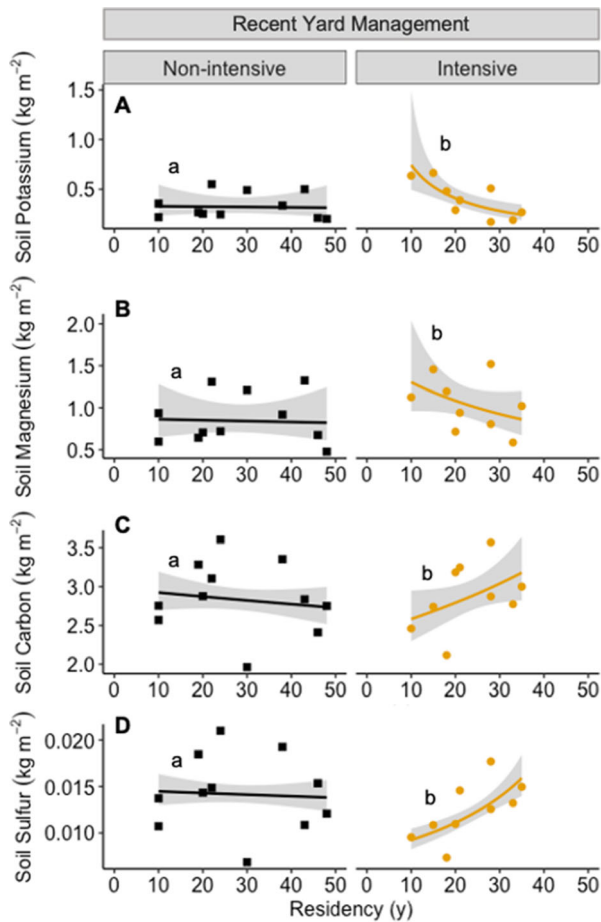


Figure 5. Mean yard soil potassium (**A**) and magnesium (**B**) pools from 0- to 20-cm depth and soil carbon (**C**) and soil sulfur (**D**) pools from 0- to 10-cm depth, in response to decades of recent yard management in residential ecosystems. Intensive managers mow weekly and export clippings. Non-intensive managers mow bimonthly and leave clippings. Lowercase letters indicate significantly different slopes ($\alpha = 0.05$). Shaded 95% confidence intervals shown from the best-fit models among competing models.

storage, required greater nutrient uptake to maintain growth, or received fewer nutrient inputs than younger yard soils. The cumulative loss of nutrients from yards where managers exported grass clippings could have been substantial, as we later discuss. In addition, we observed lower soil pH in older yards than younger yards. This could reflect less responsiveness to liming and the cumulative acidifying effect of N inputs contributing to soil base cation depletion (Wang and others 2018). Or, contrary to what our interviews suggested, older yards could have been limed less in recent times, resulting in acidic, Ca- and K-depleted soils.

We revealed the effects of residential ecosystem land use by studying a land use-intensity gradient

which controlled for site-specific pre-development land-use legacies and soil forming history (Peach and others 2019). However, our results that show changes in soil nutrient pools since development should be interpreted cautiously. It is difficult to verify past events, particularly prior to the tenure of present-day residents on centuries-old parcels. To the best of our ability, we supported the assumption that land uses were managed similarly since residential development and yards received relatively similar nutrient inputs. Yet, it is possible that commercially managed yards and recently established yards received more nutrient inputs, while older, homeowner-managed yards received fewer nutrient inputs. If so, this suggests that old yard soils were not Ca and K depleted per se, but rather contained fewer base cations than highly enriched young yard soils. With these caveats in mind, we focus our discussion on soils, with nutrient pools orders of magnitude larger than the biomass pools we measured (Figures S1, 2B).

Yard soils contained less C than neighboring fields and forests (Peach and others 2019), which we expected to result in less CEC and decreased base cation pools relative to fields and forests. But, we did not observe this. In support of our alternative hypothesis, we found that soil C, its derived CEC and base cation pools were unrelated in yards. Yard soils stored 11–93% times more Ca, K and Mg from 0- to 40-cm depth than fields or forests. Others have observed base cation enrichment of yard upper soils (Campbell and others 2014; Yesilonis and others 2016), which likely resulted in part from intentional management (for example, liming) and unintentional land use-related fertilization (for example, pet waste). Large yard upper soil base cation pools could also be due to house construction-related excavation that redistributed base cation-rich deep soil to the surface. On average, yard soils were less acidic than forest soils, which could reflect the effect of base cation accumulation in yards and less weathering of base cations in forest soils (Table S1). Soil base cations buffer soil pH, which can mitigate their loss, even in SOM-depleted yard soils, thereby leading to no association between soil C and base cation pools.

Soils in our study shared similar parent material and were low in clay content (2–3%) indicating that SOM, with pH-dependent exchange sites, were likely the primary CEC source (Johnson 2002). Yet, we observed that yard soil CEC was greater than fields and not different than forests (Figure S6A). Inorganic sorption, such as on secondary Al and Fe oxyhydroxides present in yard soils from mineral weathering, could explain the higher CEC. Yard

soil Fe pools from 0- to 20-cm depth were larger than forest Fe pools (Figure S2). Moreover, sorption and precipitation of Ca and P in yard soils, which were more concentrated with Ca and P than forest and field soils, could be an important retention mechanism. Lastly, the larger Ca, Mg and K pools in yard soils than fields or forests probably increased soil pH. Higher pH could buffer pH-dependent CEC sites, leading to greater sorption capacity even with less soil C. Yet, we observed that in yard soils CEC and pH (Figure 4) and pH and Fe-Al (Figure S8) were unrelated. Thus, we suggest that yard use decoupled soil C from CEC and inorganic mechanisms of nutrient accumulation may be playing an important role in yards.

Aboveground yards and fields contained similar quantities of nutrients, but forests stored substantially more base cations due to their larger biomass (Figure S1). In forests, nutrients immobilized in bolewood, branches, annual foliage, associated understory vegetation and the organic horizon likely resulted in their smaller upper soil base cation pools than yards and fields. In general, nutrients in trees cycle less actively between above- and belowground compartments relative to the rapid turnover of labile forbs and grasses. Notably, field and forest aboveground biomass K pools were similar, while yard biomass contained less K than forests. This may reflect legacies of K fertilization in fields and K depletion in forests and yards. Aboveground biomass nutrients, despite being a small fraction of the soil pool, if consistently exported could impact nutrient cycling and primary productivity.

In summary, when comparing 200-year-old yards with younger yards and assuming that there was relatively consistent land use and management of yards, we hypothesize that soil C and base cations are correlated. If this hypothesis is correct, this would suggest a coupling of biogeochemical cycling of C and base cations. This agrees with prior work showing Ca can promote soil C accumulation (Rowley and others 2018). In contrast, in support of our alternative hypothesis, when comparing yards with adjacent fields and forests, we show that soil C and CEC were unrelated in yards. This suggests inorganic nutrient sorption mechanisms may be more important in yard soils than in fields and forests. We expected soil C and CEC to be linked based on research in wildlands. We instead suggest that the depletion of soil C leading to decreasing CEC is no longer an active mechanism in human-dominated yards as it is in minimally managed forests.

Organic Nutrient (P, S) Cycles in Residential Ecosystems

We expected soil C losses to lead to decreases in organic nutrient pools (P, S) in residential ecosystems, in accordance with SOM stoichiometry (Kirkby and others 2013; Buchkowski and others 2019). Alternatively, P and S could accumulate from fertilization and their cycles could be dissociated from soil C dynamics by disturbance (Lajtha and others 2014; Keiser and others 2016). We instead observed a tight association of soil S and C across land uses and the accumulation of P in managed grasslands. Here, we focus on P and S, as others have shown fields accumulated N and yard management altered N dynamics (Peach and others 2019).

Yards and fields accumulated soil P since development, with their soil P pools an average 42% larger than forest soil pools. We hypothesize that this increase in P is due to greater fertilization and animal waste inputs to yards and fields than forests but could also result from net retention in the plant-soil system. Pet excrement can be a primary P source—up to 76% of P inputs to watersheds in St. Paul, Minnesota, USA—which also helped explain high exchangeable P in residential soils of Madison, WI, USA (Hobbie and others 2017; Ziter and others 2018). Further, pH increases from base cation fertilization may have increased precipitation of P with Ca. Since forests were not fertilized, we expect that their soil P depletion relative to managed grasslands was due to P immobilization in wood or net leaching losses. Conversely, in yards, a larger soil P sink could have mitigated P losses (Carpenter and others 1998; Bennett and others 2005).

Additional mechanisms for P accumulation in yards and fields may be due to denser, shallow rooting by grasses compared to larger, sparser tree roots. More effective uptake would lead to tighter cycling. In addition to hydroxyapatite precipitation, yards contained more Fe from 0- to 20-cm depth than forests. Larger yard soil Fe pools, indicative of more Fe as a secondary oxyhydroxide, would aid in P retention. These findings contradict our hypothesis that accumulation of Al and Fe as secondary oxyhydroxides in forest soils would help retain nutrients, especially P. Instead, grass-dominated land uses in residential ecosystems appear to contain legacy P with possibly greater capacity to buffer P release as the sink saturates (Goyette and others 2018; Kusmer and others 2018).

We found that soil S was tightly associated with soil C across residential ecosystem land uses (Figure S5). S or C, depending on their availability and

biotic demand for these nutrients, could limit or stimulate organic nutrient cycling. This would explain our observation of S and C depleted yard soils and S and C enriched field soils. Sulfur was two orders of magnitude less concentrated in upper soils than C, but C is often in high demand by microbes. S or C inputs, much like N, could stimulate biota and soil C gains (Fornara and others 2012; Rao and others 2014; Schulte-Uebbing and others 2018). We also measured more soil S in fields adjacent to older homes than fields adjacent to newer homes (Figure S4). Greater S deposition in fields near the intercepting forest edge and fertilization (for example, wood ash), could contribute to S and C accumulation in field soils (Weathers and others 2001; Smith and others 2018).

Yard Management of Nutrient Fluxes

We hypothesized that frequent yard mowing and subsequent grass clipping removal (intensive management; IM) would result in base cation and organic macronutrient depletion. We found mowing regularly and removing grass clippings was associated with yard soil K and Mg depletion over decades of recent management (Figure 5). These results suggest that for some base cations, but not the organic nutrients, managers who remove yard grass clippings deplete nutrient pools if there are not compensatory inputs.

Yard grass tissues were two to four times more concentrated with K than Mg, Ca, or P, further suggesting removal of clippings contributed to soil K losses. If two-thirds of lawn grass leaves are clipped and removed once a week over a five-month growing season, we estimate that the cumulative mass of K and Mg exported per unit land area exceeds the average soil K and Mg pool from 0- to 40-cm soil depth over that same area (Table S2). Because yard soils, relative to forest soils, had similar CEC and Al concentrations (as a proxy for secondary oxyhydroxides) and a higher pH, it does not appear that greater downward export by leaching was responsible for decreases in K and Mg pools. Thus, we hypothesize that lawn clipping removal can be a primary nutrient loss pathway. Regularly mown yards where clippings were exported likely heavily depend on fertilization. If land managers leave biomass in residential ecosystems they can reduce fertilizer use and sustain productivity (Kopp and others 2002; Groffman and others 2016).

Intensively managed yard soil S increases, from 0- to 10-cm soil depth, tightly covaried with C over decades of recent management (Figure 5C, D). We

estimated that after four decades, IM yard soils accumulated an average 0.01 kg S from 0- to 10-cm depth. Fertilization and mowing-related deposition of S in IM lawns could lead to the accumulation of soil S and C. Yet, accumulation of S and C in the upper soil did not compensate for yard establishment- and use-related soil C depletion to greater depths (Peach and others 2019). In summary, yard grass clipping removal likely contributed to yard soil K and Mg losses, while the tight covariance of S and C suggested their accumulation or depletion was coupled. Managers who fertilize can compensate for nutrient depletion to meet biological demand, but a fraction of these inputs are lost if they export biomass.

CONCLUSION

Residential ecosystems, a dominant feature of the Anthropocene, contain nutrient levels that are not well explained by theories generated from wildlands research. Theories from the wildlands predict ecosystems accumulate nutrients as biomass grows over a timescale of decades to centuries. We show that soil C-depleted yard soils contained an average 83% more Ca, 19% more K, 16% more Mg and 34% more P in their soils from 0- to 40-cm depth than neighboring field and forest soils. But, centuries-old yard soils were depleted in Ca and K relative to decades-old yards. In recent decades, export of yard grass clippings was related to the net loss of soil K and Mg from the upper soil. We estimate that land managers who removed grass clippings for one decade exported 1.7 to 2.4 times the average K and Mg contained in yard soils from 0- to 40-cm depth. This rate of nutrient export is unsustainable and requires compensatory inputs. Yet, we hypothesize that inputs of S and C can stimulate organic nutrient cycles and C accumulation.

Land managers can achieve efficient nutrient cycling by doing more with less—less mowing, leaving biomass and maintaining nutrient inputs that do not exceed sinks—which is key to sustainable land management. Ecosystem nutrient dynamics are difficult to manage given competing interests and uncertainties inherent to global change. Nonetheless, our work can guide managers, planners and policymakers as they consider how residential ecosystems contribute to legacies of nutrient accumulation and depletion. We hope to inspire research in human-dominated environments, where theory can be developed and solutions to environmental challenges can be found.

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DATA AVAILABILITY

Data is available upon request or at morganpeach.com.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval Resident participation was approved by Dartmouth College's Committee for the Protection of Human Subjects.

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