Development and landscaping choices differentiate heterogeneous tree and shrub communities on office developments

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ABSTRACT

In urban ecosystems, woody vegetation communities and the ecosystem functions and habitat they provide are largely controlled by humans. These communities are assembled during development, landscaping, and maintenance processes according to decisions made by human actors. While vegetation communities on residential land uses are increasingly well studied, these efforts have generally not extended to other and uses, including commercial land uses; we thus know little about the vegetation communities on these land uses and how they are assembled. To fill this gap, I surveyed tree and shrub communities on office developments located in Redmond and Bellevue, Washington, USA, and explored whether aggregated and parcel scale socio-economic variables or variables describing the outcome of development and landscaping actions better explained variation in vegetation communities. I found that both tree and shrub communities are heterogeneous, with distinct groups of sites characterized by native or ornamental vegetation. The outcome of actors' decision making also explains more variation than aggregated or parcel scale socio-economic variables found significant on residential property. The observed heterogeneity in vegetation communities suggests that different ecosystem functions and habitat quantity and quality are provided on office developments; better provision of these functions is possible using currently existing developments as models. Further, the heterogeneity and observed differences in variable importance between office developments and residential land uses suggests that future urban ecology research must more carefully consider sampling design and that models of the urban ecosystem must account for different decision pathways on land uses. Going forward, research should examine other commercial land uses, commercial land use in additional ecotypes, and decision pathways followed by actors on commercial land uses.

INTRODUCTION

Perennial vegetation community composition, structure, and distribution are largely controlled by human actions in urban ecosystems (Avolio et al., 2018; Faeth et al., 2011; Gibb and Hochuli, 2002; Mullaney et al., 2015; Peters et al., 2011; Pickett et al., 2008; Sharpe et al., 1986). These changes to the vegetation community alter ecosystem service provision and habitat quality and quantity (Byrne, 2007; Faeth et al., 2011; Lehmann et al., 2014). Despite the need to understand these processes across cities, non-residential land uses have received little research attention.

Development, landscaping, and ongoing maintenance are important milestones for vegetation management decisions and points where landowner motivations and preferences determine vegetation community characteristics. In the Puget Sound region, development has replaced fire as the primary disturbance driver and precursor to new forest stands (Gibb and Hochuli, 2002; Halpern and Spies, 1995; Sharpe et al., 1986; Walcott, 1899). The mechanisms of disturbance when clearing and grading land for development include removing vegetation, removing topsoil, and compacting soil with heavy equipment (Figure 1; Andres and Smith, 2004; Dorney et al., 1984; Grimm et al., 2017; McKinney, 2002; Turner, 2005). Decisions made by developers and land owners at the time of development determine the extent of disturbance and influence future site conditions. For example, choosing to preserve existing trees determines legacy vegetation and influences stand characteristics like age and size (Dorney et al., 1984).

Figure 1: Commercial development project located in Redmond, WA. A. clearing the site of vegetation; B. grading the site and digging foundation. Photo credit: K. Dyson

Vegetation succession in urban ecosystems is determined through ecological processes such as dispersal and regeneration from seed banks and through decisions during landscaping and ongoing maintenance (Zipperer, 2010). However, the latter has become the dominant process with decisions made by developers and landowners (Dorney et al., 1984; Faeth et al., 2011; Goodness, 2018; Grimm et al., 2017; Heezik et al., 2014; Kendal et al., 2012; Widrlechner, 1990). Plants chosen for landscaping are often ornamental introduced shrubs, trees, or grasses, though using native species in landscaping is becoming more common (Blair, 1996; Burghardt et al., 2009; Faeth et al., 2011; Germaine et al., 1998; Heezik et al., 2014; McKinney, 2002). Once planted, these require significant ongoing maintenance inputs to arrest succession and maintain the desired aesthetic (Faeth et al., 2011; LeBauer and Treseder, 2008; Lepczyk et al., 2004; Zipperer, 2010). Along with trees retained through tree preservation policies, landscape plantings represent a significant portion of the vegetation on site and of the habitat quality and quantity available to other organisms (Avolio et al., 2018; Faeth et al., 2011).

Drivers determining vegetation management decisions, actions, and outcomes are multi-scalar, and include policy, neighborhood scale social pressures, and the motivations and preferences of individual landowners (Cook et al., 2012). Relevant public policies include clearing and grading permitting processes, impervious surface maximums and minimums via parking space requirements, tree protection policies, canopy cover goals, and vegetation planting policies (DeLaria, 2008; Environmental Protection Agency, 2011; Young, 2011). These policies are frequently enacted to protect ecosystem services, including carbon sequestration and aesthetic benefits (Collins et al., 2011; Conway, 2016; Dorney et al., 1984; Elmendorf, 2008; Goodness, 2018; Wolf, 2005).

Neighborhood scale drivers include social norms and customs that influence individual behavior (Cook et al., 2012). On residential properties, homeowners alter preferences for their own yards in response to the choices of nearby neighbor's yards (Nassauer et al., 2009), though assumptions about neighborhood preference are not always accurate (Peterson et al., 2012). On commercial properties, owners may alter preferences based on prospective and existing tenants (Laverne et al., 2003; Levy and Peterson, 2013).

Individual scale drivers center on past and present decision maker's motivations and preferences. Developers for all land uses are often motivated by cost and investment decisions (Almagor, 2017); mass construction paired with removing existing vegetation is purportedly cheaper, though preserving vegetation may be less expensive in the long run (McKinney, 2002).

Landowner socio-economic status is often important in studies of residential property. While these variables are aggregated to the neighborhood scale, they reflect group membership of the individual thought to serve as a proxy for commonly held attitudes and ability to manipulate their environment (Heynen et al., 2006). Socio-economic variables correlated with canopy cover and other vegetation metrics include: current and historic household income (Avolio et al., 2015, 2018; Boone et al., 2010; Clarke et al., 2013; Heynen et al., 2006; Hope et al., 2003; Krafft and Fryd, 2016; Larsen and Harlan, 2006; Leong et al., 2018; Luck et al., 2009; Sierra-Guerrero and Amarillo-Suárez, 2017), education level (Kendal et al., 2012; Krafft and Fryd, 2016; Luck et al., 2009), ethnic composition (Grove et al., 2006; Heynen et al., 2006; Leong et al., 2018; Luck et al., 2009), home value (Mills et al., 2016), home ownership (Heynen et al., 2006), and housing age (Avolio et al., 2018; Boone et al., 2010; Clarke et al., 2013; Jim, 1993; Sierra-Guerrero and Amarillo-Suárez, 2017). However, researchers that disaggregate socio-economic characteristics find that individual attitudes may be more important than these aggregated measures that serve as a proxy (Kendal et al., 2012; Shakeel and Conway, 2014).

In municipal parks, education level and park age (Martin et al., 2004) were only occasionally important (Kendal et al., 2012). These are thought to influence vegetation through neighborhood investment, advocacy, and legacy effects (Boone et al., 2010; Rigolon et al., 2018), which are less direct than decisions by homeowners on their private property. Individual scale drivers on other land uses are poorly studied.

These management decisions which create vegetation communities and patterns in cities also impact ecosystem function, food webs, and biodiversity (Avolio et al., 2018; Dorney et al., 1984; Faeth et al., 2011, 2005; McKinney, 2002; Wittig, 2010). Different tree and shrub species have different capacity for carbon sequestration (Tang et al., 2016; Tenneson, 2013). Introduced ornamentals generally do not same insect species, or the same biomass or diversity of fauna as native habitat (Burghardt et al., 2009; Crisp et al., 1998; Mach and Potter, 2018; McKinney, 2002; Rebele, 1994). These changes to habitat quality and quantity also impact higher trophic levels (Alberti, 2005; Alberti et al., 2003; Burghardt et al., 2009; Faeth et al., 2011; Marzluff et al., 2001; Polasky et al., 2005; Rosenzweig, 2003). For the urban matrix to support conservation, decision makers across land uses need to take actions that support locally important vegetation habitat (Goddard et al., 2010; Miller and Hobbs, 2002).

While the drivers and outcomes of decision making are increasingly well studied on residential private property, other land uses have not been given the same attention (Bourne and Conway, 2014; Snep et al., 2011). For example, commercial and industrial land uses are generally included only as independent variables in remote sensing studies of factors influencing percent canopy cover (e.g. Fan et al., 2019; Mills et al., 2016). Research where the unit of analysis is defined by the area of influence of specific decision makers is also needed. Aggregated measures, such as vegetation transects through neighborhoods or canopy cover of a census block, cannot examine specific decision outcomes as they conflate different actors and their motivations and actions, and previous research shows that motivations differ between actors (Kendal et al., 2012; Tenneson, 2013).

To fill this gap, I examined vegetation community composition on office developments in Bellevue and Redmond, Washington, USA. Specifically, I examined 1) tree and shrub communities present on office developments and 2) whether aggregated or parcel specific socio-economic variables or development and landscaping outcomes better explained observed variation in vegetation communities.

I hypothesized that vegetation communities on office developments would be heterogeneous. I also hypothesized that aggregated socio-economic variables found significant in explaining vegetation patterns on residential property would not be significant on office developments (Avolio et al., 2018; Conway, 2016; Hope et al., 2003), but that parcel level variables would. Finally, I hypothesized that the outcome of development and landscaping actions would better explain variation in tree and shrub community structure. I found that vegetation communities on office developments are variable with multiple community types, and that in contrast with residential property, development and landscaping actions explain this variability better than socio-economic variables. The observed within land use variability has implications for how urban ecologists should approach sampling design

MATERIALS AND METHODS

STUDY AREA AND SITE SELECTION

Redmond (2017 population 64,000) and Bellevue (population 144,000) are located east of Seattle in King County, Washington (United States Census Bureau, 2017). Both cities share a similar ecological history, a similar disturbance timeline for logging and agriculture, and have grown considerably since the opening of the Evergreen Point Floating Bridge (SR 520) in 1963. They are at similar elevations (< 160 m) and experience the same climate and weather.

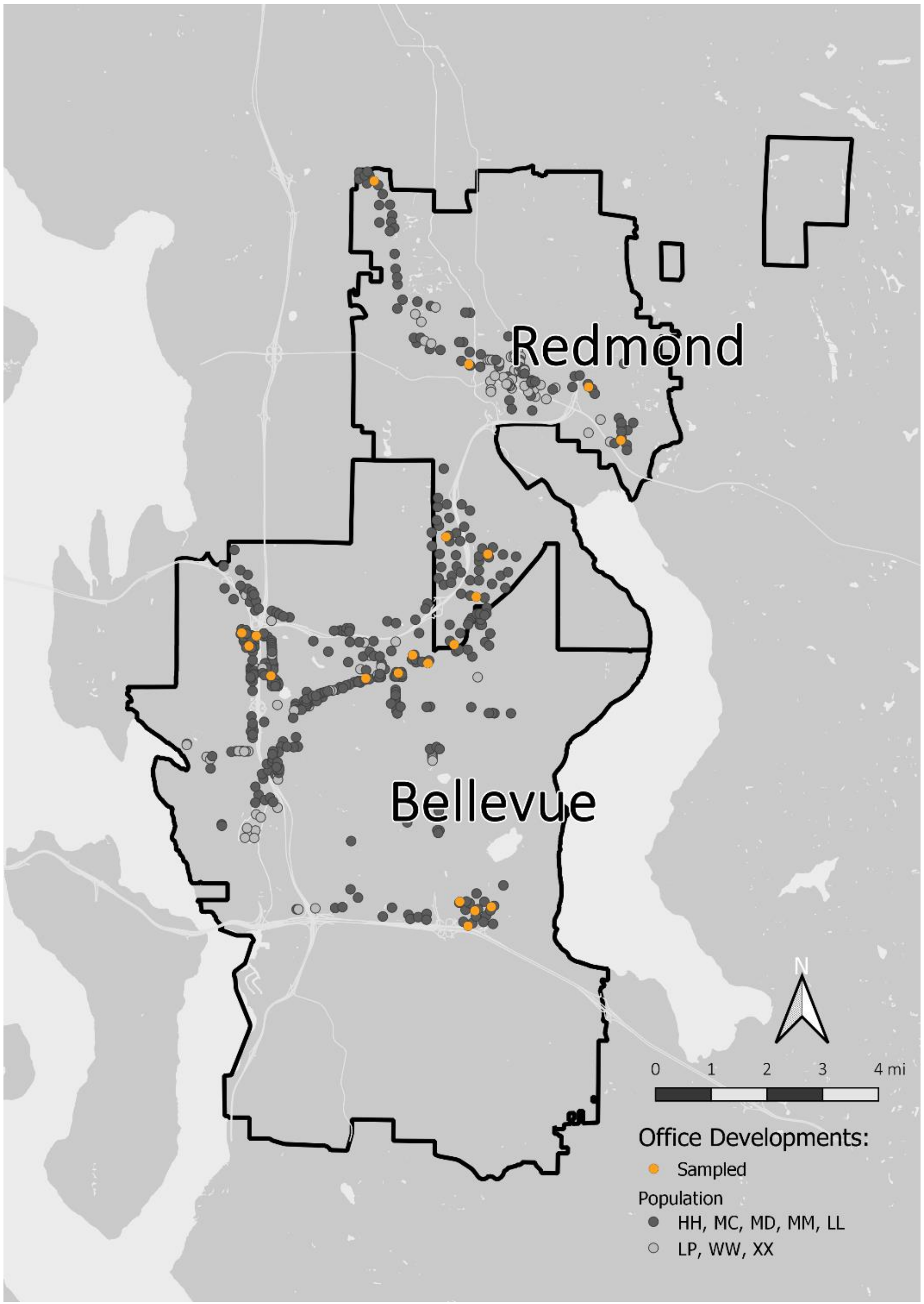

Figure 2: Map of office development study sites in Redmond and Bellevue, Washington. The population of office developments with High, Medium Canopy, Medium Diverse, Medium, and Low vegetation types are represented with dark gray circles; excluded sites (no vegetation, wetlands, and under construction) are represented with light gray circles. Sampled sites are shown with orange circles.

The sampling frame was limited to Redmond and Bellevue north of I-90, excluded developments in Bellevue's central business district, and contained parcels defined as office use by the King County Assessor's Office (Figure 2). I grouped adjacent parcels built within three years of one another and with the same owner to create a unit of analysis based on human action not cadastral boundaries. This initial population size was 492 developments.

I used disproportionate stratified random sampling to ensure that my sample included sites across the entire vegetation gradient. I classified the vegetation at each potential study site into type categories using a brief visual estimation during site visits in early 2014 (Figure 3, Table 1). Sites with no vegetation, with wetlands, or those that were currently under construction or undergoing landscape replanting were excluded from the analysis (87 sites). The remaining pool of 405 potential sites had no notable hydrological features on site.

Table 1: Vegetation type assignment criteria and strata size. Sites without vegetation and those with wetlands present were excluded from further analysis.

Vegetation Type	Tree Cover	Shrub Richness	Strata Size	Sampled (n)	Notes
High	30% native tree cover	> 5 native shrub genera	10	5	
Medium Canopy	30% native tree cover	No requirement	22	3	
Medium Diverse	15% tree cover	> 5 native shrub genera	53	4	
Medium	15% tree cover	> 5 shrub genera	264	3	
Low	< 10% tree cover	< 5 shrub genera	56	5	
No Vegetation	No trees	No shrubs	71	0	Excluded from further analysis
Wetlands	No requirement	No requirement	10	0	Wetland present, excluded from further analysis

Figure 3: Examples of each vegetation type. From top left to bottom right: High (HH); Medium Canopy (MC); Medium Diverse (MD); Medium (MM); Low (LL); no vegetation (LP; excluded); wetlands (WW; excluded).

I conducted stratified random sampling on sites with High, Medium Canopy, Medium Diverse, Medium, and Low vegetation types. I restricted the sampling pool to sites in the 25th to 85th percentile of site area and the 15th to 85th percentile of surrounding impervious surfaces. These limits were imposed to avoid confounding factors and were based on the smallest strata. Limiting sampling of these extremes reduced my ability to detect community differences along these gradients, though socio-economic variables are not covariate.

I requested property access through three mailings sent to the property owner or manager on file in the King County Assessor's database (Dyson et al., 2019). I targeted vegetation categories underrepresented in my sample in the second and third mailings. Of 46 mailed requests, 20 (43.5%) received no response or were not deliverable. Of the 26 (56.5%) responses received, 6 (23.1%) of were rejected and 20 (76.9%) were accepted in writing by an individual with authority to do so (Table 1).

Commercial use of sample sites included light industrial, white collar office space, and medical/dental offices. Some sites were fully leased to tenants, while others were either partly or fully owner-occupied. Company size ranged from less than 10 to many thousand employees.

INDEPENDENT VARIABLES

Socio-economic variables were derived from existing databases (Homer et al., 2015; King County Department of Assessments, 2014; King County GIS Center, 2014; Table 2; United States Census Bureau, 2016; Xian et al., 2011). Variables were chosen based on previous research and analyzed in QGIS 3.2 (Dana et al., 2002; Grove et al., 2014; Hope et al., 2003; Martin et al., 2004; QGIS Development Team, 2016; Walker et al., 2009).

I measured the height of dominant native conifers with a Nikon Forestry Pro Laser Rangefinder; I used this as a proxy measure for age as I did not collect tree cores due to liability concerns (Dyson et al., 2019). I used historical records and site construction plans to determine whether each site had a stand of three adjacent tree predating site development. I used *Pseudotsuga menziesii* (Mirb.) Franco, *Thuja plicata* Donn ex D. Don, and *Tsuga heterophylla* (Raf.) Sarg. counts to calculate native conifer density.

After recording broad ground cover material types on paper maps, I hand digitized them in QGIS to calculate area (QGIS Development Team, 2016). Pervious cover types recorded include dense vegetation, dirt/litter, lawn (turf grass including moss and forb species), gravel, dense ivy, mulch, and water. I used semi-structured interviews of property owners, managers, and landscaping services along with site visits to obtain maintenance regime variables (Dexter, 1970; Harvey, 2011; University of Washington Human Subjects Division Determination of Exemption #48246). Irrigation, mulching, herbicide, and fertilizer application had only three “no” responses and thus could not be used to draw any well supported conclusions.

Table 2: Definition of independent variables used in PERMANOVA and correlation analysis. Summary statistics for independent variables for both the population of office developments in Redmond and Bellevue and the sample of sites studied (405 and 20 sites, respectively). Median income ($) and proportion foreign born are included to compare patterns in commercial developments with patterns found significant in residential research. Data sources: Homer et al., 2015; King County Department of Assessments, 2014; King County GIS Center, 2014; United States Census Bureau, 2016; and Xian et al., 2011.

Variable Name	Definition	Data Source	Population	Sample
1. AGGREGATED AND PARCEL LEVEL SOCIO-ECONOMIC VARIABLES				
Area (acre)	Site area, in acres.	King County Assessor	Range: 0.14-42.51; Mean (SD): 3.61 (5.51)	Range: 0.63-5.39; Mean (SD): 2.57 (1.58)
Town	Location, Bellevue or Redmond.	King County Assessor	Bellevue: 281 Redmond: 123	Bellevue: 13 Redmond: 7
Building Age (years, in 2017)	Age of building on site (or mean age for multiple buildings) in 2017.	King County Assessor	Range: 4-99; Mean (SD): 33.2 (11.8)	Range: 9-42; Mean (SD): 32.1(9.8)
Building Quality	Categorical ‘quality class’ assigned to buildings on the site	King County Assessor	Below Average: 11 Average: 146 Average/Good: 96 Good: 120 Good/Excellent: 25	Below Average: 0 Average: 7 Average/Good: 4 Good: 7 Good/Excellent: 2
Appraised Land Value	Appraised land value divided by site area. Missing	King County Assessor	Range: 214,673-6,086,305; Mean (SD):	Range: 578,266-3,028,353; Mean (SD):

per Acre (USD)	assessed land values were replaced with population median land value.		1,845,520 (904,065)	1,679,110 (623,031)
Impervious w/in 500 m (%)	Percent impervious surface within 500 m of the site's perimeter.	National Land Cover Database 2011 Percent Developed Imperviousness dataset updated in 2014	Range: 19.5-81.1; Mean (SD): 55.8 (11.6)	Range: 48.8-67; Mean (SD): 56.8 (6.3)
Median Household Income (2014 USD)	The median household income of residents for the site's block group.	American Community Survey 2014 5-year block group	Range: 42,368-194,107; Mean (SD): 81,408 (24,957)	Range: 42,368-134,643; Mean (SD): 80,478 (22,179)
Percent Foreign-Born	The percent of residents born outside of the United States for the site's block group.	American Community Survey 2014 5-year block group	Range: 14.6-86.1; Mean (SD): 39 (16.7)	Range: 14.6-86.1; Mean (SD): 40.6 (18.3)
2. DEVELOPMENT AND LANDSCAPING OUTCOME VARIABLES				
Stands Predate Development	Binary variable indicating presence of a cluster of three+ trees that predate development.	Site survey	NA	Yes: 12 No: 8
Median Height of Dominant Conifer (m)	Median height of five dominant native conifer trees; age proxy.	Site survey	NA	Range: 0-40.6; Mean (SD): 25.8 (13.0)
Density of Native Conifers (trees/ acre)	Total density of Douglas-fir, western redcedar, and western hemlock.	Site survey	NA	Range: 0-61.3; Mean (SD): 22.5 (19.3)

3. GROUND COVER MATERIAL AND MAINTENANCE ACTION				
Ground Cover Types (%)	Ground cover types on site including lawn, mulch, and impervious surface.	Site survey	NA	Mean (SD) Grass: 7.3 (6.9); Impervious: 66.4 (10.5); Dirt/Litter: 6.0 (8.0)
Dead Wood (count)	Total abundance of stumps, logs, and snags on site.	Site survey	NA	Range: 0-40.6; Mean (SD): 25.8(13)
Irrigation	Binary variable indicating whether irrigation is used during the summer months.	Interviews and site survey	NA	Yes: 16 No: 3
Mulch, Herbicide, and/or Fertilizer Application	Binary variables (3) indicating whether landscaping crew applies mulch, herbicides, or fertilizers to a site.	Interviews and site survey	NA	Mulch Y/N: 17/3 Herbicide: 13/4 Fertilizer: 15/3

VEGETATION DATA COLLECTION

I censused vegetation communities during the summer of 2015, excluding saplings with DBH < 3“. Each tree and shrub was identified to species or genus in consultation with experts at the Center for Urban Horticulture at University of Washington (Dirr, 2009, 1997; Sibley and others, 2009). Some tree and shrub species were grouped at the genus level due to the abundance of very similar cultivars in the landscaping trade, including *Malus* Mill. (Sierra-Guerrero and Amarillo-Suárez, 2017). All cultivars Following Daniels and Kirkpatrick (2006), I grouped conifers under 2 m into a broad class of dwarf conifer species. 10 individual trees (0.506%) and 218 shrubs (2.712%) could not be identified; these were given a unique identifier code for multivariate community analysis.

I assigned tree and shrub genera to one of three provenance categories—native, non-native, or ambiguous (U.S. Geological Survey, 1999; USDA, 2016). The ambiguous category was used for genera including both native and non-native cultivated species that are difficult to distinguish, and/or frequently interbred and sold as crosses. For example, some *Mahonia* Nutt. sp. are native (*M. aquifolium* Pursh Nutt. and *M. nervosa* Pursh Nutt.), while others originate in Asia (*Mahonia japonica* Thumb. DC.) and many hybrids are bred and sold by nurseries (e.g. *Mahonia x media* “Charity” Brickell).

IDENTIFYING AND DESCRIBING VEGETATION CLUSTERS ON OFFICE DEVELOPMENTS

Prior to flexible beta clustering and PERMANOVA analysis I standardized tree and shrub abundance data and ground cover area by total site area in acres. This transformation preserves parcel boundaries as the unit of analysis and reflects developer and landowner actions during and following development that determine the amount of impervious surface and pervious area, the number of trees preserved, and the number of trees and shrubs planted. Between site standardization (e.g. Wisconsin standardization) was not needed as the vegetation on all sites was completely censused.

To delineate vegetation community clusters on office developments, I used the agnes {vegan} function with beta = -0.5 to produce an ecologically interpretable dendrogram with minimal chaining (Breckenridge, 2000; Dufrêne and Legendre, 1997; McCune et al., 2002; Milligan, 1989; Oksanen et al., 2017). For the resulting groups, I performed indicator species analysis, which assesses the predictive values of species as indicators of the conditions at site groups, using multipatt {indicspecies} (De Caceres and Legendre, 2009; De Cáceres, 2013; De Cáceres et al., 2010). I ran the permutation-based function 100 times and took the mean of the indicator statistics generated for each species (Dyson, 2018). I used proportions to extrapolate group membership as determined by flexible beta clustering to the entire population of office developments in the study area based on corresponding pre-assigned vegetation type. I modeled total tree abundance per site for the entire population using the observed mean and standard deviations for tree abundance for each of these five vegetation types.

After identifying vegetation community clusters, I used simple univariate PERMANOVA models to test if continuous variables differed between groups and Pearson’s Chi-squared test to test if categorical variables differed (adonis2 {vegan} and chisq.test {stats}; Oksanen et al., 2017). PERMANOVA is a permutation-based implementation of ANOVA/MANOVA that avoids assumptions about underlying distributions of community structure and can be used with non-Euclidian distance matrices (Anderson, 2001). Bartlett tests of homogeneity found no difference between group variances (bartlett.test {stats}).

EXPLAINING VARIATION IN TREE AND SHRUB COMMUNITY STRUCTURE

I analyzed the tree and shrub communities separately to detect if they responded differently to socio-economic gradients or development and landscaping outcomes. Additionally, the development and landscaping outcome variables are derived from measurements of the tree community. To avoid regressing the tree community against a measure of itself, I used non-metric multidimensional scaling (NMDS) to evaluate relationship between these variables and the tree community, and PERMANOVA for all other tests.

NMDS is a rank-based ordination technique that is robust to data without identifiable distribution, can be used with any distance or dissimilarity measure; here I used Bray-Curtis (McCune et al., 2002). I used 100 repetitions of the metaMDS {vegan} implementation to find a stable minimum (McCune et al., 2002; Oksanen et al., 2017). To determine the relationship between development and landscaping outcome variables and the tree community, I used convex hull plots and fitted environmental vectors (ordiplot and envfit {vegan}; Oksanen et al., 2017).

I used a multi-step approach to avoid transforming independent variables or using ordination to collapse related variables, as these actions make results less interpretable for urban planners and other professionals. I first tested each independent variable in a simple multivariate PERMANOVA model. To ensure differences in categorical variables were due to location and not dispersion, I used ANOVA to test for significant differences in dispersion (anova {stats} and betadisper {vegan}; Oksanen et al., 2017). I then constructed models using all variables with significant pseudo-F values in all possible single and multiple variable model combinations. Significance was assessed at the $\alpha \leq 0.05$ level following Holm-Bonferroni correction for multiple comparisons. I used a custom AICc function based on residual sums of squares to compare models and identify those with the best support (Dyson, 2018).

RESULTS AND DISCUSSION

Woody vegetation communities on office developments in Redmond and Bellevue, Washington are heterogenous (Table 3). Cluster analysis identified distinct “Native” and “Ornamental” community types for both trees and shrubs; extrapolating these to the population level suggests that sites dominated by native vegetation are less frequent. I found that development and landscaping actions explain this variability better than aggregated and parcel scale socio-economic variables, in contrast with residential property (Clarke et al., 2013; Hope et al., 2003; Luck et al., 2009). These findings have implications for urban conservation and public policy, as well as future urban ecology research.

OBSERVED WOODY VEGETATION COMMUNITIES

I recorded a total of 1978 individual trees and 8039 individual shrubs from 52 and 84 taxonomic groups respectively (Supplemental Tables 1 & 2). Only *Rhododendron* L. were found on all 20 sites surveyed. Four tree species and nine shrub species were found on more than half of all office developments, with 23 tree species and 30 shrub taxa found only on only one development.

Native tree species accounted for 68.1% of total individuals observed, and three of the top five most abundant species. On average, native tree species accounted for 63.4% of the trees found on each office development, though sites varied widely with 0%–99% native tree stems. *Pseudotsuga menziesii* was by far the most abundant tree species, with 37.7% of observed individuals. *Thuja plicata* (12.4%), *Acer macrophyllum* Pursh (11.0%), *Acer rubrum* L. (6.7%), and *Acer platanoides* L. (5.1%) complete the top five. *Prunus* L. and *Alnus rubra* Bong. were both widespread taxa (found on 12 and 9 sites, respectively) but were never abundant on any one site.

In contrast, native shrub species accounted for only 30.4% individual shrubs observed. On average, native shrubs accounted for 26.0% of the shrubs observed at each office development, and never more than 63.2% of individual shrubs. The two most abundant shrub species were the native *Gaultheria shallon* Pursh (15.8%), which frequently occurs in low, dense mats, and *Berberis Mahonia gp.* Nutt. (12.5%) which is comprised of native, introduced, and hybrid species. The rest of the top five most abundant shrub species were all non-native, including *Prunus laurocerasus* L. (8.5%), *Rhododendron* (7.6%), and *Cornus sericea* L. (5.2%).

Measures of tree and shrub abundance, density, and diversity varied substantially between sites (Table 3). In general, total species richness and native species richness were positively correlated (Pearson's Correlation for Trees: 0.594; Shrubs: 0.545), though four sites with above average species richness had three or fewer native species planted. Remnant large native conifer abundance, primarily *Pseudotsuga menziesii*, greatly contributed to sites with greater tree abundance (Pearson's: 0.83); consequently, Shannon diversity was generally lower on sites with more native trees (Pearson's: -0.407).

Overall, these measures are within the ranges reported by other urban ecology studies, though differences in methodology and particularly the use of small plots (e.g. Clarke et al., 2013) and remote sensing (e.g. Luck et al., 2009) in other studies and stratified sampling in this study make comparison more difficult. The most abundant tree species on office developments matched well with similar studies on residential properties in western Washington (Mills et al., 2016; Tenneson, 2013). The observed pattern of a few highly abundant species with a long tail of rare species is also consistent with other studies of urban land use (Jim, 1993; Sierra-Guerrero and Amarillo-Suárez, 2017; Thompson, 2004). Measures of diversity were generally lower than residential property (Clarke et al., 2013; Martin et al., 2004). However, the number of species observed was comparable to other commercial land uses and in city parks (Clarke et al., 2013; Martin et al., 2004) though lower than residential land uses (Clarke et al., 2013; Jim, 1993; Martin et al., 2004; Sierra-Guerrero and Amarillo-Suárez, 2017). Measures of beta diversity, suggesting low similarity between locations, was also consistent (Sierra-Guerrero and Amarillo-Suárez, 2017).

Table 3 Metrics for tree and shrub communities on sampled office developments. H' is Shannon's diversity index (Shannon and Weaver, 1949), effective species richness = exp(H') (Jost, 2006), density = individuals per acre.

Metric	Minimum	Maximum	Mean	S.D.	Median
Tree Abundance	10	240	98.9	64.4	86
Tree Density	15.2	104.8	43.5	26.2	31.4
Tree Species Richness	3	16	8.6	3.7	7
Native Tree Species Richness	0	8	3.9	2.3	4
Tree Shannon Diversity	0.6	2.2	1.5	0.4	1.5
Tree Effective Species Richness	1.9	8.7	4.8	1.9	4.7
Native Tree Shannon Diversity	0	1.6	0.7	0.6	0.9
Native Tree Effective Species Richness	1	4.7	2.4	1.2	2.5
Native Conifer Abundance	0	216	49.8	57.6	28
Native Conifer Density	0	61.3	22.5	19.3	19.7
Native Tree Abundance	0	230	67.4	68.6	42
Native Tree Density	0	103.6	32.9	30.5	26.9
Shrub Abundance	71	1789	401.9	439	220.5
Shrub Density	39.6	404	153.1	99.7	125.7
Shrub Species Richness	8	40	18.1	7	18
Native Shrub Species Richness	0	10	4	2.6	4
Shrub Shannon Diversity	1.7	3	2.3	0.3	2.3
Shrub Effective Species Richness	5.7	20.6	10.5	3.5	10.1
Native Shrub Shannon Diversity	0	1.6	0.9	0.5	1.1
Native Shrub Effective Species Richness	1	4.9	2.9	1.2	2.9
Native Shrub Abundance	0	675	122	195.6	48.5
Tree Sorensen	0.273	1	0.665	0.160	0.667
Tree Arrhenius Model z	0.348	1	0.729	0.141	0.737
Shrub Sorensen	0.357	0.92	0.630	0.109	0.613
Shrub Arrhenius Model z	0.441	0.941	0.702	0.096	0.69

DIVERGENT VEGETATION GROUPS FOUND ON OFFICE DEVELOPMENTS

I identified two groups of tree and shrub vegetation (flexible beta = -0.5; agglomerative coefficients of 0.871 and 0.76 respectively; Table 4). Using indicator species analysis, I found the Native Tree group (11 sites) is characterized by *Thuja plicata*, *Acer macrophyllum* Pursh, *Arbutus menziesii* Pursh, and *Alnus rubra* Bong, while the Ornamental Tree group (9 sites) is characterized by *Acer rubrum* L. The Native Shrub group (11 sites) is characterized by *Gaultheria shallon* Pursh, *Mahonia* Nutt., *Symphoricarpos* Duham., and *Ribes sanguineum* Pursh, and the Ornamental Shrub group (9 sites) by *Thuja occidentalis* L.

Table 4 Rank abundance of tree and shrub taxa for each community group identified by flexible-beta analysis. Asterisk indicates native tree and shrub species.

Rank	Native Tree Group	Ornamental Tree Group	Native Shrub Group	Ornamental Shrub Group
1	Pseudotsuga menziesii* (58.6)	Pseudotsuga menziesii* (11.2)	Gaultheria shallon* (106.1)	Prunus laurocerasus (57.3)
2	Thuja plicata* (20.4)	Acer rubrum (10.9)	Berberis Mahonia gp. (84)	Rhododendron sp. (36.6)
3	Acer macrophyllum* (19.4)	Acer platanoides (10.4)	Rhododendron sp. (25.7)	Cornus sericea gp. (23.4)
4	Acer rubrum (3.1)	Pinus nigra (8)	Cornus sericea gp. (18.9)	Lonicera pileata (15.1)
5	Alnus rubra* (2.2)	Callitropsis nootkatensis* (5.4)	Acer circinatum* (18.3)	Viburnum davidii (13.7)
6	Arbutus menziesii* (1.7)	Acer saccharum (4.8)	Vaccinium ovatum* (16.1)	Berberis thunbergii (13.1)
7	Populus tremuloides (1.5)	Fraxinus americana (3.9)	Prunus laurocerasus (15.1)	Gaultheria shallon* (11.1)
8	Liquidambar styraciflua (1.2)	Prunus subg. Cerasus (3.3)	Viburnum davidii (14.1)	Ilex crenata (10.1)
9	Prunus subg. Cerasus (0.8)	Thuja plicata* (2.3)	Symphoricarpos* (13)	Ornamental conifer (9.9)
10	Callitropsis nootkatensis* (0.7)	Fraxinus pennsylvanica (1.9)	Ribes sanguineum* (12.5)	Mahonia (9.2)

The two groups are distinct in the average abundance of trees and shrubs per site (Native Tree mean = 117.1, Ornamental Tree mean = 76.7 with Pr($>F$) = 0.167; Native Shrub mean = 575.6, Ornamental Shrub mean = 259.9 with Pr($>F$) = 0.111). The median height of dominant native conifers was also significantly different between Native and Ornamental clusters for trees and shrubs (tree mean values = 33.2 m and 16.8 m with Pr($>F$) = 0.001; shrub mean values = 32.6 m and 20.2 m with Pr($>F$) = 0.031). However, there was no difference in area between Native and Ornamental clusters for either trees or shrubs (tree Pr($>F$) = 0.425; shrub Pr($>F$) = 0.598).

Of the associated ground cover only impervious surface cover between Native and Ornamental Tree sites differed significantly (tree mean values = 60 and 70 with Pr($>F$) = 0.008). No other ground covers differed. Dead wood was significantly more abundant on Native Tree sites than Ornamental Tree sites (tree mean values = 13.4 and 2.4 with Pr($>F$) = 0.018), but not between shrub site groups.

There was also substantial co-occurrence between Native and Ornamental groups. Of the 20 office developments surveyed, nine sites belong to both Native Tree and Shrub community groups, and seven sites belong to both Ornamental Tree and Shrub community groups. This suggests that the sequential decisions made concerning tree preservation, tree plantings, and shrub plantings are related. The observed differences in species composition, between group differences, and high turnover (beta diversity) support the conclusion that woody vegetation communities on office developments are heterogenous.

Native Tree and Shrub communities are more rare than Ornamental Tree and Shrub communities. Extrapolation suggests there are approximately 70 Native Tree and 335 Ornamental Tree developments (17.3%), and 152 Native Shrub and 253 Ornamental Shrub developments (37.531%). The accuracy of these estimates will be influenced by the Medium vegetation type, as it is large and proportionally under sampled, and the relatively small sample size.

SOCIO-ECONOMIC VARIABLES POORLY EXPLAIN VARIATION IN TREE OR SHRUB COMMUNITY COMPOSITION

Neither aggregated measures of residential socio-economic status nor parcel scale measures of economic value and the built environment adequately explain variation in tree and shrub community composition on office developments (Supplemental Table 3). For the tree community, median household income is significant before, though not after, using the Holm-Bonferroni correction for multiple comparisons. Convex hulls fitted on NMDS do not suggest any clear pattern. All other variables for both tree and shrub communities are not significant before or after correction.

Generally, this supports my hypothesis that aggregated socio-economic variables specific to residential property are not important for commercial properties as well (Hope et al., 2003; Leong et al., 2018). Additional research is needed to determine if there is a relationship between Median Income and the tree community or if it is an artifact of multiple comparisons.

For aggregated socio-economic variables to be significant drivers of vegetation on office developments, the surrounding socio-economic context would need to influence developer and landowner choices of trees and shrubs, as in areas where office developments are adjacent to residential property. However, zoning code in Bellevue and Redmond actively screens land uses from one another. Instead, owners of office developments are likely signaling to prospective and existing tenants (Laverne et al., 2003; Levy and Peterson, 2013), in contrast with owners of residential properties, who use vegetation choices to signal to their neighbors of similar socio-economic status (Cook et al., 2012; Nassauer et al., 2009; Peterson et al., 2012).

Studies examining why decision makers on commercial property make planting decisions are fewer in number than residential homeowners, though existing studies provide important early insight. For example, factors like site aspect, appearance, and available space rated more highly in species selection than whether species are native or nearby canopy composition for landscape architects in Toronto, however city staff tried to plant native species whenever possible (Conway, 2016).

Parcel scale measures of economic value and the built environment are not significant, which fails to support my hypothesis. Previous research found that property value explained variation in the woody vegetation community (Mills et al., 2016). Similarly, site age was suggested as a determinant of woody vegetation community composition by studies on residential properties (Avolio et al., 2018; Boone et al., 2010), landscaping professionals I interviewed, and my examination of contemporaneous landscaping plans filed with the cities of Bellevue and

Redmond. Landscaping professionals mentioned trends in plant popularity, including *Pieris japonica* (Thunb.) D. Don ex G. Don in the late 1980s and increasing use of native plants like *Ribes sanguineum* since 2000. Alternative explanations for this finding include building age is a poor measure for landscaping age due to replanting; an interaction between age and landscaping budget; or that a subset of office developments are planted with in vogue landscape plants, such as the common but under sampled Medium vegetation type.

Differences in study design may also be responsible for these divergent results. Other studies use index response variables with univariate regression (Hope et al., 2003; Martin et al., 2004), measures dependent on effort (Karlik and Winer, 2001; Martin et al., 2004), and plot or transect designs which confound different actors and outcomes (Bourne and Conway, 2014; Clarke et al., 2013).

DEVELOPMENT AND LANDSCAPING OUTCOMES ARE RELATED TO TREE AND SHRUB COMMUNITY COMPOSITION

Multiple variables describing development and landscaping outcomes explain variation in tree and shrub community composition. For the tree community, convex hulls and fitted environmental vectors found strong relationships with median dominant native conifer height (a proxy for stand age), native conifer density, the presence of stands predating development, and dead wood abundance (particularly stump abundance; Figure 4). These variables were also included in the best supported PERMANOVA models for the shrub community (Table 5).

Together, these results support my hypothesis that development and landscaping actions impact vegetation communities on office developments. They agree with some residential researchers who found that homeowner attitudes and actions were more important than socio-economic descriptors (Shakeel and Conway, 2014). These results agree with clustering results and suggest that a suite of decisions is being made that results in either retaining more trees and planting native shrubs or retaining fewer trees and planting ornamental trees and shrubs.

However, development and landscaping outcomes are the end point of economic decision-making processes poorly studied in urban ecology. Though the socio-economic variables examined here were not significant, developer and landowner motivations and decision making were not considered explicitly, only their outcomes. To reach these end points, developers may consider ease of construction based on site conditions, relative cost of different construction approaches, preferences of the landowner and customer specifications, previous company experience or company aesthetic, and development regulations (which impose costs on developers; Conway, 2016; Dorney et al., 1984; Grimes and Mitchell, 2015; Häkkinen and Belloni, 2011; Nappi-Choulet, 2006). As mentioned, the intended audience of prospective and existing tenants may influence both development and landscaping decisions (Laverne et al., 2003; Levy and Peterson, 2013). These considerations may influence financing available to developers, financial risk, and the appeal of and thus demand for the completed project (Laverne et al., 2003). Further, when considering multiple competing options—such as different landscaping choices—developers and landowners may satisfice (Mohamed, 2009). That is, they search through alternatives until one meets an acceptability threshold, and that is the option chosen.

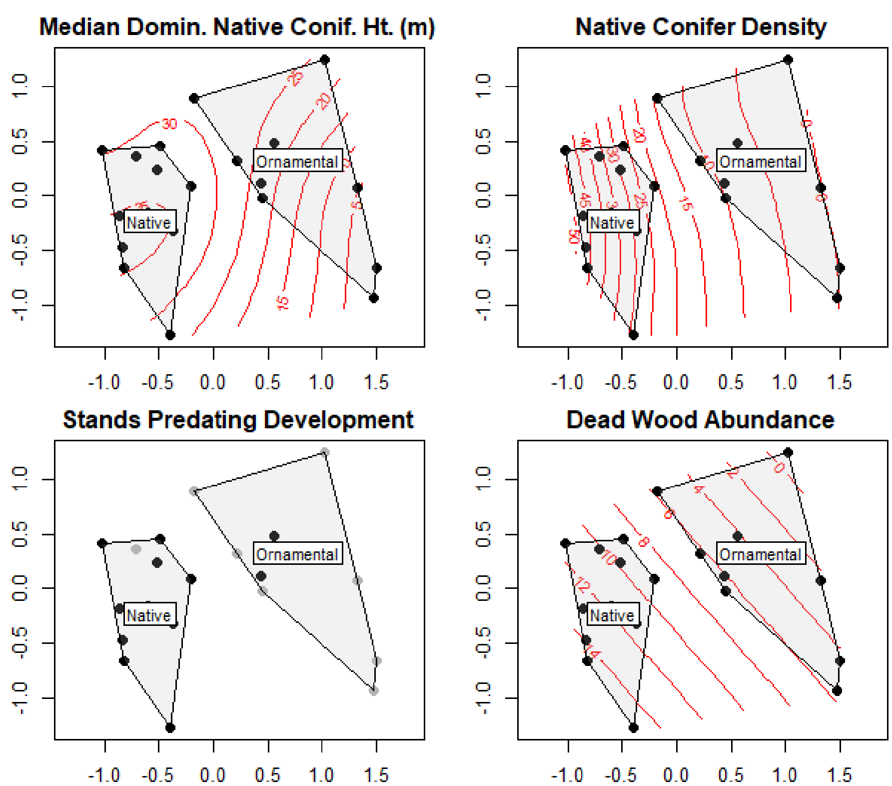

Figure 4: Two dimensional NMDS representation of tree community composition and important variables. Median dominant native conifer height, native conifer density, and the presence of stands predating development are associated with the first NMDS axis. Dead wood is associated with both axes. Black dots represent sites with stands predating development, gray dots sites without. Ordination has not been rotated prior to plotting.

Table 5: PERMANOVA model summary comparing multivariate models of shrub community composition. Note that none of the models explain more than 25% of the variation in shrub community composition.

Model	Pseudo-F	p-value	AICc Value	Delta AICc
Median Douglas Fir Height	3.08	0.002	35.1	0.00
Tree Group Membership	2.86	0.002	35.4	0.21
Native Conifer Density	2.82	0.003	35.4	0.25
Tree Group + Median DF Height	2.44	0.001	36.1	0.91
Median DF Height + Native Conifer Density	2.27	0.003	36.4	1.22
Stands Predate Development	2.26	0.012	35.9	0.79
Median DF Height + Stands Predate Development	2.20	0.001	36.5	1.35
Tree Group + Native Conifer Density	1.87	0.016	37.1	1.97
Tree Group + Stands Predate Development	1.80	0.021	37.3	2.11
Stands Predate Development + Native Conifer Density	1.80	0.013	37.3	2.11

IMPLICATIONS FOR URBAN HABITAT QUALITY AND QUANTITY

The variation in woody vegetation communities I observed on office developments suggests that better habitat conservation during and following development is possible using currently existing developments as models.

As local biological communities are largely determined by this vegetation, sites with more trees preserved and a greater abundance of native conifers likely provide higher habitat quality and quantity to other organisms (Avolio et al., 2018; Faeth et al., 2011, 2005; McKinney, 2002; Wittig, 2010) as native vegetation is more likely to support native insects and native birds than ornamental plantings (Belaire et al., 2014; Burghardt et al., 2009; Chong et al., 2014; Dyson, 2019; Narango et al., 2018; Paker et al., 2014; Pennington and Blair, 2011). One estimate suggests native vegetation volume must be above 70% in order to maintain populations of native insectivorous bird species (Narango et al., 2018); sites with high numbers of trees preserve likely already hit this target.

We can point to actions and policies more likely to support high quality habitat and benefit other trophic levels, including tree preservation policies, promoting native tree and shrub planting, and removing policy barriers to native vegetation (Dyson, 2019; Le Roux et al., 2014; Threlfall et al., 2016). However, the motivations driving exemplary adoption of these actions are currently opaque. Anecdotes shared during fieldwork suggest owner-occupied office space, cost, and personal values and connections to nature may be important factors in determining development and landscaping actions, as with homeowners (Beumer, 2018; Goddard et al., 2013; Helfand et al., 2006; Kendal et al., 2012; Kiesling and Manning, 2010; Nassauer, 1993; Peterson et al., 2012).

IMPLICATIONS FOR FUTURE URBAN ECOLOGY RESEARCH

Observed within land use heterogeneity and between land use differences in socio-economic variable importance both have implications for urban ecology research. Within land use heterogeneity I observed results in vegetation distributions that are non-normal, with likely kurtosis and heteroscedasticity (Figure 5). In this system and others like it, the choice of sampling design and statistical method can result in inaccurate conclusions, particularly in conjunction with small sample size (McIntyre et al., 2000). Additionally, potential solutions already extant on the landscape may be overlooked. This provides support for stratified sampling designs, larger sample sizes, and choosing analysis methods robust to broken assumptions of normality of the sampled population (e.g. De Winter, 2013).

Researchers should choose their sampling strategy carefully based on research questions and the underlying distribution of key variables in urban contexts with long environmental gradients (Ellis and Schneider, 1997; McIntyre et al., 2000; Telford and Birks, 2011). If the phenomena of interest is related to the vegetation community, researchers should attempt to better understand and sample the vegetation gradient (e.g. stratified sampling) instead of sampling only along a measure of the built gradient (e.g. housing density; Lerman and Warren, 2011).

Between land use differences in socio-economic variable importance suggests that creating vegetation models of land use within a city is likely inaccurate if all land uses are assumed to respond equivalently. Researchers cannot assume that vegetation gradients and socio-economic gradients are parallel; these gradients may also interact resulting in heteroscedasticity. Decision pathways to support carbon sequestration and habitat models need to be constructed based on research for each land use separately.

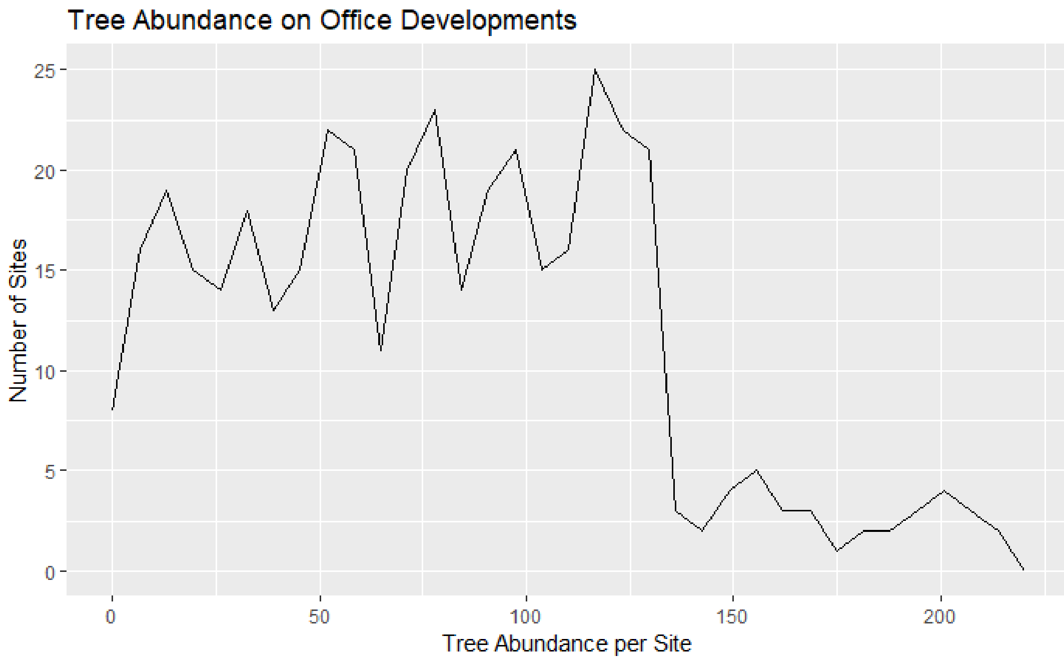

Figure 5: Extrapolated distribution of the number of trees on office developments based on observed mean and standard deviations for each vegetation class used in sampling. Heavy right tail from High and Medium Canopy sites (kurtosis); each vegetation class also has a different variance (heteroscedasticity).

CONCLUSION

Humans control perennial vegetation communities in urban ecosystems, influencing ecosystem service provision and habitat quality and quantity. Commercial land uses, including office developments, have largely been overlooked in studies of urban woody vegetation composition and studies examining how these communities are assembled. I filled this gap by examining woody vegetation on office developments in Redmond and Bellevue, Washington, USA.

I found that the vegetation communities on these developments are heterogenous, with distinct groups of sites characterized by Native and Ornamental Tree and Shrub vegetation communities. I also found that aggregated and parcel scale socioeconomic measures were less important in explaining variation in community composition than variables describing specific outcomes of decision makers’ actions.

This research contributes to our understanding of vegetation communities outside of municipal parks and residential land uses. It is also one of few studies that uses site surveys where the unit of measurement is based on how management decisions are made, instead of methods derived from wildlands vegetation research (Bourne and Conway, 2014; e.g. transects and plots; Clarke et al., 2013) or remote-sensing (e.g. Luck et al., 2009).

The observed heterogeneity in vegetation communities suggests that different ecosystem functions and habitat quantity and quality are provided on office developments; better provision of these functions is possible using currently existing developments as models. Further, the heterogeneity and observed differences in variable importance between office developments and residential land uses suggests that future urban ecology research must more carefully consider sampling design and that models of the urban ecosystem must account for different decision pathways on land uses.

Going forward, research should examine other commercial land uses, commercial land use in additional ecotypes, and particularly decision pathways followed by actors on commercial land uses. This research agrees with Shakeel and Conway (2014) that specific actions are more important than aggregated socio-economic variables. Additional research is needed to link decision makers' personal values and aesthetic preferences, economic motivations, and social norms with tree and shrub community composition on commercial land following work on residential property by Cook et al. (2012) and Shakeel and Conway (2014). Needed studies include interviews to better understand tree preservation and planting motivations (Conway, 2016; Häkkinen and Belloni, 2011); aesthetic preference studies as on residential developments (Harris et al., 2012; Larson et al., 2009); and tracing decision making pathways based on previous land use (Yang et al., 2017). A better understanding of these processes may improve habitat quality and quantity on commercial property (Uren et al., 2015).

Finally, research is also needed to determine if vegetation inequity observed on residential properties (Heynen et al., 2006) is perpetuated on commercial properties; the No Vegetation type excluded from analysis here was often adjacent to retail use, where worker compensation is generally less than in medical/dental, software, and other white collar jobs in office developments.

ACKNOWLEDGEMENTS

This research would not have been possible without the cooperation of the office development land owners and managers who allowed me access to their property.

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