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Biogeochemical and socioeconomic drivers of above- and below-ground carbon stocks in urban residential yards of a small city

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ABSTRACT

Research on patterns of below-ground carbon (C) storage in urban lawns has focused on biogeochemical mechanisms, with human activities playing an important but somewhat secondary role. By contrast, studies of above-ground vegetation in urban areas have emphasized socioeconomic factors that influence greenness, abundance, and diversity, without explicitly considering biogeochemical mechanisms. Here we examine how both biogeochemical and socioeconomic factors influence patterns of C storage in urban yards both above- and below-ground. We combined measurements of above- and below-ground C stocks in 36 lawns located in the small city (<200,000 residents) of Manchester, New Hampshire, USA with a suite of indicators such as housing age, population density, median income, home value, and residence duration that we obtained from public assessment databases, the decennial census, and the American Community Survey. We found that for this small city, housing age was the only variable that was significant and positively correlated with soil C stocks. Median income, median resident age, and percent married couples were significant and positively related with above-ground biomass C, with housing age playing a secondary role. The disparity that we observed in how biogeochemical and socioeconomic factors shape the distribution of C stocks in urban yards highlights the need for management approaches tailored to sequestering C in above- versus below-ground pools. Understanding the C dynamics of small cities is critical to ensuring that urban areas of all sizes can enhance urban C storage and minimize urban C loss.

1. Introduction

Urban areas are important contributors to the global carbon (C) cycle. Although they currently make up only 3% of the U.S. land surface (Nickerson, Ebel, Borchers, & Carriazo, 2011) and 0.5% of global land cover (Schneider, Friedl, & Potere, 2009), urban emissions account for ~70% of global fossil-fuel carbon dioxide (CO_2) emissions (Gurney et al., 2015). With the proportion of the world's population residing in cities expected to exceed 66% by 2050 (United Nations, 2015), understanding some of the biogeochemical and socioeconomic drivers that shape the urban ecosystem may inform efforts to reduce such high emission rates.

Residential landscapes make up 50% of urban areas (Loram, Tratalos, Warren, & Gaston, 2007), and thus play a significant role in driving urban CO_2 dynamics. Much of the focus on managing the C cycle in residential areas has centered around building emissions, smart growth, and other anthropogenic factors associated with greenhouse gas emissions storage or loss (e.g., the climate action plan Greenovate Boston 2014, www.cityofboston.gov). However, the biogenic uptake, storage, and release of C in vegetation and soils also contribute to urban C dynamics (Decina et al., 2016; Lerman & Contosta, 2019). Most of an urban residential parcel consists of the biogenic C pool and its associated fluxes, containing an actively managed yard with vegetation such as turf grass (i.e., lawn), a scattering of trees and shrubs, and vegetable or flower gardens (Robbins, 2007, Larson, Harlan, & Yabiku, 2009). Some parcels also include unmanaged remnant forest patches, usually at the periphery. Vegetation within a yard can sequester C in biomass, with trees comprising the preponderance of this C sink (e.g., Jo & McPherson, 1995, Golubiewski, 2006). Below-ground, soils can store at least twice as much C as above-ground biomass, and thus may provide substantial C storage in urban residential areas (Jo & McPherson 1999, Golubiewski, 2006; Edmondson, Davies, McHugh, Gaston, & Leake, 2012).

Past research focused on understanding patterns of soil C storage beneath urban yards has generally examined how biogeochemical factors, as mediated by human activities, influence soil C stocks. These human-mediated biogeochemical drivers of soil C storage in urban yards include disturbance history, climate, soil type, plant species composition, and management regime (Golubiewski, 2006, Raciti et al., 2011; Campbell, Seiler, Wiseman, Strahm, & Munsell, 2014; Huyler, Chappelka, Prior, & Somers, 2014; Townsend-Small & Czimczik, 2010; Law & Patton, 2017). Within this context, prior land use and housing age may be construed as aspects of disturbance history that may affect below-ground C storage. The transition from native or agricultural land use to residential land typically depletes soil C due to the stripping of most, if not all, vegetation and topsoil during home construction

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(Pouyat, Groffman, Yesilonis, & Hernandez, 2002). Following construction, revegetation of the parcel through the planting of grass, trees, shrubs, and other ornamental plants slowly rebuilds soil C, both by reducing erosion and by rebuilding the soil organic matter pool via the microbial decomposition and stabilization of plant litter (Jo & McPherson, 1995; Huyler et al., 2014; Law & Patton, 2017). Thus, soils in older neighborhoods may store more C as they recover from the disruption of land use conversion and the removal of vegetation and topsoil (Golubiewski, 2006, Raciti et al., 2011; Campbell et al., 2014). Likewise, human settlement patterns that drive population density and the urban heat island may exert climatic controls on soil C storage below urban lawns by accelerating litter decomposition and soil respiration given higher temperatures in more densely populated areas (Groffman et al., 2006b; McDonnell et al., 2008)). Human decisions, such as the selection of ornamental trees or adding fill, replace native vegetation and affect plant species composition and soil type (Pouyat, Szlavecz, Yesilonis, Groffman, & Schwarz, 2010; Horn, Escobedo, Hinkle, Hostetler, & Timilsina, 2015; Yesilonis, Pouyat, Russell-Anelli, & Powell, 2016). Finally, management activities such as irrigation, fertilization, and mowing may alter C soil stocks, with soil C levels generally higher with greater levels of management intensity (Kaye, McCulley, & Burke, 2005; Pouyat, Yesilonis, & Golubiewski, 2009; Campbell et al., 2014; Townsend-Small & Czimczik, 2010; Law & Patton, 2017).

Prior studies elucidating patterns of above-ground vegetation have tended to examine how social forces shape urban vegetation cover, greenness, and biodiversity, without explicitly focusing on biogeochemical determinants of above-ground C stocks. Population density and housing age, common indicators that represent these social forces (e.g., Giner, Polsky, Pontius, & Runfola, 2013; Grove et al., 2006; Grove, Locke, & O'Neil-Dunne, 2014; Strohbach & Haase, 2012; Lin et al., 2017), are two of the same metrics used in research examining human-mediated biogeochemical patterns of below-ground C stocks. In the context of above-ground vegetation, population density often serves as a proxy for urban development intensity and the amount of plant-able space in urban areas due to the displacement of vegetation with buildings, roads and other grey infrastructure (Grove et al., 2006). Thus, as the number of people per square km is higher, vegetation cover is lower (Smith et al., 2006; Grove et al., 2006; 2014), in turn reducing above-ground C storage (Strohbach & Haase, 2012). Housing age is also often correlated with urban intensity whereby older neighborhoods have more impervious surface due to infill construction, and consequently, less plant-able space (Loss, Ruiz, & Brawn, 2009; Robbins and Birkenholtz, 2003; Troy, Grove, O'Neil-Dunne, Pickett, & Cadenasso, 2007). Regardless of size, older parcels might be expected to have older and larger trees, though vegetation cover in similarly aged neighborhoods may not be uniform due to different rates of growth and mortality (Grove et al., 2006).

In addition to population density and housing age, prior research has also quantified how other socioeconomic factors such as income and lifestyle might shape human behavior and urban development, which in turn, may affect urban C storage in a variety of ways. Socioeconomic status, such as income, has predicted the richness, abundance, and greenness of vegetation based on the idea of the "luxury effect" (*sensu* Hope et al., 2003), in which higher income households make greater investments in landscaping their private yards and public spaces, resulting in greater plant diversity and density (Hope et al., 2003, Kirkpatrick, Daniels, & Davison, 2011, Luck, Smallbone, & O'Brien, 2009, Jenerette et al., 2013, Leong, Dunn, & Trautwein, 2018). Social stratification theory posits that an empowered citizenry has greater influence on investment in public spaces, leading to increased numbers of street trees and canopy cover (Grove et al., 2014). Expanding upon income and homeownership, Grove et al. (2006) noted that different lifestyles and life stages (e.g., marital status, age of household) also influence the type of vegetation and their subsequent management. This "ecology of prestige" reflects group identity, adherence to social norms, and perception of social status, and provides additional context for land management decisions (Grove et al., 2006; Grove et al., 2014). Since the yard serves as an extension of the home (Clayton, 2007), the space may be designated to provide different social functions, which might vary amongst lifestyles. Families with young children might prefer and manage more yard area to provide a safe play space (Larson et al., 2009). The duration a resident has lived at a location might also dictate landscaping behaviors and preferences. Long-time residents of the arid city of Phoenix, AZ demonstrated an affinity for lawns and other mesic-type landscapes due to legacy effects of "greening the desert" in older neighborhoods (Yabiku, Casagrande, & Farley-Metzger, 2008).

Absent from these prior efforts to characterize soil C storage and vegetation cover in urban yards is a framework that explicitly integrates the socioeconomic and biogeochemical factors that may impact above- and below-ground urban C dynamics alike. While previous research has examined how both socioeconomic and ecological drivers influence rates of fertilizer application and soil nitrogen loss (e.g., Law, Band, & Grove, 2004), we are not aware of prior work that has deliberately combined these drivers for understanding the cycling of C in urban vegetation, soils, or both. Here we propose that the concept of "bio-geo-socio-chemistry" (*sensu* Groffman et al., 2006a) might encapsulate the ways in which biogeochemical cycling interacts with human activities to influence patterns of C storage in urban yards both above- and below-ground. For example, motivation to adhere to social norms may drive people to differentiate between their front yards, which are public-facing, and back yards, which are private and hidden from view, when making landscaping decisions regarding plantings and/or when determining the frequency of mowing and irrigation (Nassauer, Wang, & Dayrell, 2009; Visscher, Nassauer, & Marshall, 2016; Locke et al., 2018). However, the extent to which cultural norms dictate management activities may vary as function of parcel size, with larger parcels (e.g., > ~0.2 ha) containing a higher proportion of unmanaged area that can store greater amounts of C in vegetation (Nassauer et al., 2014; Visscher, Nassauer, Brown, Currie, & Parker, 2014). Management activities might also differ according to socioeconomic status, such that higher income households are more likely to apply lawn fertilizer and irrigate (Harlan, Yabiku, Larsen, & Brazel, 2009; Jenerette et al., 2013; Law et al., 2004; Polsky et al., 2014; Steer et al., 2006; Templeton et al., 1999). Patterns in management decisions, whether due to differences in front yard versus backyard management, within small versus large parcels, or because of socioeconomic status and identity, may have cascading effects on biogeochemical pathways of C storage above- and below-ground (Qian et al., 2003; Pouyat, Yesilonis, & Nowak, 2006; Raciti et al., 2011).

Moreover, the preponderance of research examining urban C storage in vegetation and soils as well as vegetation cover, greenness, and, diversity has occurred in cities with populations exceeding 1.5 million residents (e.g., Jo & McPherson, 1995; Martin, Warren, & Kinzig, 2004; Golubiewski, 2006; Pouyat et al., 2009; Jenerette et al., 2011; Fissore et al., 2012; Lowry, Baker, & Ramsey, 2012; Giner et al., 2013; McPherson, Xiao, & Aguaron, 2013; Grove et al., 2014; Raciti, Hutyra, & Newell, 2014). Small cities, defined as having between 50,000 to 200,000 residents (Organization for Economic Cooperation and Development, 2019), are experiencing some of the fastest growth of all urban areas in the U.S. (U.S. Census, 2018). Yet these small cities are much less represented in the urban C cycle literature, though examples do exist (e.g., Edmonson et al., 2012; Campbell et al., 2014; Huyler et al., 2014; Lerman & Contosta, 2019; Strohbach & Haase, 2012), and it is not clear whether small cities exhibit unique patterns of C storage

The goal of this study was to explore how bio-geo-socio-chemical factors impact above- and below-ground C stocks in urban yards of a small city. We hypothesized that C storage in vegetation and soils: 1) increases with housing age as yards recover from disturbance that occurred during land use conversion (below-ground) and as vegetation matures (above-ground); and 2) decreases with higher population density due to a combined effect of higher temperatures accelerating

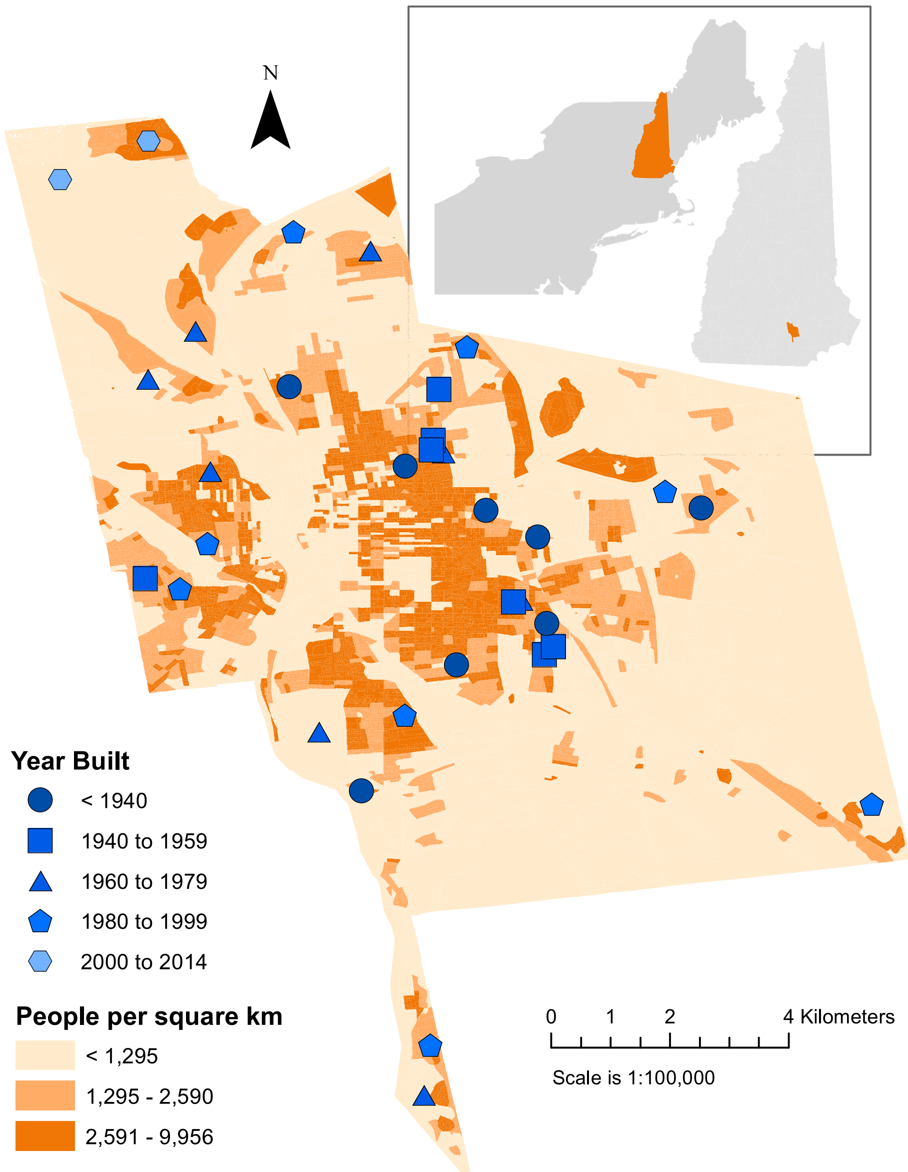

Fig. 1. Map of sampling sites across a range of population densities (people km^{-2}) and housing ages. The location of Manchester, New Hampshire, USA is shown in the upper right inset.

below-ground soil C loss and lack of space constraining the presence of above-ground vegetation that would sequester C. We also explored how additional bio-geo-socio-chemical variables affected C storage in urban lawns, for example examining whether the concept of the "luxury effect," in which higher income households are associated with greater vegetation cover, might extend to include greater C stocks above- and below-ground.

2. Methods

2.1. Study area

This study took place in 36 single-family parcels located across Manchester, NH, USA (Fig. 1). Manchester is the largest city in New Hampshire, with a population of 109,565 residents as of the 2010 decennial census (U.S. Census Bureau, 2012a). Median housing age is 61 years and ranges from housing built in the 17th century during the period of European colonization to brand new housing stock. Mean annual temperature (1981–2010) is 10 °C, with average summer temperatures at 21 °C and average winter temperatures at −2°C. Average total annual precipitation is 1132 mm, spread equally throughout the year and occurring as snow during winter (Arguez et al., 2012).

2.2. Plot establishment

Housing parcels were selected throughout the city to represent the range of two bio-geo-socio-chemical factors hypothesized to affect C storage in urban ecosystems: population density and housing age. Population density was assessed using 2010 U.S. Census data TIGER shapefiles at the census block scale (U.S. Census Bureau, 2012a). Housing age was determined with the City of Manchester tax assessment database that was administered by Vision Government Solutions, Inc., and was translated into geographic information system (GIS) shapefiles by the City of Manchester, NH Geographic Information Systems Department. To ensure equal representation of old and new housing stock, and dense and sparsely populated neighborhoods, we binned population density into three categories that aligned with U.S. Census definition of the urban core and surrounding census blocks: >2590 people per km^2, between 1295 and 2590 people per km^2, and <1295 people per km^2 (U.S. Census Bureau, 2012b). We grouped housing age into five categories based on the normal distribution of housing ages throughout the city. Age classes were based on time since 2014, which was the most recent year included in the tax assessment database at the time of the study, and included: >75 years old (built before 1940), 56 – 75 years old (built from 1940 to 1959), 36–55 years old (built from 1960 to 1979), 16–35 years old (built from 1980 to 1999), and 0–15 years old (built from 2000 to 2014). We then performed a stratified random sampling from these two classification schemes, where strata include all possible combinations of five age classes and three density classes, resulting in 15 total groups. Five percent of single-family homes were randomly selected within each stratum, producing a database of 750 individual parcels. We focused on owner-occupied single-family homes to avoid potential complications in obtaining landowner permissions for rented residential and commercial properties. We split the dataset of 750 parcels in half to create two separate databases, each with 375 addresses, which allowed us to establish sites over a two-year period from two distinct sampling pools. Response rates were similar between years. In 2015, we received 47 replies (or a 12.5% response rate), 40 of which indicated interest in participating in our research. In 2016, we received 77 replies (or a 20% response rate), 66 of which indicated interest. For each year, we had to remove about a third of the potential sites where attempts to contact residents failed due to incorrect email addresses or phone numbers (usually due to illegible handwriting), lack of response to email or phone follow-ups, or residents ultimately declining to participate. From the remaining responses, we selected 36 sampling sites (2015: n = 19; 2016: n = 17) based on representativeness of a range of population density and housing age classes that we hypothesized would impact our results, as well as other yard characteristics such as availability of space in the yard portion (i.e., space available after accounting for the presence of decks, porches, swing sets and other permanent structures) of the parcel for sample collection. When applying these more qualitative criteria, we removed only three yards from the site selection process, primarily because the amount of yard available for sampling once we accounted for yard structures had soil that was shallow to bedrock and thus would not have allowed for soil coring. The numbers of parcels in each of our population density, housing age, and density × age classes are provided in Table S1, with two to three parcels selected per strata. Because a primary aim of this study was to examine relationships between C storage and socioeconomic factors that may influence management decisions, we focused our efforts on the managed portion (the 'zone of care'; Nassauer et al., 2014) of each parcel, i.e., the yard. Prior research has established that management decisions exert greater influence on C storage dynamics in yards than on remnant natural vegetation within a parcel (Nassauer et al., 2014; Visscher et al., 2014). For each parcel, we determined the yard area by first overlaying the Vision Government Solutions parcel map onto 2015 1-ft aerial photos of Manchester, NH obtained from the New Hampshire Geographically Referenced Analysis and Information Transfer System (NH GRANIT; scale = 1:1000, minimum mapping unit = 3 m). We then drew a polygon representing the non-yard portion of the parcel, which included unmanaged vegetation, such as remnant forest patches at the edges of the parcel, as well as paved surfaces such as driveways. This was similar to the approach of Currie, Kiger, Nassauer, Hutchins, Marshall, Brown, Riolo, Robinson, and Hart (2016), who used aerial photointerpretation to divide parcels into distinct "ecological zones." We followed the protocol of Robbins and Birkenholz (2013) to determine the footprint of the house within the parcel, which was calculated as the house square footage divided by number of floors. Thus, yard area was the total lot size minus the footprints of both the building and other non-yard features determined from aerial photography as described above. The proportion of the parcel occupied by yard varied between 52% and 99%, with a median of 91%.

2.3. Soil sampling and determination of below-ground C stocks

Soil sampling occurred between July and December 2015 and between July and September 2016 following the methods of Conant, Smith, and Paustian (2003). Three areas within each yard were selected for coring, one in the front yard and two in the back. Sampling was divided between front and backyards both for practical purposes (front yards were smaller than back yards) and to enable the testing of hypotheses about how C stocks may vary within different areas of a yard (Nassauer et al., 2009; Visscher et al., 2016; Locke et al., 2018). At each area, a soil core was taken using a nine cm hollow-core concrete drill attached to a gas-powered auger. Soils were sampled to 50 cm depth, divided into ten cm depth increments, and returned to the University of New Hampshire (UNH) for analysis. All soil was kept at 4 °C until processing. Each sample was weighed field wet (for bulk density determination), sub-sampled to measure soil moisture (105 °C overnight), sieved (2 mm), and air-dried. The upper 10 cm of each soil core was analyzed for pH using at 1:1 soil to water suspension, and the upper 20 cm was analyzed for texture according to Kettler, Doran, and Gilbert (2001). Bulk density was calculated for each 10-cm depth increment using the moisture-corrected weight of the fine earth fraction divided by the total soil volume (Throop, Archer, Monger, & Waltman, 2012). For each depth increment, a 10 g subsample was also finely ground in a ball-mill grinder and analyzed in triplicate for total C and N concentration on a Perkin Elmer 2400 CHNS/O Series II Elemental Analyzer at the UNH Water Resources Research Center instrument (n = 3 analytical replicates per sample). Soil C content on an aerial basis (i.e., kg C m^{-2}) was determined by multiplying carbon concentration by bulk density.

2.4. Vegetation sampling and determination of above-ground C stocks

Above-ground carbon storage in tree biomass was determined in October and November 2016 using the methods outlined by Jo and McPherson (1995) and Nowak and Crane (2002). Briefly, diameter at breast height (DBH = 1.37 m) was measured for all trees ≥5 cm DBH that were located either inside the yard or within 1 m of the yard edge (e.g., not in an adjacent remnant forest). Location was recorded as "front yard" or "back yard," with trees located in the "side yard" considered to be "back yard" trees as they were largely behind fences and concealed from public view. Due to the limited species-level information for most urban areas (Troxel, Piana, Ashton, & Murphy-Dunning, 2013), biomass was estimated using generalized allometric equations for North American tree species from (Chojnacky et al., 2013), which were based on Jenkins, Chojnacky, Heath, and Birdsey (2003). More detailed information on the equation parameters used for species and species groups is in SI Table 2. Biomass values were multiplied by 0.8 to adjust for trees grown and maintained in residential areas, which have lower biomass than what would be predicted using a forest-derived equation (McPherson, Nowak, & Rowntree, 1994; Nowak, 1994; Currie et al., 2016). Estimates of above-ground biomass were then converted to C by multiplying them by 0.5 and were scaled to units of kg C m^{-2} by dividing total biomass within each yard by the yard area. To determine the kg C m^{-2} of trees in the front yard, we divided the biomass of these trees (kg C) by the total yard area (m^2). We did the same calculation to estimate the biomass of trees in the back yard. Recognizing that vegetation cover in similarly aged neighborhoods may not be uniform due to different rates of growth and mortality (e.g., Grove et al., 2006), we also separated total above-ground biomass for the entire yard into three diameter size classes to evaluate how trees of different sizes might vary as a function of housing age and other bio-geo-socio-chemical variables. We used the U.S. Forest Service Forest Inventory and Analysis (FIA) classification system to delineate trees as saplings (<12.7 cm DBH); pole timber (≥12.5 cm DBH < 22.9 cm for softwoods; ≥ 12.5 cm DBH < 27.9 cm for hardwoods); and saw timber (≥22.9 cm for softwoods; ≥27.9 cm for hardwoods).

Table 1
Descriptions of independent variables used to analyze biogeochemical and socioeconomic drivers of above- and below-ground C storage at the scale of the parcel and/or the census block within the study area. Values are medians (min, max).

Variable set	Variable name	Description	Parcel-level	Census block group-level
General	Housing Age	Age of building in years as of 2014 (continuous)	53 (8, 149)	61 (0, 315)
	Population Density	Number of people per km^2 as of 2010 (continuous)	NA	1930 (58, 5971)
Biogeochemical	Soil Texture	Percentage of silt in upper 20 cm of soil	9 (0, 27)	NA
	Canopy Composition	Percentage of deciduous trees	78 (0, 100)	NA
Social Stratification	Household Income	Mean household income (1000$)	NA	61 (31, 115)
	Home Value	Total assessed value (1000$)	197 (167, 391)	200 (0, 953)
	Occupied Housing	Percentage occupied housing	NA	97 (71, 100)
	Non-White	Percentage non-white residents	NA	4 (0, 31)
Lifestyle Behavior	Marriage Status	Percentage of households with married residents	NA	54 (17, 91)
	Residence Duration	Duration of residence (years)	9 (0, 31)	8 (0, 54)
	Age of Residents	Age of residents (years)	NA	42 (28, 79)

2.5. *Bio-geo-socio-chemical factors and urban C stocks*

In addition to the factors that guided our selection of urban yards (i.e., housing age and population density), yard size, and sampling locations within yards (i.e., front versus back), we considered nine additional variables to evaluate how biogeochemical and socioeconomic factors might explain patterns of above- and below-ground carbon storage (Table 1). Biogeochemical variables included percent silt (Huyler et al., 2014) and proportion of above-ground biomass comprised of deciduous species (e.g., Trammell, Pouyat, Carreiro, & Yesilonis, 2017). Socioeconomic variables were informed by Giner et al. (2013) and Grove et al. (2014) and included the social stratification proxies of median household income, median home value, percent non-white residents, and percent vacant parcels. Lifestyle behavior metrics consisted of marriage status, residence duration, and median age of residents. All socioeconomic data were available from the 2010 U.S. Census for the 27 census block groups within which parcels were located, except for median household income, which was obtained from the American Community Survey 5-year estimation product (2006–2011) aggregated at the census block group level. We assumed that demographic characteristics within a census block group were somewhat homogenous (Jenerette et al., 2007). Nevertheless, to determine how representative individual parcels were of the census block in which they were situated, we calculated the median, minimum, and maximum value of variables for which we had both parcel and/or census scale data (Table 1).

2.6. *Statistical analysis*

We used a mixed effects modeling framework that included ANOVA-type and regression-type models to examine how C stocks in urban yards differed with yard location, yard size, housing age, population density, and other possible bio-geo-socio-chemical drivers. All statistical analyses were conducted in R 3.5.2 (R Core Team, 2018). Preliminary data analysis based on the protocol of Zuur, Ieno, and Elphick (2010) revealed the presence of outliers for above-ground tree biomass, median income and residence duration, and these were removed from the dataset prior to modeling. In addition, Mantel tests showed no significant spatial autocorrelation among yards for below-ground soil C ($P = 0.58$) or above-ground tree biomass C ($p = 0.26$), and thus spatial autocorrelation was not fit as a random effect in any of the models.

The ANOVA-type models explored: 1) how soil C stocks varied among depth increments (e.g., soil C densities can decline with depth and may also be less responsive to above-ground drivers); 2) how above-ground biomass C stocks differed across diameter size classes; and 3) how below-ground soil C and above-ground tree biomass C stocks varied between front and back yards. We utilized the protocol outlined in Zuur et al. (2010) using the *nlme* package (Pinheiro, Bates, DebRoy, & Sarkar, 2016) to determine whether possible random intercept effects of yard, and variance structures, such as yard location or depth increment, improved overall model fit. We did not nest yard within census block group since we had almost as many census blocks groups ($n = 27$) as yards ($n = 36$) and did not want to over-parameterize our models. Dependent variables were soil C and tree biomass C stocks. Independent variables were yard location (front or back), depth increment (for soil C), tree diameter size class (for above-ground tree biomass), and interactions between depth increment × yard location and size class × yard location. Model-level *P*-values were obtained using the *anova* function to generate type II Wald's F-tests. Pairwise differences between means were evaluated using the *glht* function in the *multcomp* package (Hothorn, Bretz, & Westfall, 2008), with Bonferroni corrections for multiple comparisons.

Regression-type models evaluated how above- and below-ground C stocks might vary as a function of a suite of bio-geo-socio-chemical variables. Dependent variables were stocks of C in soils and above-ground tree biomass. Independent variables were hypothesized bio-geo-socio-chemical variables listed in Table 1. Because C stocks can vary with yard size (Nassauer et al., 2014; Visscher et al., 2014), we also examined relationships between yard area and both above- and below-ground C. We used yard-level data as independent variables where both yard and census block data existed, and either yard or census block data when only one or the other data source was available. We ran separate regressions for each depth increment (0–10, 10–20, 20–30, 30–40, 40–50 cm) as well as across the entire soil profile sampled (0–50 cm). Likewise, we evaluated the relationship between tree biomass and our suite of bio-geo-socio-chemical variables for each diameter size class (sapling, pole timber, saw timber) and for all size classes combined. When modeling above-ground biomass as a function of housing age, we used both linear regression and quadratic regression. Quadratic regression recognizes the potential lagged effects of changes in neighborhood socioeconomic status on vegetation cover (Grove et al., 2006). It can also capture an inflection point in above-ground biomass, which may linearly increase with housing age for about 50 years, after which biomass may decline due to tree mortality (Grove et al., 2006). Initial data exploration indicated that aside from the relationship between housing age and tree biomass, none of the other models exhibited nonlinear behavior. Preliminary data analysis also showed that none of the regression model fits were improved with the addition of a random intercept effect of yard. We thus concluded that the data fit the assumptions of linear modeling (Littell, Henry, & Ammerman, 1998) and were able to use a standard linear regression approach. We supplemented univariate regression analysis with multiple regression models that included predictors exhibiting significant ($\alpha = 0.05$) relationships with either above- or below-ground C stocks as single regression terms. Prior to performing these multiple regression models, predictor variables were evaluated for collinearity using the variance inflation factor statistic (VIF) (Zuur et al., 2010). Following multiple regression, we partitioned the relative contribution of each term to the total model r^2 using the *lmg* function in the *relaimpo* package (Grömping, 2006). Finally, we examined the relationship between below-ground soil C

Table 2
General site characteristics. Values are medians (min, max) within the entire yard, within front yards, and within back yards. Soil bulk density values are for the 0–10 cm depth increment. Soil C stocks are for the entire soil profile sampled (0–50 cm), and tree variables (number of trees, number of species, and biomass C stock) are for all diameter size classes combined. The areal extent of front versus back lawns was not measured; we only calculated total yard area without differentiating between front and back.

	Entire yard	Front yard	Back yard
Parcel area (m^2)	1100 (500, 8000)	—	—
Yard area (m^2)	1073 (309, 7576)	—	—
Bulk density ($g\ cm^{-3}$)	0.76 (0.30, 1.24)	0.82 (0.48, 1.23)	0.76 (0.30, 1.24)
Soil C stock ($kg\ m^{-2}$)	10.83 (6.53, 18.74)	12.55 (9.10, 16.69)	11.19 (6.53, 21.37)
Number of trees	3.5 (0, 46)	2 (0, 13)	4.5 (0, 43)
Number of species	3 (0, 9)	2 (0, 7)	4 (0, 8)
Biomass C stock ($kg\ m^{-2}$)	1.43 (0, 4.78)	0.10 (0, 2.80)	0.56 (0, 4.78)

storage to 50 cm and total above-ground C storage in tree biomass to both compare their relative pool sizes and to explore how they might co-vary across the urban residential landscape.

3. Results

3.1. Soils and vegetation within yards

Soil textural classes within our study yards varied between loamy sand and silt loam, and pH ranged between 4.12 and 6.99. We did not find any carbon-containing artifacts in the soils we sampled, such as coal ash or asphalt, though soils within one of the study yards contained glass shards that we treated in the same way as rocks when determining bulk density. For above-ground vegetation, we measured a median of 3.5 individual trees and three species per yard (Table 2). The most commonly occurring species were white cedar (*Thuja occidentalis* L., n = 73), crab apple (*Malus sylvestris* P. Mill., n = 51), white pine (*Pinus strobus* L., n = 45), arborvitea (*Thuja* spp., n = 42), and red maple (*Acer rubrum*, n = 41), with red oak (*Quercus rubra* L., n = 13), Norway maple (*Acer platanoides* L., n = 13) and silver maple (*Acer saccharinum* L., n = 12) also somewhat common. We measured 15 individual deciduous trees that we were not able to identify, and for these we used general allometric equations for hardwood species to estimate biomass. In a few instances, there were no trees on the property, either because they did not meet our size class threshold of 5 cm at DBH, or because the presence of stumps indicated recent removal. General yard characteristics are located in Table 2. A full list of species measured within our 36 study sites is in SI Table 2.

Neither below- nor above-ground C stocks significantly varied ($P > 0.05$) with location in the yard (front or back). Soil C stocks across the entire soil profile sampled (0–50 cm) had median values of 12.55 $kg\ m^{-2}$ in front yards and 11.19 $kg\ m^{-2}$ in backyards (Table 2). While median tree biomass C stocks in front yards (0.10 $kg\ m^{-2}$) were lower than those in backyards (0.56 $kg\ m^{-2}$), this was not a statistically significant difference (Table 2).

Overall, C stocks did not vary with yard size. We found no significant relationship between yard size and below-ground soil C density ($P > 0.05$; data not shown). Except for saw-timber, there was also no significant correlation between above-ground biomass C and yard size. For the saw-timber size class, however, vegetation C stocks were higher in smaller yards ($P = 0.04$, $r^2 = 0.13$; Fig. S1).

3.2. Below-ground C stocks

Soil C stocks differed among depth increments and with housing age. Differences in soil C within the profile were highly significant ($P < 0.0001$; Fig. 2), with soil C densities highest closest to the soil surface and decreasing with depth. Pairwise comparisons indicated that soil C stocks significantly differed among the 0–10, 10–20, and 20–30 cm depth increments, and were similar between 30–40 and 40–50 cm depth increments. In addition to differences within the soil profile, soil C stocks also varied with housing age, with soil C levels higher in older parcels.

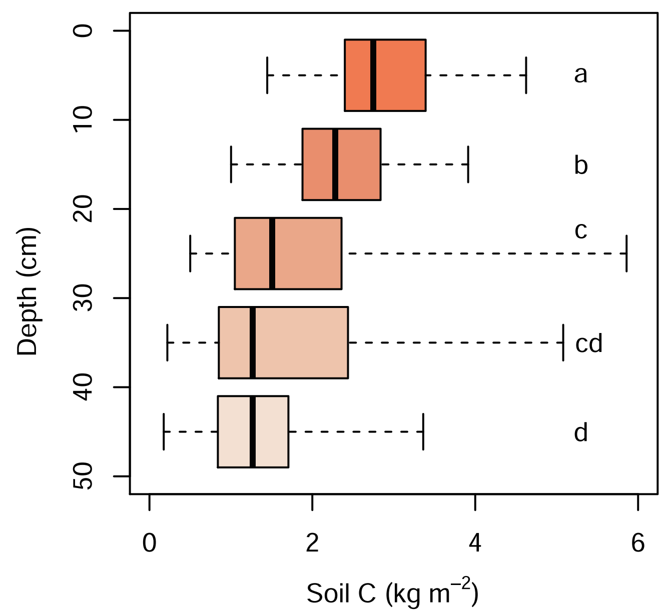

Fig. 2. Soil carbon stocks across depth increments in the soil profile. Lower case letters indicate pairwise differences in soil C stocks between depth increments.

Significant, positive relationships between housing age and soil C stocks occurred at all measured depth increments, except at the 40–50 cm increment ($P = 0.07$, $r^2 = 0.17$, Table 3, Fig. 3). We also found a significant, positive correlation between housing age and total soil C stocks summed across the soil profile, with housing age explaining 26% of the variation in soil C from 0 to 50 cm ($P = 0.015$, $r^2 = 0.26$; Table 3).

Aside from housing age, none of the other bio-geo-socio-chemical variables included in our analysis explained patterns in soil C stocks (Table 3). Factors such as population density, percent silt, and percentage of deciduous trees exhibited no significant relationships with soil C. Social stratification proxies of median household income and median home value were likewise uncorrelated with below-ground soil C densities at all depth increments measured. Similarly, variables associated with lifestyle behavior and group identity, such as median age of residents within the census block, were unrelated to soil C at both the soil surface and throughout the soil profile.

3.3. Above-ground C stocks

Carbon stored in above-ground tree biomass varied among diameter size classes ($P < 0.0001$), with saw timber sized trees exhibiting significantly higher C stocks as compared to either saplings or pole timber trees (Fig. 4). Of these diameter classes, only saw timber trees showed a marginal relationship with housing age when modeled with either a linear or quadratic regression ($P = 0.057$; $r^2 = 0.16$ for the quadratic model of C stocks in saw timber biomass as a function of housing age;

Table 3
Summary statistics for regression models evaluating how soil C stocks at five depth increments and across the entire sampled profile varied as a function of biogeochemical and socioeconomic variables. Values in bold indicate statistical significance at α ≤ 0.05.

		0–10 cm		10–20 cm		20–30 cm		30–40 cm		40–50 cm		0–50 cm	
Variable Set	Variable Name	*P*	r^2	*P*	r^2	*P*	r^2	*P*	r^2	*P*	r^2	*P*	r^2
General	Housing Age	**0.001**	**0.28**	**0.036**	**0.10**	**0.037**	**0.11**	**0.033**	**0.16**	0.067	0.13	**0.015**	**0.26**
	Housing Age^2	**0.003**	**0.27**	0.110	0.07	0.119	0.08	0.111	0.11	0.134	0.12	**0.038**	**0.25**
	Population Density	0.907	−0.03	0.764	−0.03	0.354	0.00	0.671	−0.04	0.875	−0.05	0.714	−0.05
Biogeochemical	Soil Texture	0.282	0.01	0.704	−0.03	0.349	0.00	0.088	0.09	**0.004**	**0.33**	0.066	0.14
	Canopy Composition	0.698	−0.03	0.942	−0.03	0.521	−0.02	0.450	−0.02	0.979	−0.06	0.443	−0.02
	Household Income	0.786	−0.03	0.923	−0.03	0.518	−0.02	0.253	0.02	0.367	−0.01	0.742	−0.06
Social Stratification	Home Value	0.150	0.035	0.910	−0.03	0.828	−0.04	0.903	−0.05	0.954	−0.06	0.981	−0.06
	Occupied Housing	0.606	−0.02	0.380	−0.01	0.336	0.00	0.554	−0.03	0.813	−0.05	0.889	−0.06
	Non-White	0.674	−0.03	0.127	0.04	0.656	−0.03	0.521	−0.03	0.429	−0.02	0.645	−0.05
Lifestyle Behavior	Marriage Status	0.371	−0.01	0.399	−0.01	0.298	0.00	0.456	−0.02	0.832	−0.05	0.876	−0.06
	Residence Duration	0.606	−0.02	0.074	0.07	0.054	0.10	0.349	0.00	0.363	−0.01	0.235	0.03
	Age of Residents	0.140	0.04	0.228	0.02	0.879	−0.04	0.957	−0.05	0.568	−0.04	0.874	−0.06

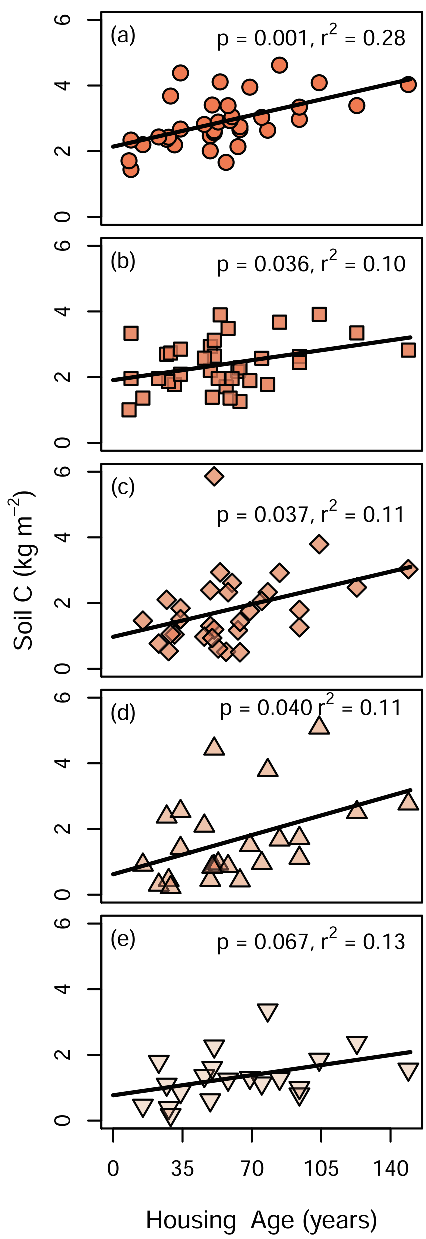

Fig. 3. Soil C stocks as a function of housing age at: (a) 0–10 cm; (b) 10–20 cm; (c) 20–30 cm; (d) 30–40 cm; and (e) 40–50 cm.

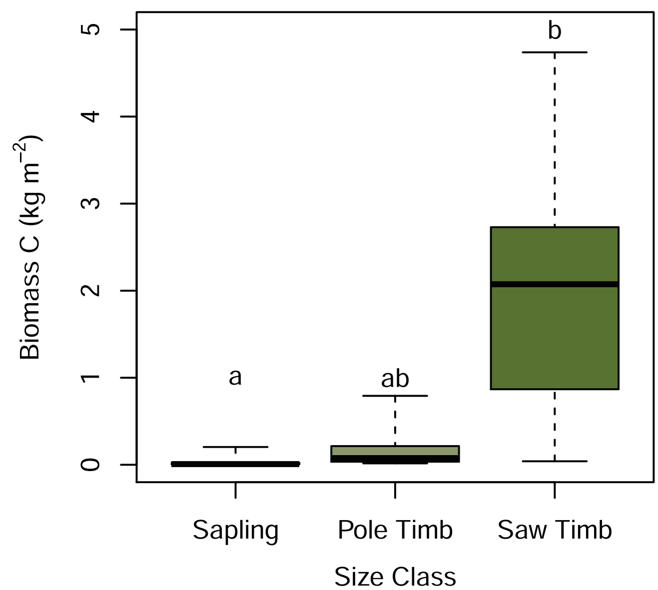

Fig. 4. Above-ground biomass C stocks distributed across three diameter size classes: saplings, pole timber, and saw timber. Lower case letters indicate pairwise differences in biomass C stocks between size classes.

Table 4). In this case, biomass C increased in saw timber-sized trees until housing age reached ~50 years, after which it declined (Fig. 5). Other significant relationships between above-ground C stocks and bio-geo-socio-chemical variables largely occurred for total above-ground C stocks as opposed to individual diameter classes. However, C stocks in pole timber sized trees showed a significant and positive relationship with percent of households classified as married ($P = 0.015$; $r^2 = 0.22$). Likewise, C stocks in saw timber sized trees were significantly positively correlated with median income ($P = 0.036$; $r^2 = 0.16$; Table 4).

Total above-ground biomass C stocks (combining all diameter size classes) varied as a function of both median income and median age of residents, but not with any of the other bio-geo-socio-chemical variables in the data set. When modeled singly, median income and median age were both significant predictors of above-ground biomass C (median income: $P = 0.008$, $r^2 = 0.20$, Fig. 6a; median age: $P = 0.011$, $r^2 = 0.18$; Fig. 6b). When added into a multiple regression model, the combination of median income and median resident age explained 27% of the variation in above-ground biomass C (model-level $P = 0.008$, $r^2 = 0.27$; Fig. 6c), with the contribution of each model term to the model-level r^2 approximately equal (relative importance of median income and median resident age in contributing to total r^2 was 49% and 51%, respectively). Other variables such as housing age and percent silt

Table 4
Summary statistics for regression models evaluating how above-ground biomass C stocks for three diameter size classes and for all size classes combined varied as a function of biogeochemical and socioeconomic variables. Values in bold indicate statistical significance at α ≤ 0.05.

		Sapling		Pole Timber		Saw Timber		Total Tree Biomass	
Variable Set	Variable Name	*P*	r^2	*P*	r^2	*P*	r^2	*P*	r^2
General	Housing Age	0.458	−0.03	0.351	0.00	0.846	−0.04	0.667	−0.03
	Housing Age^2	0.764	−0.10	0.619	−0.05	0.057	0.16	0.198	0.04
	Population Density	0.668	−0.05	0.705	−0.04	0.431	−0.02	0.139	0.04
Biogeochemical	Soil Texture	0.211	0.04	0.157	0.05	0.631	−0.03	0.621	−0.03
	Canopy Composition	—	—	—	—	—	—	—	—
	Household Income	0.246	0.03	0.944	−0.05	**0.036**	**0.16**	**0.008**	**0.20**
Social Stratification	Home Value	0.492	−0.03	0.168	0.05	0.085	0.09	0.142	0.04
	Occupied Housing	0.589	−0.05	0.964	−0.05	0.918	−0.04	0.358	0.00
	Non-White	0.135	0.09	0.256	0.02	0.194	0.03	0.363	0.00
Lifestyle Behavior	Marriage Status	0.550	−0.04	**0.015**	**0.22**	0.822	−0.04	0.488	−0.02
	Residence Duration	1.000	−0.07	0.361	−0.01	0.164	0.04	0.410	−0.01
	Age of Residents	0.404	−0.02	0.819	−0.05	0.059	0.11	**0.011**	**0.18**

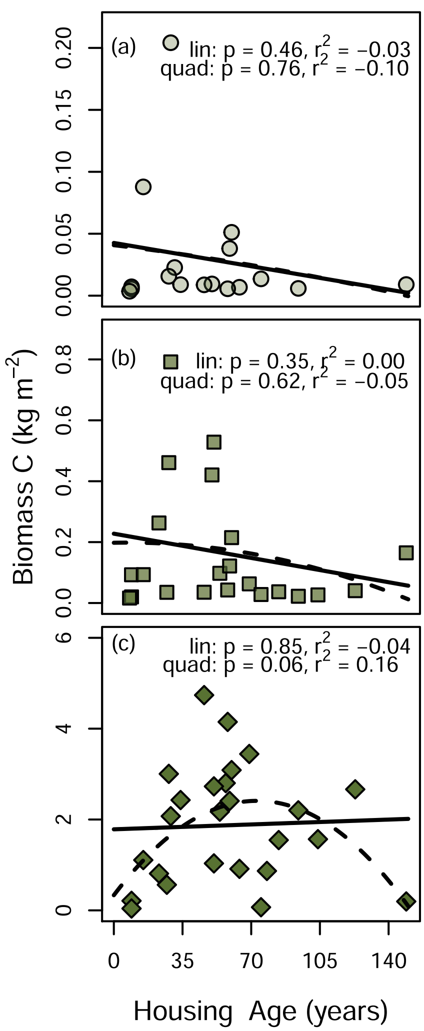

Fig. 5. Above-ground biomass C stocks as a function of housing age for three diameter size classes: (a) saplings; (b) pole timber; and (c) saw timber. Each panel shows the fit of two regression models. Linear regression fits are depicted as solid lines, and quadratic regressions are shown as dashed lines.

showed no significant relationship with total above-ground C density (Table 4). Social stratification and lifestyle behavior proxies such as total assessed home value and percent and residence duration also were not significant predictors of biomass C (Table 4).

3.4. Relationship between above- and below-ground C stocks

There was no significant correlation between above- and below-ground C stocks ($P = 0.789$; $r^2 = -0.05$). When summed across the entire soil profile from 0 to 50 cm, soil C stocks ranged from 6.53 to 18.74 kg m^{-2}, with a median value of 10.83 kg m^{-2}. These values were an order of magnitude higher than those for above-ground tree biomass C stocks, which ranged from 0 to 4.78 kg m^{-2}, with a median of 1.42 kg m^{-2} (Table 2).

4. Discussion

4.1. Housing age and below-ground C stocks

Our results supported our hypothesis that soil C stocks would be higher as housing age increased. Other studies have also reported a positive correlation between time since development and soil C density (Scharenbroch, Lloyd, & Johnson-Maynard, 2005; Townsend-Small & Czimczik, 2010; Raciti et al., 2011; Selhorst & Lal, 2013; Campbell et al., 2014; Huyler et al., 2014). This positive correlation is to be expected: the transition to residential land can involve the disturbance or removal of topsoil during home construction, which may be followed by the addition of low-organic matter fill (e.g., Pouyat et al., 2002). In a residential yard, the subsequent planting of grass helps to stabilize the soil, preventing wind and water erosion, while also building up the soil organic matter pool through the microbial decomposition and stabilization of C inputs from grass clippings (if not collected during mowing), thatch, root litter, and root exudates (Jo & McPherson, 1995; Huyler et al., 2014; Law & Patton, 2017). Over the chronosequence we sampled, which ranged from 8 to 149 years, we estimate that soils in Manchester yards accumulated C at a rate of 0.05 kg C m^{-2} y^{-1}. This is comparable to Raciti et al. (2011), who observed a soil C accumulation rate of 0.082 kg C m^{-2} y^{-1} at residential sites in Baltimore, MD that had previously been in agriculture.

Beyond housing age, soil C stocks did not vary with any of the other bio-geo-socio-chemical variables in our data set. Soil physical conditions, such as texture, might be expected to influence C storage, such that finer-textured soils with more silt and clay content would physically and chemically protect greater amounts of organic matter (Burke et al., 1989; Plante, Conant, Stewart, Paustian, & Six, 2006). Unlike Golubiewski (2006) and Huyler et al. (2014), we did not observe any significant correlations between percent silt content and soil C stocks, which may have been due to yard management (e.g., irrigation or applying fertilizer) overriding any role that soil textural characteristics might play in soil C stabilization (Trammell et al., 2017). Since we did not explicitly consider these management practices, we cannot rule out their importance in influencing correlations between soil texture and C

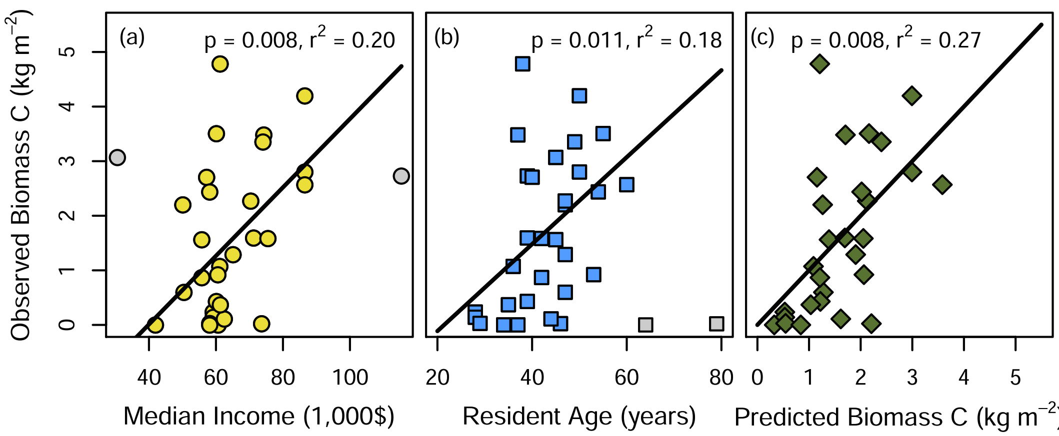

Fig. 6. Above-ground biomass C stocks as a function of: (a) median income; (b) resident age; and (c) predicted above-ground biomass determined from a multiple regression model that includes both median income and resident age. Points that appear in gray were removed from the analysis as outliers.

stocks. Likewise, the composition of above-ground canopy vegetation—i.e., trees— might be predicted to drive patterns of soil C stocks, with more labile litter inputs from deciduous trees resulting in lower soil C densities as compared to more recalcitrant litter inputs from conifers (e.g., Finzi, Van Breemen, & Canham, 1998). We found no relationship between the percent above-ground biomass comprised of deciduous broadleaved trees and soil C stocks (Table 2). The common practice of raking and removing leaf litter in autumn (e.g., Fissore et al., 2012) may decouple above-ground tree canopy composition and below-ground C storage in residential yards, explaining this lack of correlation.

As with more traditional biogeochemical indicators of soil texture and tree canopy composition, none of the socioeconomic metrics that we included in our analysis were significantly correlated with below-ground C storage. Irrigation and applying fertilizer are common lawn management practices that can elevate soil C content compared to lawns with less intensive management regimes (Campbell et al., 2014; Huyler et al., 2014) or compared to native land cover (Kaye et al., 2005; Pouyat et al., 2009). Social stratification theory predicts that greater affluence (which is associated with income) and higher social status (which may be associated with race) result in more intensive management (Grove et al., 2006; Zhou, Troy, Morgan Grove, & Jenkins, 2009; Giner et al., 2013), and perhaps greater soil C storage. At the same time, factors associated with the "ecology of prestige," or lifestyle behaviors related to variables such as marital status, age, and family size might also drive patterns in yard management (Grove et al., 2006; Grove et al., 2014), and by extension, might also drive patterns in soil C stocks. We did not directly compare management activities with the socioeconomic variables or soil variables included in our study, and thus cannot explicitly connect them to the soil C storage dynamics we documented in Manchester yards. However, in a study of six metropolitan areas located across the U.S., Polsky et al. (2014) noted weak correlations among socioeconomic status, lifestyle behavior, and management activities such as fertilization and irrigation within cities. Future work might determine whether homogenous patterns of yard management, both in Manchester and elsewhere, drive a lack of relationship between socioeconomic variables and soil C stocks.

4.2. Above-ground C storage and the role of socioeconomic drivers

Our findings partially supported our hypothesis that C storage would be higher as housing age increased; the significant, quadratic relationship we observed between biomass C and housing age mirrored reports from Grove et al. (2006) and Troy et al. (2007), who, like us, noted that vegetation cover increased until parcels were between 40 and 50 years old and then declined. Trees in older neighborhoods might experience higher rates of mortality due age-related loss (Nowak, Kuroda, & Crane, 2004). It is not clear whether newly planted trees can ultimately replace the C sink lost when larger and older trees are removed from the landscape, though we recognize that tree species, potential pest outbreaks, drought, storm damage and other urban conditions could further complicate relationships between tree age and mortality. Encouraging householders to replace moribund trees, in concert with cities investing resources into tree planting in older parks, streets, and private parcels could help maintain or expand C storage in woody biomass in old and new neighborhoods alike.

In addition to changing in tandem with housing age, we also found that above-ground C stocks varied as a function of median income, which is a proxy for social stratification. While previous research has not explicitly examined the relationships among socioeconomic status and biomass C storage (but see Raciti et al., 2014), prior work has demonstrated similar linkages with vegetation cover, greenness, and diversity (Kirkpatrick et al., 2011, Luck et al., 2009, Jenerette et al., 2013; Schwarz et al., 2015; Leong et al., 2018). Our results extend this phenomenon of the "luxury effect" (*sensu* Hope et al., 2003) to include increases in biomass C storage that accompany higher median incomes. We only observed this correlation for the saw timber size class (≥22.9 cm DBH for softwoods; ≥27.9 cm DBH for hardwoods) or the combination of all size classes (Table 4), illustrating that higher median incomes were associated with the biomass of larger trees. This pattern, which fits with previous studies demonstrating a positive relationship between income and canopy cover (Schwarz et al., 2015), may have resulted from higher income homebuyers purchasing properties with larger trees, given that properties with large trees sell for higher prices (Anderson & Cordell, 1988). Higher income residents may also be more able to pay arborists to maintain larger trees as opposed to simple removal (Heynen, Perkins, & Roy, 2006, Warren, Ryan, Lerman, & Tooke, 2011).

Perhaps less intuitive than the ability for "money to buy green" (e.g., Schwarz et al., 2015)—or in this case for higher income households to be associated with greater amounts of above-ground biomass C—were the linkages that we observed between lifestyle behavior metrics and vegetation C stocks. The significant, positive relationship we found between percent married residents and C stocks in pole-sized timber trees resonates with the idea that married couples might manage their yards for family recreation, and thus for fewer, larger trees (Giner et al., 2013). Likewise, the significant correlation observed between resident age and total above-ground biomass C may reflect a phenomenon whereby older residents manage for greater numbers of trees and less turf due to the less intensive management required for maintaining trees compared with weekly maintenance for lawns (Troy et al., 2007).

Finally, we generally did not detect a relationship between yard size and C storage, which might be expected given that median parcel size was 1100 m^2, or 0.27 acres. This is below the size thresholds that

Nassauer et al. (2014) and Visscher et al. (2014) established, beyond which parcels are more likely to contain large trees or remnant vegetation that store more C. However, we did observe that saw-timber sized trees were significantly, negatively correlated with yard size. We interpret this negative relationship as arising from the fact that three of the four largest parcels in our dataset (yard size >0.3 ha) were also three of the newest (housing age <10 years) and therefore did not contain many large trees. Removing these three parcels from the analysis results in no significant correlation between yard size and above-ground biomass C (Fig. S1).

4.3. Linkages between below- and above-ground C stocks in residential yards

The only clear pattern we detected in examining above- and below-ground C stocks in urban residential yards were differences in their magnitude. Median soil C density (10.83 kg m^{-2}) was almost eight times higher than median tree biomass C (1.43 kg m^{-2}). In other words, soil C from 0 to 50 cm comprised 88% of the total biogenic C pool in the yards we studied. This contribution of soil C to the total pool corresponds to values reported previously (e.g., ~80% in Chicago, USA, Jo & McPherson, 1995; 84% in Leicester, UK, Edmonson et al., 2012). Few other studies have directly compared above- and below-ground dynamics in residential areas across gradients of housing age, population density, or socioeconomic status, though Huyler et al. (2014) found a positive relationship between tree biomass C (as kg of C) and soil C stocks (as kg C m^{-2}) in residential yards across Auburn, AL, USA. However, most of these correlations were related to distance of the soil core to a nearby tree, suggesting that temperature and moisture conditions beneath trees might drive soil C dynamics more than management activities or tree litter inputs (e.g., Edmondson et al., 2016; Lerman & Contosta, 2019).

The lack of relationship between below- and above-ground C stocks is not surprising given the differential controls that seem to shape their distribution across urban yards. This disparity might also highlight the homogeneity of one aspect of yard maintenance, lawn care, while describing the heterogeneity of another aspect of yard maintenance, tree care. Assuming turf grass, clippings, and root litter are the dominant sources of organic matter entering the soil in residential yards whose productivity would be enhanced with irrigation and fertilization (e.g., Zirkle, Lal, & Augustin, 2011; Law & Patton, 2017), the ubiquitous desire for a neat, manicured, green lawn (Robbins, 2007) may tend to synchronize lawn management activities irrespective of socioeconomic status (Polsky et al., 2014). The result would be similar for inputs of water, fertilizer, and turf litter into soils, which would gradually accumulate C over time. By contrast, if the planting or maintenance of large trees is unaffordable to some, perhaps due to income constraints (Heynen et al., 2006), or less desirable to others, depending on lifestyle, then the distribution of C in above-ground biomass might vary to a greater extent across the residential landscape.

Disparity in patterns of below- and above-ground C storage might also illustrate the possibilities and limitations of trying to manage the biogenic C pool for enhancing and promoting C sequestration in urban residential areas. Housing age, or time since disturbance, is a key factor driving soil C stocks, which comprise 88% of the total biogenic C stock in a residential parcel. An important avenue of future research would therefore be to identify techniques for maintaining or enhancing the soil C pool in residential yards.

4.4. Urban carbon stocks in small cities

The lack of differences in C stocks between front and back yards plus the lack of correlations between C stocks and factors such as population density, race, total assessed value, and residence duration together suggest that current theories of how social processes shape urban vegetation cover may not always translate to C storage. This may be especially important when considering how bio-geo-socio-chemical factors drive patterns of C storage among cities of varying size. Prior research on above- and below-ground C dynamics has largely occurred in cities with over one million residents (e.g., Jo & McPherson, 1995; Nowak & Crane, 2002; Golubiewski, 2006; Pouyat et al., 2006; McDonnell et al., 2008; McPherson et al., 2013; Grove et al., 2014) or in metropolitan areas within a megalopolis such as the Boston to Washington corridor of the north-eastern U.S. (e.g., Raciti et al., 2011; Giner et al., 2013; Trammell et al., 2017). Theories developed from these more populated, larger cities about how socioeconomic status and lifestyle behavior drive patterns of C storage might not always fit smaller cities, particularly when these smaller cities are more homogenous. Manchester, NH, USA lacks the racial, ethnic, and economic diversity typical of larger cities (Table 1), such that gradients in home values, percentages of minority residents, and income may not be steep enough to affect C storage dynamics in residential areas.

In addition to city size, methodological limitations of this study may account for our failure to detect relationships between some socio-economic and lifestyle behavior metrics and above- and below-ground C stocks. Our focus on single family, detached homes excluded multi-family dwellings that may have encompassed a greater range of incomes, ethnicities, and neighborhood features. Our relatively small sample size (n = 36 yards) also may not have been large enough to capture broad gradients in the socioeconomic status and group identity variables of interest. In addition, the approach we used for estimating C stocks in vegetation, in which we applied allometric equations to tree DBH and then multiplied the results by 0.8 (McPherson et al., 1994; Nowak, 1994; Currie et al., 2016), may not have always represented allometry in urban areas where trees experience different growth conditions (McHale, Burke, Lefsky, Peper, & McPherson, 2009; Smith, Dearborn, & Hutyra, 2019). Nevertheless, our study highlights the growing need for challenging our assumptions about the bio-geo-socio-chemical drivers of both above- and below-ground C stocks particularly in small cities of <200,000 residents.

5. Conclusions

We proposed that the concept of "bio-geo-socio-chemistry" (*sensu* Groffman et al., 2006, a) might provide a coherent framework for understanding how biogeochemical cycling interacts with human activities to influence patterns of C storage in urban yards both above- and below-ground. However, the patterns we observed for above- and below-ground C storage were decoupled from one another, as evidence by the lack of a correlation between C stocks in soil and in vegetation. Instead, we found that soil C density responded to a single biogeochemical driver, housing age, which might be analogous to time since disturbance (e.g., Golubiewski, 2006; Raciti et al., 2011). By contrast, tree biomass C was most strongly related to the social stratification variable of median income and the lifestyle behavior metrics of median resident age and percent married couples, with housing age playing a more secondary role. The difference in the magnitude of above- and below-ground C stocks, plus the disparate ways in which they varied across the landscape, together underscore the limitations of trying to enhance biogenic C sequestration in urban yards using a "one-size-fits-all" approach (e.g., tree planting efforts; McPherson, 1998). Considering the nuanced ways in which bio-geo-socio-chemical factors affect biogenic C storage may be especially important when devising policies for small cities which are underrepresented in research on above- and below-ground C dynamics in urban yards.

Reference Data

Data available in data repository Zenodo at 10.5281/zenodo.3588461.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2019.103724.

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