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Key Points:
- Leaf and soil C and N content and isotopic composition were correlated with income and housing age in Los Angeles and Salt Lake City
- Leaf N was higher in low-income areas of Los Angeles and isotopically enriched in low income areas in both Los Angeles and Salt Lake City
- Results may be explained by spatial patterns in atmospheric pollution, which disproportionately affects low-income areas in Los Angeles

Supporting Information:
- Data Set S1
- Supporting Information S1

Correspondence to:
L. A. E. Cobley,
lae.cobley@utah.edu

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Housing Age and Affluence Influence Plant and Soil Nitrogen and Carbon Cycles in Two Semiarid Cities

L. A. E. Cobley[1], D. E. Pataki[1], H. R. McCarthy[2], S. A. Martin[3], and J. R. Ehleringer[1]

[1]School of Biological Sciences, University of Utah, Salt Lake City, UT, USA, [2]Department of Microbiology and Plant Biology, University of Oklahoma, Norman, OK, USA, [3]Martin & Nicholson Environmental Consultants, Park City, UT, USA

Abstract While human activities have altered the urban nitrogen (N) and carbon (C) cycles, the relationships between social and biophysical processes in cities are not well understood. Here we evaluated relationships between sociodemographic variables (median household income and housing age) and N and C contents and stable isotope ratios of vegetation in the Los Angeles Metropolitan Area (LA), California, and the Salt Lake Valley, Utah. We hypothesized that (1) N content and stable isotope ratios would be negatively related to income via increased N deposition in lower-income areas; (2) N and C content and N stable isotope ratios would have a positive relationship with age due to soil organic matter accumulation and increased exposure to N losses over time, respectively; and (3) $\delta^{13}C$ would increase with income as a result of increased fossil fuel-derived CO_2 concentrations in lower-income areas. We found that $\delta^{15}N$ values decreased with median household income in both cities and N content decreased with income in LA. In addition, atmospheric NO_2 concentrations decreased with income in LA. Soil N and C content increased with housing age. However, $\delta^{15}N$ had opposing relationships with age in the two cities. Finally, foliar $\delta^{13}C$ values were more isotopically depleted with both increasing household income and increasing NO_2 concentrations in LA. These results show that urban foliar and soil isotopic composition are associated with sociodemographic variables and that affluence, as well as housing age, influences urban plant and soil function.

1. Introduction

Urban areas across the United States are rapidly expanding as human populations continue to migrate to cities (Alig et al., 2004; Grimm, Faeth, et al., 2008). This urban expansion dramatically alters the land surface with cascading impacts on biogeochemical cycles (Kaye et al., 2006). Relationships between human actions and the urban biophysical environment are influenced by complex interactions among social, cultural, economic, biological, and geophysical processes (Grimm, Foster, et al., 2008; Kaye et al., 2006; Kinzig et al., 2005). Among these, household income and lifestyle behaviors have both been shown to be significantly correlated with aspects of urban ecosystem structure including biodiversity (Kinzig et al., 2005) and vegetation cover (Grove et al., 2006).

Cities have highly altered nitrogen (N) cycles (Howarth et al., 2002; Lorenz & Lal, 2008). This is partly the result of large N inputs via deposition (Bettez & Groffman, 2013; Fenn et al., 2003) and fertilizer (Howarth et al., 2002; Zhu et al., 2006). Urban areas are hot spots of N deposition (Du et al., 2014) relative to less and nonurbanized areas (Bettez et al., 2013; Lovett et al., 2000; Rao et al., 2014), with major traffic sources of NO_x, N_2O, and NH_3 (Bettez et al., 2013; Cape et al., 2004; Kirchner et al., 2005). Patterns of N deposition are also affected by sociodemographic and neighborhood characteristics, as vehicle NO_x emissions have been shown to decrease with increasing per capita income (Carson et al., 1997; Wilhelm et al., 2009). Urban N inputs via fertilization are large and are affected by sociodemographic and socioecological factors. In fact, more than 50% of households in the United States apply fertilizer, and in some neighborhoods this percentage is as high as 80% (Cook et al., 2012; Law et al., 2004; Osmond & Hardy, 2004). Fertilization rates have been shown to be influenced by housing values, age of development, soil bulk density, and soil N content (Law et al., 2004), with middle and high-income residents generally applying more fertilizer than low-income residents (Osmond & Hardy, 2004). Moreover, overall N availability has been shown to have complex relationships with socioecological variables at neighborhood scales, such as population density (Hope et al., 2005).

Urban areas also have highly altered carbon (C) cycles that are affected by a myriad of ecological and sociological factors. For example, urbanized areas have elevated CO_2 concentrations that may exceed 500 ppm during nighttime stable atmospheric conditions (Gratani & Varone, 2005; Idso et al., 1998; Koerner & Klopatek, 2002; Pataki et al., 2003, 2007). Urban fossil fuel emissions have also been shown to be impacted by population densities and socioeconomic factors (Pataki et al., 2006). For example, carbon monoxide (CO) emissions and concentrations exhibit negative correlations with per capita income and other neighborhood metrics, including percent unemployment (Carson et al., 1997; Wilhelm et al., 2009). The social justice literature has highlighted that both race and class tend to be correlated with air pollution concentrations (Brown, 1995; Sexton et al., 1993).

To further study patterns of urban N and C cycling, stable isotopes of these elements can serve as useful tracers of plant, soil, and atmospheric processes in urban areas, as they integrate plant-atmosphere interactions over space and time (Evans, 2001; Pataki et al., 2005; Robinson, 2001; W. Wang & Pataki, 2012). Nitrogen stable isotope ratios have been used as indicators of pollution (W. Wang & Pataki, 2012) and fertilizer (Kendall et al., 2007) uptake by plants. $\delta^{15}N$ generally follows a pattern of isotopic enrichment of atmospheric NO_x in urban areas and isotopic depletion of NH_x in agricultural areas (Pearson et al., 2000). Isotopically enriched foliage has been found in urban areas relative to less urbanized areas in New York City trees (Falxa-Raymond et al., 2014), UK mosses (Pearson et al., 2000), and Los Angeles grasses (W. Wang & Pataki, 2010). Synthetic inorganic fertilizers have $\delta^{15}N$ values of near 0‰ (Bateman & Kelly, 2007; Kendall et al., 2007; Vitòria et al., 2004), and plants in fertilized yards have been found to have more depleted $\delta^{15}N$ values than plants in unfertilized yards (Trammell et al., 2016). Environmental conditions, such as water availability and pollution concentrations, can play a significant role in plant carbon uptake and can thus influence foliar $\delta^{13}C$ (Farquhar et al., 1989). For example, leaf $\delta^{13}C$ is inversely related to metrics of water availability, including average rainfall (Stewart et al., 1995) and plant drought stress (Warren et al., 2001). In addition, CO_2 emitted from fossil fuel combustion is highly depleted in $\delta^{13}C$ relative to the background atmosphere, such that urban plants tend to be depleted in $\delta^{13}C$ relative to nonurban plants (Pataki et al., 2006; W. Wang & Pataki, 2010). These gradients of plant $\delta^{13}C$ between urban and rural plants may reflect existing gradients of CO_2 concentrations, which may be 80 ppm or higher in urban areas (Pataki et al., 2007). Within urban regions, plants near high traffic roads have been shown to have more depeleted $\delta^{13}C$ values relative to plants further away from roads (Kiyosu & Kidoguchi, 2000; Lichtfouse et al., 2003). As a result, organic matter isotopic composition can provide a useful biomonitor of pollution within cities and across urbanization gradients (Pataki et al., 2005; W. Wang & Pataki, 2012).

In this study, we examined the influence of sociodemographic and socioecological variables on urban nitrogen and carbon in plants and soils. Specifically, we examined the influences of household income and housing age (time since development) on vegetation and associated soils across urban landscapes in two semiarid, western U.S. metropolitan regions: the Los Angeles metropolitan area in California (LA) and the Salt Lake Valley (SLV) metropolitan area in Utah. Arid land cities are expected to increase in size and population density in the future under conditions of increasingly limited water resources (Koerner & Klopatek, 2002). For example, California is currently the most urbanized state in the United States and Utah is the eighth most urbanized state, as well as one of the fastest growing states in the United States (US Census Bureau, 2010). In addition, the Los Angeles area and Salt Lake City area ranked as the seventh and eighth most polluted cities, respectively, in regard to short-term particle pollution (American Lung Association, 2018). Both urbanized regions are intermountain basins with winter wet, summer dry climates and have relatively high air pollution concentrations.

We tested three hypotheses: (1) leaf N content and $\delta^{15}N$ values would be negatively related to neighborhood affluence based on higher N deposition in lower-income neighborhoods; (2) leaf and soil N and C content and isotopic enrichment will increase with housing age due to accumulation of soil organic matter (SOM) over time and increased exposure to N losses over time, respectively; and (3) leaves in lower-income areas would be depleted in $\delta^{13}C$ relative to higher-income areas due to higher atmospheric concentrations of fossil fuel-derived CO_2. A conceptual diagram of these hypothesized relationships can be found in Figure 1. Ultimately, we evaluated these hypotheses with measurements of urban trees in LA and annual grasses and soils in SLV. We expected that trends in both cities would be similar given their comparable climates and high pollutant concentrations. The overall goal of this study was to better understand the influences of sociodemographic and socioecological variables (income and time since development) on C and N cycles in urban areas.

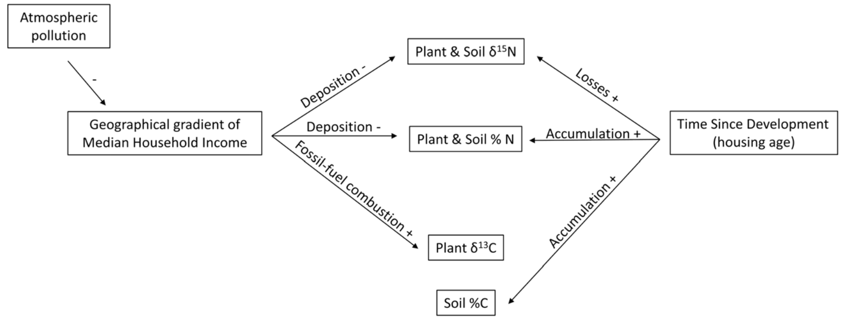

Figure 1. Conceptual diagram of hypothesized relationships between sociodemographic variables (median household income and time since development) and plant and soil leaf chemistry: Nitrogen (%N) and carbon (%C) content and stable isotope ratios ($\delta^{15}N$, $\delta^{13}C$). The proposed mechanism and direction of each relationship is described and noted by a plus (+) or minus (−) sign indicating a positive or negative relationship, respectively.

2. Methods

2.1. Site Descriptions

2.1.1. Los Angeles

The first study region was the LA metropolitan area in California, specifically Los Angeles County (LAC) and Orange County (OC), which are within the LA Basin. The LA Basin is a coastal plain bounded by the Pacific Ocean and the Peninsular and Transverse Mountains. The region has a Mediterranean climate, characterized by fog, relatively mild and wet winters, and dry summers (Rundel & Gustafson, 2005; Schoenherr, 1992). The native vegetation is dominated by shrubland and is largely absent of trees at lower elevations (Rundel & Gustafson, 2005). Irrigation is required to sustain mesic landscaping in urban areas.

2.1.2. Salt Lake Valley

The second study location was Salt Lake County, Utah, a metropolitan area located in northern Utah's SLV. SLV is similar in topography to the LA Basin but is surrounded by the Wasatch Mountains to the east, the Oquirrh Mountains to the west, the Traverse Mountain Range to the south, and the Great Salt Lake to the north. SLV is also seasonally dry in the summer and has a semiarid climate (Alder et al., 1998; Bush et al., 2008). Similar to other valleys in the Intermountain West, the native vegetation prior to urbanization was a mix of grasslands and shrublands, dependent on fire history. Native trees were largely absent in valleys, except along riparian corridors, and similar to Los Angeles, irrigation is required to sustain mesic vegetation.

2.2. Sample Collection and Preparation

2.2.1. LA Trees

Plant sampling in LA focused on urban trees. A total of 25 neighborhoods (13 in LAC and 12 in OC) were selected across municipalities in LAC and OC. Neighborhoods were chosen to span ranges of household income and age of development estimated with census tract data. There were generally 3–5 census tracts per neighborhood. Neighborhood boundaries in LA were defined using the Mapping LA project (http://maps.latimes.com/neighborhoods/), and neighborhood boundaries in OC were chosen and digitized using maps available from city and local real estate websites. Within each neighborhood, 10 circular plots, 11.2 m in radius (0.04 ha), were randomly placed using a geographic information system tool in the Urban Forest Effects model (Nowak et al., 2005). This resulted in a total of 250 plots. Sampling occurred primarily between June and September 2010 and between June and August 2011; however, several samples were collected in October and November 2010 and January and February 2011. Each plot was surveyed using the Urban Forest Effects/i-Tree protocol (Nowak et al., 2005). For each plot location, species inventory and diameter at breast height were assessed. In addition, 5–15 sunlit leaves were collected from lower tree canopies that could be reached with a 14-foot extendable pole. If a given plot contained trees that could not be sampled (e.g., on a rooftop, in a private backyard, and permission to access denied), a new location was chosen close to the original plot that contained a similar number of trees and ground covers. Because many of these trees were highly urbanized with little available soil (i.e., growing in sidewalk grates), soils were not sampled in this portion of the study.

Tree leaves collected at each plot were dried at 60 °C for a minimum of 3 days and ground into a fine homogenous powder. Approximately 1.5 mg was placed into tin capsules and analyzed with an elemental analyzer (Carlo Erba NA 1500 NC, Milan, Italy) coupled to an isotope ratio mass spectrometer (Thermo Finnigan Delta Plus, San Jose, CA. USA) for nitrogen and carbon stable isotopes and content: $\delta^{15}N$, %N, $\delta^{13}C$, and %C. Nitrogen stable isotopes ($\delta^{15}N$) were referenced to the atmospheric standard, and carbon stable isotopes ($\delta^{13}C$) were referenced to the Pee Dee Belemnite standard. Note that analyses were conducted at the plot scale by averaging measured foliar chemistry and isotope ratios for all trees within each plot.

All of the plots in LA were sampled in neighborhoods that varied in median household income and age. The household income and age (time since development) associated with each plot were obtained from the U.S. Census American Community Survey 5-year estimates from 2007–2011 at the census block scale. The income associated with each tree was the median household income of its respective block group. Time since development at each plot was estimated as the year of sampling (2010) minus the median year a structure was built at that respective block group. Of the plots that were included in the final analysis, household income ranged from $13,000 to $250,000 and time since development ranged from 6 to 71 years. Some plots were not included in the final analysis because the location did not contain trees or because all variables were not available. There were 83 plots in the final analysis.

2.2.2. SLV Grasses and Soils

The vegetation and soil samples used in this analysis were collected between 16 and 22 April 2003, with sample collection focusing on *Bromus tectorum*, a common exotic invasive, winter annual grass that undergoes C_3 photosynthesis. This species was chosen due its ubiquitous abundance in this region. Five leaf and stem samples of *B. tectorum* were collected at each site in a 30 cm^2 area. If five shoots were not present, the area was extended until that number could be found. The shoots collected contained seed heads unless there were no mature samples at that site. However, this occurred less than 5% of the time. Soils were also collected at each location. Samples had a volume of 10 cm^2 in area and 2 cm in depth.

A random subsampling of the five collected shoots from each site was ground for 1.5 min, and 2 ± 0.02 mg was used for analysis with an elemental analyzer (EA 1108 CHN, Fisons Instruments, Beverly, MA) coupled to an isotope ratio mass spectrometer (Finnigan MAT delta S, Thermo Electron Co, San Jose, CA). Soil was also collected at each of the sampling locations. Soil samples were dried for 72 hr at 35 °C within 72 hr of collection. The soils were then passed through a 2-mm sieve, and a 100-mg portion from each plot sample was ground for 25 s. Thirty milligrams of soil was then analyzed with an elemental analyzer (EA 1108 CHN, Fisons Instruments, Beverly, MA) coupled to an isotopic ratio mass spectrometer (Finnigan MAT delta S, Thermo Electron Co, San Jose, CA) to obtain total N and C concentrations and $\delta^{15}N$ and $\delta^{13}C$ values. All samples were analyzed at the Stable Isotope Ratio Facility for Environmental Research at the University of Utah, and in all analytical runs the data met quality assurance and quality control requirements.

The sampling locations in SLV were selected to capture spatial variability across the metropolitan region (Kammerdiener, 2004). As a result, soil and shoot (leaves and stems) samples were collected in approximately every square mile across the entire valley. This resulted in a total of 258 sampling sites that reflected different land covers, including the downtown core, roadways, suburban residential areas, industrial sites, and rural areas. Although the sampling was not stratified by household income or age, the thoroughness of the sampling design allowed us to capture a range of incomes and times since development. The income associated with each sampling location was the median household income of the respective block group, and the time since development was the year of sampling (2003) minus the median year a structure was built at that respective block group. Household incomes associated with individual plots sampled in the SLV ranged from $13,750 to $135,852 and the time since development ranged from 4 to 63 years. All values for income and time since development were obtained from Summary File 3 of the 2000 U.S. Census at the census block group scale. Two hundred forty-nine plots were analyzed.

2.3. Other Variables

2.3.1. Atmospheric Pollution

Estimates of atmospheric NO_x, NO_2, and NO concentrations at each sample collection site in Los Angeles were derived by kriging atmospheric measurements from monitoring stations, similar to W. Wang and Pataki (2010). We obtained 2010 data of daily average (24 hr), morning average (6 a.m. to 6 p.m.), and daily maximum concentrations (ppm) of NO_x, NO_2, and NO from 38 California Air Resources Board (http://www.

arb.ca.gov/aqmis2/aqdselect.php) monitoring stations spread throughout 6 counties (Imperial, Los Angeles, Orange, Riverside, San Diego and Ventura) in Southern California. To estimate NO_x concentrations at each plot during the growing season (May to October), we interpolated the data with the Ordinary CoKrigging method (ArcMap, Geostastical Analyst) (McCoy & Johnston, 2001; Mitchell, 1999; W. Wang & Pataki, 2010). For our analysis, we ultimately used only daily maximum NO_2 values because they had the highest explanatory power. A similar spatially explicit analysis was not possible in SLV due to an inadequate number of air quality monitoring stations; however, daily maximum NO_2 concentrations from two monitoring stations in SLV were obtained from the AirData database of the U.S. Environmental Protection Agency.

2.3.2. Elevation

Both LA and SLV have extremely variable topography, which has been shown to influence foliar $\delta^{15}N$ (Biswas et al., 2008). To account for this, we obtained local elevation models for each region. The elevation above sea level of LA plots was obtained using the National Oceanic and Atmospheric Administration's Coastal Relief Model of Southern California, version 2. This digital elevation model was downloaded at a 1-arc-second (approximately 30 m) resolution. Individual raster files from the Coastal Relief Model that expanded over our study area were merged together with the Mosaic tool (ArcMap, 10.3.1, Data Management Tools), and LA plot elevations were extracted using the *Extract Values to Points* tool (ArcMap, 10.3.1, Spatial Analyst Tools). To obtain the elevations of our SLV plots, we used the National Elevation Dataset from the U.S. Geological Survey. We accessed a mosaicked 10-m National Elevation Dataset through the Utah Automated Geographic Reference Center. Elevations of SLV plots were obtained using ArcGIS's Extract Values to Points tool (ArcMap, 10.3.1, Spatial Analyst Tools).

2.4. Data Analysis

2.4.1. Los Angeles

In LA, we analyzed leaves in a total of 83 plots containing 203 trees and representing 61 different species. We calculated the average leaf C and N content and stable isotope ratios of all the trees found in each plot, with the exception of nitrogen fixing species, which were removed from the data set. Because the study sites were located in two different counties, LAC and OC, we tested for homogeneity of slopes between LAC and OC for each of our correlations in LA to determine if samples from the counties could be combined. The slopes for these two data sets were always homogenous; thus, the data for both counties were combined in all our analyses. Normality of each variable was assessed from histograms, and data were natural log transformed when necessary for statistical analyses. Data that were log transformed included income, NO_2 concentrations, and tree leaf %N. All statistical analyses were completed in the software program R (R development Core Team, 3.0.2, Vienna, Austria).

Pearson product correlation analyses was used to assess relationships between leaf chemistry variables (%N, $\delta^{15}N$, %C, and $\delta^{13}C$) and several factors including household income, age, elevation, and NO_2 concentrations. These relationships were also evaluated using forward and backwards stepwise regression analyses. The MASS package was used to conduct the stepwise regressions (Venables & Ripley, 2002), and the relaimpo package was used to calculate partial regression coefficients (Grömping, 2006). Also, the car package (Fox & Weisberg, 2001) was used to calculate the variance inflation factors (VIFs) of explanatory variables used in the regression model. VIF values were used to evaluate multicollinearity between explanatory variables (Zuur et al., 2010). Thus, while age was correlated with both income and elevation in LA, all relationships observed with these factors were independent because factors with high VIF values were not included in final models.

In addition, a comparison between the two cities was made for each of the variables (%N, $\delta^{15}N$, %C and $\delta^{13}C$, C/N, income, age, elevation, and NO_2 concentrations) using Welch two sample *t* test.

2.4.2. Salt Lake Valley

In SLV, we analyzed both soil and *B. tectorum* leaf data from 249 plots. We evaluated relationships between leaf (%N, $\delta^{15}N$, and $\delta^{13}C$) and soil chemistry (%N, %C, and $\delta^{15}N$) and several factors including household income, age, and elevation with Pearson's product moment correlation. Forward and backward stepwise multiple regression analyses in the MASS package (Venables & Ripley, 2002) was also used to assess all of these relationships. The relaimpo package was used to calculate partial regression coefficients (Grömping, 2006), and the car package (Fox & Weisberg, 2001) was used to calculate VIF values. We used VIF values to

Table 1
Averages and Ranges of Median Household Income, Time Since Development, Elevation, and Daily Maximum NO_2 Concentrations for Our Study Plots in the Los Angeles Metropolitan Area (LA) and Salt Lake Valley (SLV)

	LA	SLV
Median household income (thousand dollars)	105.5 ± 60.9[a] (13.0–250.0)	55.1 ± 24.6 (13.8–135.9)
Time since development (years)	41.3 ± 18.1[a] (6–71)	29.1 ± 17.1 (4–63)
Elevation (m)	72.5 ± 80.1 (0–345)	1391.6 ± 127.2[a] (1284.9–2303.8)
Daily maximum NO_2 (ppb)	29.8 ± 3.1 (24.5–35.4)	39.8 ± 9.0[a] (11.0–70.0)

Note. Mean ± standard deviation. Ranges are shown in parentheses. Median household income was obtained from the U. S. Census. Time since development is the year of sampling (2010 in LA and 2003 in SLV) minus the year a structure was built in each census block group. Elevation was calculated from digital elevation models, and NO_2 concentrations were obtained from the California Air Resources Board and U.S. Environmental Protection Agency for LA and SLV, respectively.
[a]Indicates a significantly greater mean ($p < 0.05$) from a two sample *t* test.

address multicollinearity; thus, explanatory factors with high VIF values were not included in final models. As a result, all the relationships shown are independent, despite correlations between income, age, and elevation in SLV. Soil %N, soil %C, and income and age were natural log transformed to obtain normality, and these transformations were used for data analyses.

3. Results

3.1. Sociodemographic Variables

We found that sociodemographic variables differed between SLV and LA, with higher household incomes (t = 7.33, p = 0.01; Table 1), older housing developments (t = 5.37, p = 0.01; Table 1), and lower elevations (t = 172.68, p = 0.01; Table 1) associated with sampling plots in LA versus SLV. Throughout the growing season (May through October), SLV had significantly higher mean concentrations of atmospheric NO_2 (t = −13.08, p = 0.01; Table 1).

Time since development and median household income were negatively correlated in both LA and SLV (r = −0.305, p = 0.01, r = −0.405, p = 0.01 respectively). In addition, elevation and income were not correlated in LA (p = 0.13) but showed a positive relationship in SLV (r = 0.562, p = 0.01). Elevation and time since development were negatively correlated in LA but did not show a relationship in SLV (r = −0.358, p = 0.01, p = 0.10, respectively).

3.2. Foliar Chemistry

Overall, foliar chemistry also varied between SLV and LA. SLV grasses had significantly greater mean foliar N and lower C:N ratios than LA tree leaves (t = −9.79, p = 0.01, t = 9.71, p = 0.01, respectively; Table 2). In addition, SLV grasses had significantly greater foliar N content than SLV soils (t = 47.87, p = 0.01; Table 2). Foliar $\delta^{15}N$ was significantly more enriched in LA trees than SLV grasses (t = 2.87, p = 0.01; Table 2); however, leaf $\delta^{13}C$ did not vary significantly between the two cities (p = 0.07; Table 2). $\delta^{15}N$ of SLV soils was enriched relative to SLV grasses (t = −12.41, p = 0.01; Table 2).

Table 2
Averages and Ranges of Carbon and Nitrogen Content and Isotope Ratios in Los Angeles (LA) Tree Leaves and Salt Lake Valley (SLV) Grasses and Soils

	LA (trees)	SLV (grasses)	SLV (soils)
%N	1.6 ± 0.6 (0.8–3.6)	2.4 ± 0.7[a,b] (1.1–4.9)	0.2 ± 0.2 (0.02–1.2)
%C	--	--	4.2 ± 2.70 (0.55–20.7)
C:N	32.5 ± 10.4[a] (12.8–61.3)	20.7 ± 6.2 (9.1–41.1)	--
$\delta^{15}N$ (‰)	3.3 ± 2.6[a] (−2.7–9.3)	2.4 ± 2.3 (−6.4–10.2)	4.8 ± 2.0[b] (−0.1–11.2)
$\delta^{13}C$ (‰)	−28.1 ± 1.8 (−33.0 to −24.7)	−28.5 ± 1.2 (−31.8 to −23.7)	--

Note. Mean ± standard deviation. Ranges are shown in parentheses.
[a]Indicates a significantly greater mean %N, or $\delta^{15}N$ ($p < 0.05$) from two sample *t* test comparisons of LA tree leaves and SLV grasses. Foliar $\delta^{13}C$ was not significantly different in LA and SLV. [b]Indicates a significant greater mean %N, or $\delta^{15}N$ ($p < 0.05$) from two sample *t* test comparisons of SLV grasses and SLV soils.

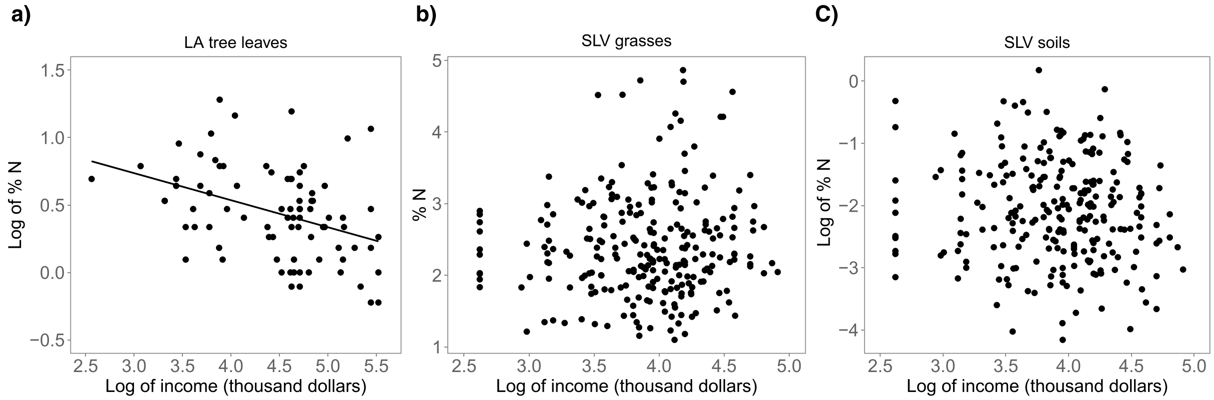

Figure 2. Correlations between %N (percent total nitrogen) and median household income (thousand dollars) in LA tree leaves, SLV grasses, and SLV soils, respectively: (a) $r = -0.387$, $p = 0.01$, (b) $p = 0.25$, and (c) $p = 0.22$. LA = Los Angeles; SLV = Salt Lake Valley.

3.3. N, C, and Income

The relationships between income and our response variables varied between cities. Leaf %N was negatively correlated with median household income in LA ($r = -0.387$, $p = 0.01$; Figure 2a). However, there was no correlation between %N and median household income for SLV grasses ($p = 0.25$; Figure 2b) or soils ($p = 0.22$; Figure 2c). $\delta^{15}N$ in LA tree leaves ($r = -0.550$, $p = 0.01$; Figure 3a), SLV grasses ($r = -0.20$, $p = 0.01$; Figure 3b), and SLV soils ($r = -2.09$, $p = 0.01$; Figure 3c) were also negatively correlated with median household income. Finally, daily maximum NO_2 concentrations were also negatively correlated with income ($r = -0.333$, $p = 0.01$; Figure 4).

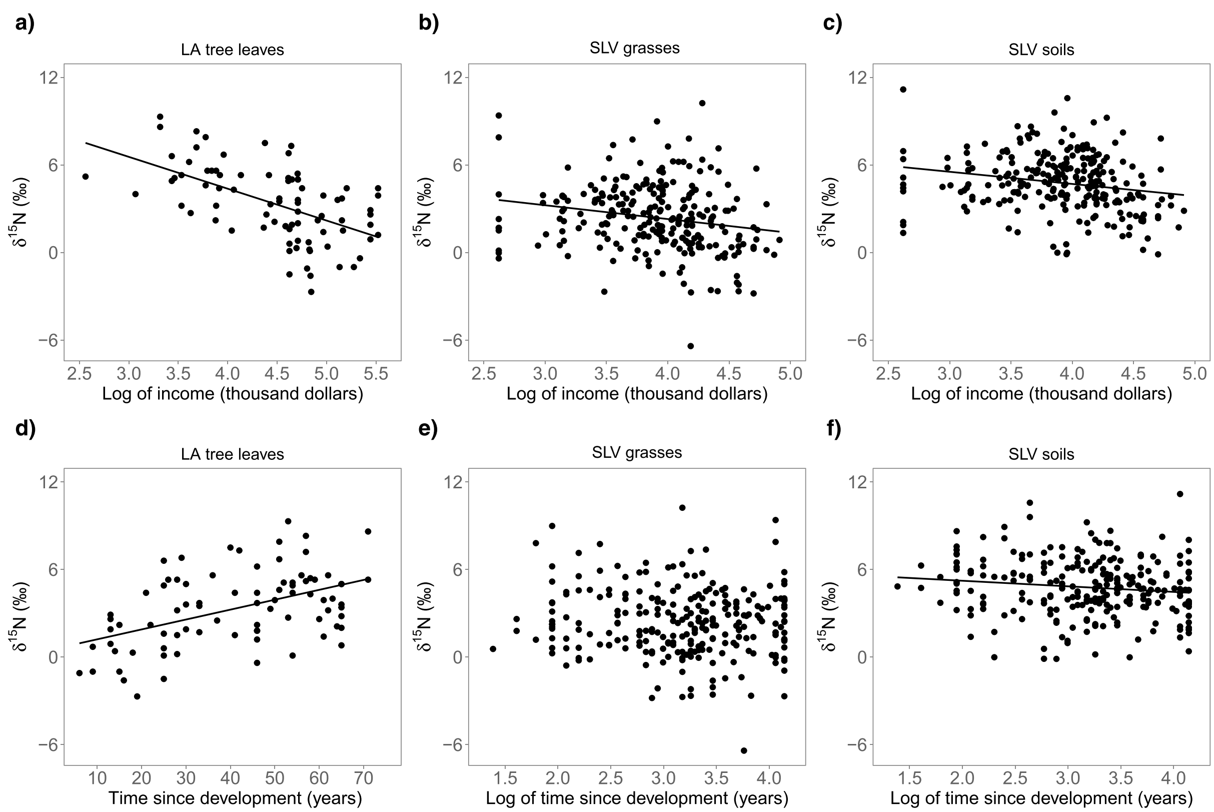

Figure 3. Correlations between $\delta^{15}N$ (nitrogen stable isotopes in per mil notation) and medium household income (thousand dollars) (a) $r = -0.550$, $p = 0.01$, (b) $r = -0.20$, $p = 0.01$, and (c) $r = -0.209$, $p = 0.01$ and time since development (years) (d) $r = 0.476$, $p = 0.01$, (e) $p = 0.16$, and (f) $r = -0.129$, $p = 0.04$ in LA tree leaves, SLV grasses, and SLV soils, respectively. LA = Los Angeles; SLV = Salt Lake Valley.

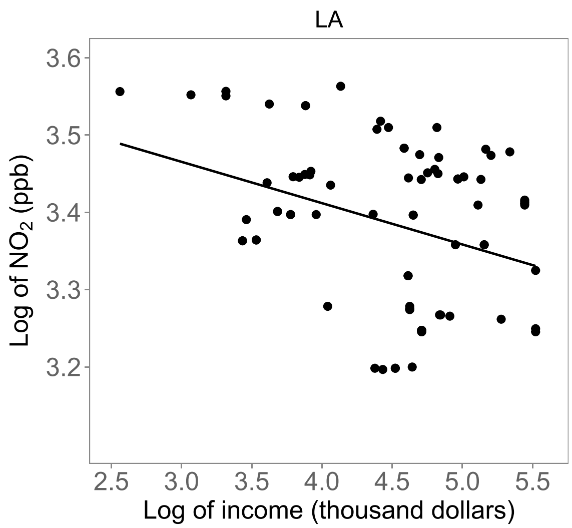

Figure 4. Correlation between daily maximum NO_2 concentrations (parts per billion) and median household income (thousand dollars): (a) $r = -0.333$, $p = 0.01$. LA = Los Angeles.

There was no correlation between $\delta^{13}C$ and income in LA tree leaves (0.12) or SLV grasses (0.17).

3.4. N, C, and Time Since Development

We also found varied relationships between time since development and our response variables in each city. Leaf %N was not related to time since development in LA ($p = 0.10$) or SLV ($p = 0.51$). However, both %N and %C of SLV soils had a positive relationship with time since development ($r = 0.276$, $p = 0.01$, $r = 0.438$, $p = 0.01$, respectively; Figure 5). Tree leaf $\delta^{15}N$ was also positively correlated with time since development ($r = 0.476$, $p = 0.01$; Figure 3d) in LA. This contrasts with SLV, where $\delta^{15}N$ was not related to time since development in grasses ($p = 0.16$; Figure 3e) but negatively correlated with it in soils ($r = -0.129$, $p = 0.04$; Figure 3f).

3.5. Multiple Regression Models

In addition to correlation analyses, we also assessed our data sets with multiple regression analyses in order to further explain the variation we observed. Multiple regression analyses confirmed the relationship between %N and income in LA tree leaves, but did not show any relationships with time since development, elevation, or NO_2 ($r^2 = 0.139$, $p = 0.01$; Table 3). Furthermore, there was no relationship between %N and any of the explanatory variables for SLV grasses ($p = 0.25$; Table 3). However, multiple regression analyses also confirmed the positive relationship between %N and time since development in SLV soils but showed no other relationships with income or elevation ($r^2 = 0.072$, $p = 0.01$; Table 3).

We also used multiple regression analysis to assess relationships between $\delta^{15}N$ and our explanatory variables. The multiple regression model showed significant relationships between $\delta^{15}N$ and income, time since development, and elevation for LA tree leaves. Furthermore, it also highlighted a negative relationship between $\delta^{15}N$ and atmospheric NO_2 ($r^2 = 0.546$, $p = 0.01$; Table 4). While the model showed relationships between $\delta^{15}N$ and time since development and elevation in SLV grasses, income was not significant ($r^2 = 0.122$, $p = 0.01$; Table 4), which contrasts with the results for individual correlations. However, $\delta^{15}N$ in SLV soils was related to time since development, elevation, and income ($r^2 = 0.129$, $p = 0.01$; Table 4). Daily maximum NO_2 concentrations decreased with both increasing income and elevation in the multiple regression model ($r^2 = 0.141$, $p = 0.0$; Table 5).

The positive relationship between soil %C and time since development in SLV was confirmed with multiple regression analyses; furthermore, soil %C was shown to decrease with increasing elevation ($r^2 = 0.211$,

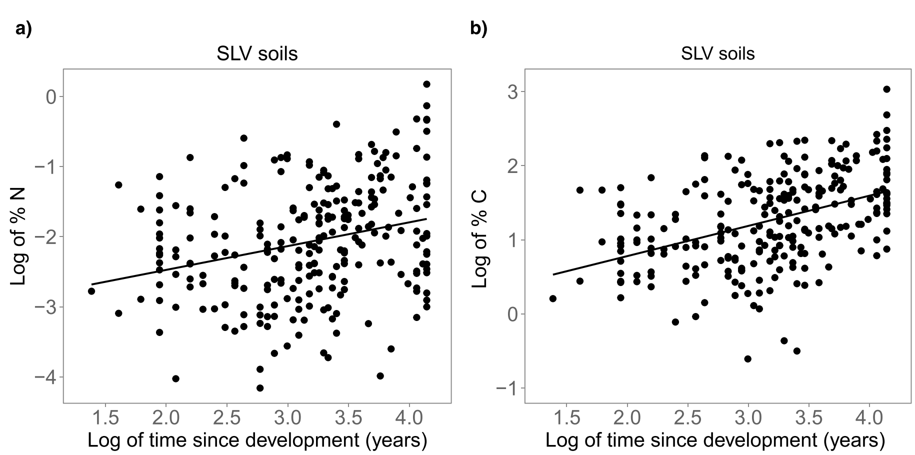

Figure 5. Correlations between %N (percent total nitrogen) and time since development (years) (a) $r = 0.276$, $p = 0.01$ and %C (percent soil carbon) and time since development (b) $r = 0.438$, $p = 0.01$ in SLV soils. SLV = Salt Lake Valley.

Table 3
Coefficients of Multiple Regression Models of Plant and Soil %N in the Los Angeles Metropolitan Area (LA) and Salt Lake Valley (SLV)

Dependent variable	All independent variables	Independent variables in model	t	$Pr > \|t\|$
LA Trees Adj. r^2 *= 0.139, p = 0.01*				
%N	Income	Income	−3.757	0.001
	Age			NS
	Elevation			NS
	NO_2			NS
SLV Grasses p = 0.25				
%N	Income			NS
	Age			NS
	Elevation			NS
SLV Soils Adj. r^2 *= 0.072, p = 0.01*				
%N	Age	Age	4.516	0.001
	Income			NS
	Elevation			NS

Note. Income and age refer to median household income (thousand dollars) and time since development (years), respectively. NO_2 is in parts per billion, and elevation is in meters. NS indicates variables that were not significant in the multiple regression model. Some variables in these relationships were log transformed for normality, including %N, income, and NO_2 in LA and income, age, and soil %N in SLV.

$p = 0.01$; Table 6). The final multiple regression model for foliar $\delta^{13}C$ in LA showed significant negative relationships with both income and atmospheric NO_2 concentrations ($r^2 = 0.177$ $p = 0.01$; Table 7). This contrasts the model for SLV grasses, which only showed a weak relationship between $\delta^{13}C$ and time since development ($r^2 = 0.03$, $p = 0.01$; Table 7).

4. Discussion

Our overall goal was to evaluate the influence of affluence (median household income) and housing age (time since development) on foliar and soil N and C content and stable isotope ratios in two cities (Figure 1) with similar geography and pollution levels. The results supported our hypotheses as %N and $\delta^{15}N$ of leaves and soils were negatively related to median household income (although N content was not consistently correlated with income). Furthermore, soils showed accumulations of N and C over time. However, $\delta^{15}N$ had varying relationships with time since development in the two cities. Finally, $\delta^{13}C$ was negatively related with income. These results provide several lines of evidence that the isotopic composition of urban plants may be used as indicators of atmospheric pollution and urban N and C cycling.

4.1. N and Income

The relationship between affluence and leaf and soil N elucidates some of the mechanisms underlying human influences on urban nutrient cycles. For the first time, we report a negative relationship between foliar N and median household income. We observed a decrease in foliar %N with increasing income in LA but no relationship between these variables in SLV grasses or soils (Figure 2 and Table 3). This suggests that NO_2 or other atmospheric pollutants such as wet or dry N deposition may have influenced leaf N, as NO_2 concentrations were higher in low-income neighborhoods (Figure 4 and Table 5). However, there was no relationship between %N and NO_2 concentrations in LA (Table 3). While studies have shown that trees are able to assimilate NO_2 directly through foliar uptake (Sparks et al., 2001; Thoene et al., 1991), other pollutants such as HNO_3 can also be assimilated into leaf amino acids and proteins (Padgett et al., 2009). Thus, we cannot rule out other forms of N pollution as

Table 4
Coefficients of Multiple Regression Models of Plant and Soil $\delta^{15}N$ *in the Los Angeles Metropolitan Area (LA) and Salt Lake Valley (SLV)*

Dependent variable	All independent variables	Independent variables in model	t	$Pr > \|t\|$	Partial r^2	VIF
LA Trees Adj. r^2 *= 0.546, p = 0.01*						
$\delta^{15}N$	Income	Income	−5.672	0.001	0.226	1.223
	Age	Age	2.352	0.021	0.118	1.240
	Elevation	Elevation	−5.275	0.001	0.210	1.226
	NO_2	NO_2	−1.880	0.064	0.013	1.198
SLV Grasses Adj. r^2 *= 0.122, p = 0.01*						
$\delta^{15}N$	Age	Age	−2.113	0.036	0.012	1.011
	Elevation	Elevation	−5.834	0.001	0.117	1.011
	Income			NS		
SLV Soils Adj. r^2 *= 0.129, p = 0.01*						
$\delta^{15}N$	Age	Age	−3.346	0.001	0.032	1.229
	Elevation	Elevation	−3.430	0.001	0.074	1.501
	Income	Income	−2.002	0.046	0.033	1.776

Note. Income and age refer to median household income (thousand dollars) and time since development (years), respectively. $\delta^{15}N$ is in per mil notation (‰), NO_2 is in parts per billion, and elevation is in meters. NS indicates variables that were not significant in the multiple regression model. Some variables in these relationships were log transformed for normality, including income and NO_2 in LA and income and age in SLV. Variance inflation factor (VIF) values are for correlated explanatory factors in regression models.

Table 5
Coefficients of Multiple Regression Models of NO_2 Concentrations in the Los Angeles Metropolitan Area (LA)

Dependent variable	All independent variables	Independent variables in model	t	$Pr > \|t\|$	Partial r^2	VIF
LA Plots Adj. r^2 = 0.141, p = 0.01						
NO_2	Income	Income	−2.817	0.006	0.097	1.029
	Elevation	Elevation	−2.192	0.031	0.064	1.029
	Age			NS		

Note. Income and age refer to median household income (thousand dollars) and time since development (years), respectively. NO_2 concentrations are in parts per billion, and elevation is in meters. NS indicates variables that were not significant in the multiple regression model. Some variables in these relationships were log transformed for normality, including income and NO_2. Variance inflation factor (VIF) values are for correlated explanatory factors in regression models.

a driver of foliar %N. We were unable to assess spatial patterns of atmospheric NO_2 concentrations in SLV due to an insufficient number of air monitoring stations.

The relationship between income and %N in LA may also be influenced by species differences in high- versus low-income areas. The LA urban forest is very species rich (Avolio, Pataki, Gillespie, et al., 2015; Clarke et al., 2013), and very few tree species were present in multiple sampling plots in this study. Hence, we could not constrain our analysis to specific genera. However, socioeconomic factors have been shown to affect urban tree community composition and planting preferences in Southern California (Avolio, Pataki, Pincetl, et al., 2015; Clarke et al., 2013). As a result, varying tree community composition as a function of income could explain some of the variability in foliar N.

Overall, foliar and soil $\delta^{15}N$ also declined with increasing income in both SLV and LA (Figures 3a–3c and Table 4). However, there was no relationship between $\delta^{15}N$ of SLV grasses and income in multiple regression models, highlighting interactions with other variables. The relationships between $\delta^{15}N$ and income can be informative for evaluating mechanisms underlying variation in N cycling and may be driven by either atmospheric pollution or fertilizer use. Therefore, it is necessary to attempt to distinguish between pollution and fertilizer effects on urban plant N cycling. Studies have shown that more affluent homeowners are more likely to fertilize their landscapes than less affluent homeowners (Fraser et al., 2013; Robbins et al., 2001). The nitrogen isotope ratio of a variety of synthetic inorganic fertilizers is usually near 0‰ and can range between −4 and + 4‰ (Bateman & Kelly, 2007; Kendall et al., 2007; Vitòria et al., 2004). Furthermore, analysis of ammonium nitrate fertilizer showed that both ammonium and nitrate have depleted $\delta^{15}N$ as compared to the atmosphere (Howa et al., 2014). Our measured values of foliar and soil $\delta^{15}N$ were very similar to this range in more affluent areas and more enriched in low-income areas (Figure 3). However, two pieces of evidence suggest that varying rates of fertilizer application is not a dominant mechanism underlying the observed patterns of $\delta^{15}N$: (1) The study sites in SLV were unfertilized and still showed a relationship between $\delta^{15}N$ and income. (2) Foliar %N was higher in low-income neighborhoods than in high-income neighborhoods in LA (Figure 2a and Table 3), which is the opposite of the expected relationship if higher fertilizer application in high-income neighborhoods was the underlying mechanism.

Table 6
Coefficients of Multiple Regression Models of Soil %C in the Salt Lake Valley (SLV)

Dependent variable	All independent variables	Independent variables in model	t	$Pr > \|t\|$	Partial r^2	VIF
SLV Soils Adj. r^2 = 0.211, p = 0.01						
%C	Age	Age	7.433	0.001	0.184	1.011
	Elevation	Elevation	−2.810	0.005	0.033	1.011
	Income					

Note. Income and age refer to median household income (thousand dollars) and time since development (years), respectively. Elevation is in meters. Some variables in these relationships were log transformed for normality, including income, age, and soil %C in SLV. Variance inflation factor (VIF) values are for correlated explanatory factors in regression models.

Table 7
Coefficients of Multiple Regression Models of Plant $\delta^{13}C$ in the Los Angeles Metropolitan Area (LA) and Salt Lake Valley (SLV)

Dependent variable	All independent variables	Independent variables in model	t	$Pr > \|t\|$	Partial r^2	VIF
LA Trees Adj. r^2 = 0.177 p = 0.01						
$\delta^{13}C$	Income	Income	−2.979	0.004	0.06	1.125
	NO_2	NO_2	−4.059	0.001	0.137	1.125
	Age			NS		
	Elevation			NS		
SLV Grasses Adj. r^2 = 0.03, p = 0.01						
$\delta^{13}C$	Age	Age	−3.09	0.002		
	Income			NS		
	Elevation			NS		

Note. Income and age refer to median household income (thousand dollars) and time since development (years), respectively. $\delta^{13}C$ is in per mil notation (‰), NO_2 is in parts per billion, and elevation is in meters. NS indicates variables that were not significant in the multiple regression model. Some variables in these relationships were log transformed for normality, income, and NO_2 in LA and income and age in SLV. Variance inflation factor (VIF) values are for correlated explanatory factors in regression models.

The isotopic composition of NO_x emitted from vehicular exhaust has been reported to range between −13 and −2‰, and NO_x from coal-fired boilers has been reported to range from +6 to + 13‰ (Heaton, 1990). However, another study reported more enriched values of $\delta^{15}N$ from vehicular NO_x with an average of +5.7‰ for NO_2 and + 3.1‰ for NO (Ammann et al., 1999). Enriched $\delta^{15}N$ values have also been found in roadside mosses (+3.66‰) and urban grasses (>3.0‰, max 13.3‰) (Pearson et al., 2000; W. Wang & Pataki, 2010). In this study, foliar $\delta^{15}N$ values ranged between −2.7 and 9.3‰, and −6.4 and 10.2‰ for LA and SLV plants, respectively. Nitrogen stable isotopes of SLV soils ranged between −0.1 and 11.2‰. Hence, the relationship between $\delta^{15}N$ and income (Figure 3 and Table 3) may be explained by greater exposure to N pollution in lower-income neighborhoods. However, the multiple regression model showed a decrease in $\delta^{15}N$ with increasing NO_2, although this relationship was statistically very weak (Table 4). This is contrary to expectations, given that higher pollutant concentrations are often associated with $\delta^{15}N$ enrichment. It may be that NO_2 is a nondominant form of atmospheric N pollution in our study areas, and other N forms may have stronger relationships with $\delta^{15}N$. More research is needed to better understand the connection between plant $\delta^{15}N$ and atmospheric pollution, as inconsistent relationships have previously been reported (Stewart et al., 2002). Additional mechanistic studies would further improve the application of nitrogen isotopes as tracers of atmospheric N pollution. Due to the high degree of spatial heterogeneity in urban areas, complex spatial patterns of N deposition are difficult to understand through atmospheric or traffic monitoring alone, as there are practical limitations, including financial cost, of intensively sampling pollution and traffic patterns at the scales necessary for understanding environmental justice and socio-ecological interactions (Maantay, 2007; Ott, 1977).

4.2. N, C, and Time Since Development

Relationships between leaf and soil N and C and housing age, a proxy for time since development, likely show the influence of soil disturbances associated with urbanization on N cycling. Ultimately, our results supported our second hypothesis that N and C accumulated over time in urban soils in that soil %N and %C increased with time since development (Figure 5 and Tables 3 and 6). Accumulation of soil C and N over time has been reported in other cities (Raciti et al., 2011) with Scharenbroch et al. (2005) highlighting increases in SOM over time in a few western U.S. cities. The values of N and C content in SLV soils ranged between 0.02% and 1.2% and from 0.55% to 20.7%, respectively, which is somewhat higher than values reported in other urban areas. N content of soils along highly developed roadsides in Hong Kong ranged between 0 and 0.47%, and C content ranged between 0.09 and 7.36% (Jim, 1998), although climatic and soil conditions differ markedly from our study area. A previous study in LA reported soil %N values of 0.04 ± 0.008% to 0.49 ± 0.057 (W. Wang & Pataki, 2012). In our study, the spatially extensive soil sampling in SLV led to a wide range of values for soil N and C, likely due to a wide range of microsite conditions and land use histories. Furthermore, we analyzed bulk soil C in this study, which includes both organic and inorganic C. While studies have shown variable ratios of organic to inorganic soil carbon in different ecosystems (Y. Wang et al., 2010), data are scarce for urban ecosystems.

Patterns of C:N and %N were similar; %N is shown in these analyses for brevity, but absolute values of C:N can be informative for understanding ecosystem processes. Average C:N in LA tree leaves (32.5) and SLV grasses (20.7) was relatively low, which suggests high substrate quality for decomposition and N mineralization. N is mineralized in most terrestrial ecosystems when leaf litter C:N is less than 40, with the exception of arid grasslands that showed no relationship between leaf litter quality and decomposition rates (Parton et al., 2007).

In addition to relationships with income, foliar $\delta^{15}N$ values increased with increasing time since development in LA (Figure 3 and Table 4) but decreased with increasing time since development in SLV grasses and soils (Table 4). (Note that $\delta^{15}N$ was not correlated with housing age in SLV grasses, but a negative relationship was apparent in multiple regression analysis.) The relationship between $\delta^{15}N$ and age in LA may be the result of soil N losses over time. A study of foliar and soil $\delta^{15}N$ values in Hawaii also observed $\delta^{15}N$ enrichment with increasing substrate age, which was attributed to losses of N via nitrification, leaching, and denitrification in soils and gaseous losses of N and transformations in leaves (Martinelli et al., 1999). In addition, a study analyzing foliar $\delta^{15}N$ in residential lawns across cities in the U.S. found isotopic enrichment with increasing housing age in Baltimore, Boston, and LA (Trammell et al., 2016). Further research is needed to better understand the mechanisms underlying this relationship given that $\delta^{15}N$ values decreased, or became more depleted, with time since development in SLV grasses and soils (Table 4).

Mechanistically, time since development may be a proxy for other, more direct influences on C and N cycling. For example, land use prior to urban development has been shown to play a significant role in determining soil dynamics (Raciti et al., 2011). Thus, land developed at similar times may have had similar, preurban land use legacies. If so, some of the variation that we attributed to soil age may be associated with other environmental factors or previous land use. However, Scharenbroch et al., 2005 observed that time since disturbance played the most significant role in the development of urban soils, including reducing soil bulk density, increasing microbial biomass and activity, and increasing SOM over time. This is consistent with the suggestion by Pouyat et al. (2009) that disturbance caused by construction, including site grading and vegetation and top soil removal, results in a loss of SOM followed by accumulation of soil and N and C during ecosystem development. We suggest that time since disturbance is likely an important direct mechanism driving N accumulation and enrichment in this study, but we cannot yet rule out other, indirect drivers of neighborhood environmental similarity.

4.3. $\delta^{13}C$ and Income

We assessed relationships between $\delta^{13}C$ and income in order to further examine the interactions between human activities and urban vegetation. We hypothesized that $\delta^{13}C$ would be related to income because of increased fossil fuel combustion from traffic. We did find a relationship between $\delta^{13}C$ and income in LA, but it was negative, showing more depleted values in higher-income neighborhoods. This is contrary to the expectation for lower fossil fuel emissions in high-income neighborhoods. However, we did find a negative relationship between $\delta^{13}C$ and NO_2 concentrations in LA, which is consistent with the expected pollution effect (Table 7). These opposing findings could be explained by less plant water stress in higher-income neighborhoods due to greater irrigation, in addition to $\delta^{13}C$ depletion caused by pollution. Higher irrigation volumes have been associated with higher incomes in LA (Mini et al., 2014). Given the other evidence for increased traffic emissions in low-income neighborhoods, including the correlations between income and NO_2 in LA and $\delta^{15}N$ and income in both LA and SLV, the results for $\delta^{13}C$ are partially consistent with this pattern but show the additional effects of variations in plant gas exchange.

4.4. N, C, and Socioecological Variables

We used multiple regression analyses to further understand the variation in N and C content and stable isotope ratios. We found that $\delta^{15}N$ had an independent, negative relationship with elevation in LA trees, SLV grasses, and SLV soils (Table 4). Decreases in $\delta^{15}N$ with elevation have been attributed to greater nitrification rates in relation to water availability (Biswas et al., 2008). The relationship between $\delta^{15}N$ and elevation could also be driven by atmospheric pollution considering greater NO_2 concentrations at low elevation in LA (Table 5). In addition, we found that bulk soil C content decreased with elevation in SLV (Table 6). Soil organic carbon stocks have been found to increase with elevation (Dieleman et al., 2013) due to higher decomposition rates (Vitousek et al., 1994). While we found the opposite trend between soil C content and elevation in SLV, this may be the result of several factors including climate, atmospheric composition, and soil types, which are highly heterogeneous in urban areas. Finally, multiple regression analyses also highlighted a relationship between δ^{13}C and time since development in SLV grasses (Table 7). These patterns either reflect greater sources of fossil fuel-derived CO_2 in these neighborhoods or physiological responses to differing environmental conditions reflected in changes in leaf c_i/c_a. Given the relatively depleted foliar values, which were as low as −31‰, fossil fuel-derived CO_2 likely has an important influence.

5. Conclusions

We report for the first time that affluence strongly influences isotopic ratios of urban plants and soils, as well as their C and N content, in two cities in the semiarid, western United States. In SLV, the N and C content of urban soils increased with housing age while foliar N content decreased with increasing income in LA. In both cities, δ^{15}N of tree leaves and soils was inversely related to median household income, which may be associated with greater concentrations of N pollution in low-income areas. Because both NO_2 concentrations and leaf %N declined with increasing affluence in LA, we suggest that foliar N isotope enrichment is at least partially influenced by spatial variability in atmospheric pollution. More detailed studies are needed to further explore the mechanisms underlying these patterns, but these results are a first indication that the isotopic composition of urban plants and soils is a useful measure of relationships between C and N cycling and sociodemographic characteristics.

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