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What can a midsized, semi-arid city teach us about human-made forests?

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Abstract

Research has shown that urban tree canopy (UTC) provides a multitude of ecosystem services to people in cities, yet the benefits and costs of trees are not always equitably distributed among residents and households. To support urban forest managers and sustainability planning, many studies have analyzed the relationships between UTC and various morphological and social variables. Most of these studies, however, focus on large cities like Baltimore, MD, Los Angeles, CA, and New York, NY. Yet, small and midsized cities are experiencing the most growth globally, often having more opportunity to alter management strategies and policies to conserve and/or increase canopy cover and other green infrastructure. Using both a linear and spatial regression approach, we analyzed the main drivers of UTC across census block groups in Fort Collins, CO, a midsize, semi-arid city projected to undergo significant population growth in the next 20-30 years. Results from Fort Collins indicated that block groups with older buildings and greater housing density contained more UTC, with 2.2% more canopy cover for every 10 years of building age and 4.1% more for every 10 houses per hectare. We also found that distributional inequities may already be developing within this midsized city, as block groups with more minority communities were associated with lower UTC. We compared the drivers of UTC in Fort Collins to other cities located in different climate regions, or biomes, and in various stages of urban development. Based on these results, we suggested future urban forest management strategies for semi-arid cities like Fort Collins.

Keywords Urban forestry · Urban landscapes · Tree canopy · Equity · Lifestyles · Urban morphology · Urban ecology · UTC

Introduction

With urban areas expanding rapidly around the world (United Nations 2019), proper provisioning of ecosystem services will become increasingly important to ensure high quality lives for urban residents.

One way to provide ecosystem services to urban residents is by increasing urban green space, and in particular, urban tree canopy (UTC). Many governments and organizations have undertaken progressive tree planting campaigns due to the well-documented ecosystem services produced by trees (e.g. Plant a Billion Trees campaign; Million Trees LA initiative, 2020) (Merse et al. 2008; McPherson et al. 2011; Grove et al. 2014; Pataki et al. 2021). Increasing UTC provides direct shade that reduces the overall surface thermal energy absorption and aids in mitigating the Urban Heat Island (UHI) effect, which can improve human health and reduce both energy use and a city's carbon footprint (Pataki et al. 2006; McHale et al. 2007; Gomez-Muñoz et al. 2010; Colter et al. 2019). These benefits may be even more pronounced in arid and semi-arid climates, where fewer tree species grow naturally (Reich et al. 2010; McHale et al. 2017; Kim and Coseo 2018).

Despite the range of benefits provided by UTC, it is also important to consider the potential disservices associated with trees. Such disservices can include increased water

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demand, maintenance costs, allergies, and safety concerns (Nesbitt et al. 2018; Fernandes et al. 2019; Roman et al. 2021). Relative size of costs and benefits will depend on a city's local climate, resource vulnerability and water supply pricing, social-demographic preferences, built environment characteristics, and financial feasibility of UTC maintenance (Schwarz et al. 2015). Semi-arid systems, for example, must consider the trade-off between the benefits of canopy shade and the costs of increased water demand, whereas regions with ample rainfall may be more focused on the costs and benefits of planting trees in areas with poor drainage. Ultimately, the goals and priorities concerning UTC will vary between cities based on their framing of costs and benefits, as the unique environment of each city must be considered in this assessment process.

Provisioning of ecosystem services and disservices often needs to be considered in context of the local social-ecological system (Andersson et al. 2015; Pickett et al. 2017; McHale et al. 2018). In this context, many studies of urban ecosystems compare drivers of UTC within and between cities. This comparative research has been conducted to evaluate the drivers of UTC (e.g. Iverson and Cook 2000; Nesbitt and Meitner 2016; Grove et al. 2014; Locke et al. 2016), assess whether inequities in UTC access are consistent across different regions of the US (e.g. Chuang et al. 2017; Schwarz et al. 2015; Nesbitt et al. 2018), and analyze the potential for urban ecosystem convergence (e.g. Pouyat et al. 2006; Bigsby et al. 2014; McHale et al. 2017).

Drivers of UTC have often been categorized into three main social-ecological themes: 1) Urban morphological patterns (e.g. parcel area, building density, pervious surface area); 2) Social-demographic characteristics (e.g. income, education, household size); and 3) Lifestyle preferences (e.g. individual and group behavior, motivations for conservation [see Conway et al. 2011; Bigsby et al. 2014; Greene et al. 2018; Bonney and He 2019]). Whether urban morphological patterns limit or enhance UTC depends on the age of the city, the timing of the city's urbanization, and the natural biome of each city (Ramage et al. 2013, Edreny et al. 2017, Hilbert et al. 2019). Furthermore, studies show that there are some predictable social-demographic inequities in many cities, like greater UTC in higher socioeconomic status neighborhoods, and/or those neighborhoods with a higher percentage of self-designated white/Caucasian households (Schwarz et al. 2015; Chuang et al. 2017; Danford et al. 2014; Garrison 2019). Alternatively, sometimes information indicative of lifestyle preferences, like marketing data that show how people spend money, explains more of the variability in UTC (Grove et al. 2006). All these drivers, both presently and in the past, need to be considered when trying to understand how urban ecosystems might be developing over time (Lowry et al. 2012; Bigsby et al. 2014; Roman et al. 2018).

Most of what is understood about UTC has arisen from research focused on large, developed cities such as New York, NY, Philadelphia, PA, Baltimore, MD, and Raleigh, NC, in temperate biomes (e.g. Schwarz et al. 2015; Bigsby et al. 2014). Although it is increasing in prominence, research in small and midsized cities, as well as those in semi-arid and arid biomes, still receives less focus than larger cities in temperate biomes. Our work aims to contribute to growing research in these small and midsized cities, especially those that are still in the early phases of development, or those in semi-arid and arid ecosystems (McHale et al. 2013, 2017). In particular, our work contributes to the research gap in growing cities where there are more opportunities to alter development policies and patterns, and where existing infrastructure does not limit these potential changes (McHale et al. 2013; Childers et al. 2015; Pickett et al. 2016; Grove et al. 2016).

Our goal was to evaluate the urban morphological, social-demographic, and lifestyle drivers of UTC in Fort Collins, CO, a midsized yet rapidly growing, semi-arid city. We expected the drivers of Fort Collins UTC to differ from larger cities often studied in temperate climates. First, we hypothesized that urban morphological variables, like impervious cover and housing density, would describe much of the UTC variability across the city. Since Fort Collins is located in a semi-arid grassland, we hypothesized that UTC would be higher in older, denser areas where people have actively planted and maintained UTC for a longer period of time. Further, unlike larger temperate cities, we did not expect to see evidence that distributional inequities currently exist. Fort Collins is still early in the development process and is not yet as ethnically or racially diverse as some "older" cities in the US. As we aspire to inform future management priorities for the City of Fort Collins, we discuss our results in context of the "Three P's" framework: where planting is possible, preferable and has potential (see Grove et al. 2006; Locke et al. 2010).

Methods

Study location

Fort Collins, CO is a midsize college city with a population of roughly 170,000 (U.S. Census Bureau Quickfacts 2019). It is located at the base of the Rocky Mountains on the northern Front Range, founded along the Cache la Poudre River. It sits about an hour north of Denver via a major interstate (I-25), and 40 min northeast of Boulder. Fort Collins was originally a popular agricultural center that further developed upon establishment of Colorado State University in the late 1800s, now home to over 30,000 students that drive much of the local housing market. A large portion of the college rental market is located near Colorado State University,

which is adjacent to the most historic part of town; commonly referred to as "Old Town", this historic urban center contains many large, aged trees.

However, Fort Collins is naturally dominated by semi-arid grassland and receives little annual precipitation to support a sizeable urban forest. From 2016 – 2019, Fort Collins received an average of ~ 367 mm of precipitation per year (NOAA 2020). Meanwhile, summers can be mild or hot, with persistent low humidity. This environment typically limits native trees to riparian corridors, with common species including plains and narrowleaf cottonwood (*Populus deltoides* and *P. angustifolia*), peachleaf willow (*Salix amygdaloides*) and thin leaf alder (*Alnus incana*). The greater montane region around Fort Collins, particularly toward the foothills, contains more upland species like Douglas-fir (*Pseudotsuga menziesii*), blue spruce (*Picea pungens*) and ponderosa pine (*Pinus ponderosa*). However, the UTC primarily consists of many deciduous species that do not grow naturally, such as green ash (*Fraxinus pennsylvanica*), honey locust (*Gleditsia triacanthos*) and bur oak (*Quercus macrocarpa*) (City of Fort Collins 2020).

Despite the climatic limitations, Fort Collins recognizes the ecosystem services trees provide and prides itself on an extensive UTC, even having a "Notable Tree Tour" to educate the public on almost 30 distinguished trees throughout the city that are related to a famous or historical person, place or event (City of Fort Collins 2008). The city also takes highly proactive tree maintenance measures (City of Fort Collins 2017) and maintains a rigorous public tree inventory, currently with over 300 species mapped (City of Fort Collins Forestry, unpublished data).

Morphological and social-demographic data

We considered a variety of morphological, social-demographic and lifestyle data in our analysis of Fort Collins UTC. The U.S. Census Bureau's American Community 5-Year Survey program for 2016 contains both morphological and social-demographic information. All Census data are provided at a block group scale, as block groups are the smallest unit available for social-demographic information. One block group consists of several Census blocks within the same Census tract (U.S. Census Bureau 2020). Based on previous studies (Lowry et al. 2012; Roman et al. 2014; Greene et al. 2018; Riley and Gardiner 2020), we analyzed housing density, building age, race and ethnicity, tenure, household size, median household income and educational attainment (Table 1).

Lifestyle characteristics

Indicators of lifestyle characteristics were obtained from ESRI's 2018 Tapestry LifeMode Group data, a demographic dataset that provides detailed descriptions of neighborhood block group residential areas based on purchasing

Table 1 Morphological and social-demographic predictors tested (n = 104 Census block groups)

Variable	Description	Min	Mean	Max	Variable Set
Median Building Age (years)	Median age of buildings in block group in years	13.00	38.33	81.00	Morphological
Median Building Age ^2 (years)	Square of median age of buildings in years	169.00	1655.00	6561.00	Morphological
Average Parcel Size (m^2)	Average size for parcels in block group	671	4,395	33,889	Morphological
House Density (per hectare)	Households per hectare	0.60	6.67	38.84	Morphological
Population Density (per hectare)	Population per hectare	1.36	17.61	64.96	Social-demographic
% White / Caucasian Population	Percent of population that self identifies as "white" or "Caucasian"	71.45	89.95	100.00	Social-demographic
% Black / African American Population	Percent of population that self identifies as "black" or "African-American"	0.00	1.28	8.12	Social-demographic
% Hispanic / Latino Population	Percent of population that self identifies as "Hispanic" or "Latino"	0.00	12.52	66.12	Social-demographic
% College Graduates	Population with at least a Bachelor's degree	6.98	35.06	60.70	Social-demographic
% Renter Households	Percent of renter-occupied housing units	1.16	39.41	93.68	Social-demographic
% Owner Households	Percent of owner-occupied housing units	0.00	55.93	98.84	Social-demographic
% Single Person Households	Percentage of single person-occupied housing units	3.24	23.81	64.32	Social-demographic
% 3 + Person Households	Percentage of households with three or more people (non-family)	0.00	5.54	31.33	Social-demographic
% Family Households	Percent of family households	9.63	59.36	88.12	Social-demographic
% Married Households	Percent of married-couple family households	3.52	47.77	81.17	Social-demographic
Median Household Income ($)	Median household income of the block group adjusted for 2016 inflation	18,550	65,156	130,139	Social-demographic
Average Home Value ($)	Average home value adjusted for 2016 inflation	55,000	284,558	512,000	Social-demographic

preferences along with socioeconomic status and demographic characteristics (Tapestry Segmentation 2018). The dataset describes possible lifestyle behaviors, such as financial decisions, favorite pastimes and preferred media platforms. This information is then used to sort block groups into various lifestyle groups based on purchasing preferences (Table 2).

Land cover data

We used high resolution raster 2016 land cover classification data (1 m^2) derived from an object-oriented classification (Zhou and Troy 2008; Beck et al. 2016) utilizing a combination of Worldview 2 imagery (NASA Worldview) and aerial LiDAR provided by the City of Fort Collins. A custom post-processing classification model was applied, that uses ancillary building footprint and pavement vector data to distinguish between seven land cover classes: trees, grass and shrubs, bare soil, water, buildings, roads and railroads, and "other" paved surface cover, like driveways (*See* Rasmussen et al. 2021) (Fig. 1). Within each block group, we calculated the percentage of tree cover for our response variable, and then the percentage of grass cover as a predictor. We integrated the buildings, roads and railroads, and other paved surface classes to create a single predictor for the percentage of impervious cover (Table 3). Water and bare soil were not included in this analysis due to their minimal cover across all block groups.

Statistical analyses

Pearson's correlation coefficients were analyzed to identify the direction and strength of the relationship between each explanatory variable and tree cover using the *cor.test* function from the stats package (Version 3.6.2) (R Core Team, 2018). We incorporated all continuous and categorical variables in an ordinary least squares (OLS) multiple-linear regression to assess the most important characteristics for explaining UTC variability. First, we tested a full model that included all our predictors and then used a backward stepwise selection process for model parsimony (Locke et al. 2016). In R, the *lm* function from the stats package (Version 3.6.2) (R Core Team, 2018) was used for the multiple linear model, while the *MASS* package provided the *stepAIC* function to run the stepwise selection process (Venables & Ripley, 2002). This process identified the variable subset that minimized the Akaike Information Criterion (AIC).

We used the variance inflation factor (VIF) to test for multicollinearity in our OLS model. A common VIF threshold of 5 is considered high correlation and would require us to adjust predictor variables (James et al. 2013). Using the *vif* function from the *car* package (Fox and Weisberg, 2019) to test the VIF in R, we then systematically removed variables until collinearity no longer exceeded 5 for any variable.

An important consideration when applying an OLS model to spatially explicit data is the potential for spatial autocorrelation. This phenomenon occurs when either the dependent or independent predictors are inherently correlated spatially, thus reducing standard errors in the linear model. To account for spatial autocorrelation, a Moran's I test was run separately on the tree cover estimates and OLS model residuals. A spatially random configuration would yield a Moran's I estimate of approximately 0; a clustered spatial configuration would yield closer to + 1; and a dispersed spatial configuration would yield -1. If statistically significant clustering or dispersion occurs, it is necessary to apply a spatial model to avoid inflating our confidence through inappropriately small standard errors.

To run the Moran's I test, we first applied the *poly2nb* function from the *spdep* package (Version 1.1.3) (Bivand and Wong 2018) to create spatial neighbors. Given the irregularity in block group configuration, we chose a queen contiguity matrix. Then we used the function *lm.morantest*, also part of the *spdep* package, to run the Moran's I test on the residuals of the OLS regression model. When spatial autocorrelation is detected in the model residuals, a Spatial Autoregressive (SAR) model should be evaluated (Lichstein et al. 2002).

SAR model development was informed using the *lm.LMtests* function of the *spdep* package, which applies the Lagrange Multiplier diagnostics for spatial dependence to the OLS model. Testing indicated the use of a spatially lagged dependent variable to account for autocorrelation of the OLS residuals. We applied the *lagsarlm* function from the *spdep* package to control for spatial effects by adopting a lagged response variable (Browning et al. 2019). We compared the OLS and SAR models based on the presence

Table 2 Neighborhood classifications used as lifestyle predictors

Lifestyle Group	Block Group Count
Affluent Estates	12
Upscale Avenues	4
Uptown Individuals	1
Family Landscapes	9
GenXurban	18
Middle Ground	24
Senior Styles	1
Rustic Outposts	2
Midtown Singles	9
Next Wave	1
Scholars and Patriots	23

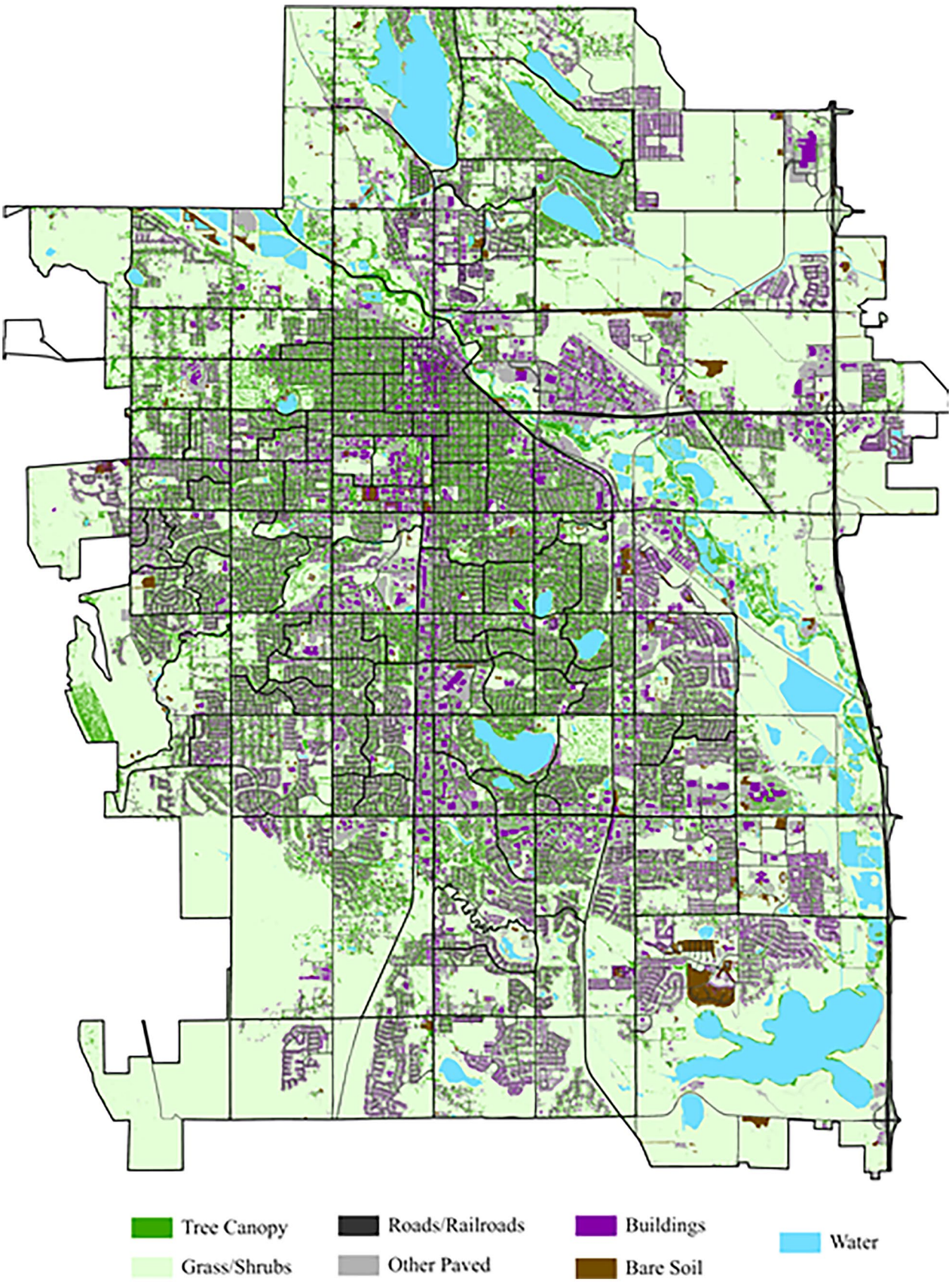

Fig. 1 Land cover in Fort Collins, CO. Black lines represent block group boundaries

Table 3 Descriptive statistics of land cover data across all block groups

Variable	Description	Min	Mean	Max
Percent Tree	Percentage of tree coverage	3.34	21.62	43.51
Percent Grass	Percentage of grass coverage	12.60	37.13	90.53
Percent Building	Percentage of building coverage	0.91	10.80	19.22
Percent Other Paved	Percentage of other paved surface coverage	1.80	15.49	40.76
Percent Road/Railroad	Percentage of road/railroad coverage	1.97	11.63	20.86
Percent Impervious Cover	Percentage of impervious cover	6.01	37.19	71.51

of significant autocorrelation and which one minimized the AIC score.

Results

Correlation analysis

Correlation analysis revealed significant relationships ($p < 0.001$), with strong correlation coefficients (exceeding |0.45|) between UTC and morphological characteristics such as building age, housing density, population density, and percent grass cover. Meanwhile, the most strongly correlated social-demographic characteristics were indicative of socio-economic status, including percentage of married and family households, and percentage of 3 + person or renter-occupied households. Although there were statistically significant relationships between social-demographic characteristics and UTC, these relationships were not as strong (indicated by a correlation coefficient <|0.35|) (Fig. 2).

Regression analysis

The OLS model selection process reduced the 30 predictors to a final seven-variable model comprised of four morphological and three social-demographic parameters that minimized AIC, while also ensuring VIF values less than 5. Testing of OLS model residuals revealed significant spatial clustering ($p = < 0.001$) with a Moran's I value of 0.542 and Lagrange Multiplier diagnostics that indicated the use of a spatial lag model. This led to development of a SAR lag model (Table 4) with the same parameters that resulted in a nonsignificant ($p = 0.491$) Moran's I value of -0.011. Additionally, the SAR lag model reduced AIC to 592.7 compared to 615.0 for the OLS model, further supporting the use of the spatial model.

The spatial lag model showed that greater building age and housing density resulted in greater UTC, corresponding to a 2.2% increase in UTC for every 10 years of building age and 4.1% more UTC for every 10 houses per hectare. Conversely, a greater percentage of grass and impervious cover resulted in less UTC in the model (Table 4). The only significant social-demographic characteristics were the percentages of 3 + person households and renter-occupied households, which related to UTC in opposite ways. A 10% increase in 3 + person households resulted in 1.5% more UTC, while a 10% increase in renter-occupied households reduced UTC 1.1%. Similarly, a greater percentage of Hispanic / Latino communities reduced overall UTC, although it was not significant ($p = 0.202$). In contrast, the morphological variables provided the strongest direct and indirect impacts on the prediction of UTC, all of which having a larger impact than the social-demographic variables (Table 4).

Discussion

Morphological variables explain most of the variation in UTC across Fort Collins

Urban morphological characteristics consistently had stronger correlation than social-demographic or lifestyle characteristics, and also described more of the variability in UTC within Fort Collins based on their total impacts. Median building age and housing density had some of the strongest impacts on UTC variability. In Fort Collins, we expect that morphological characteristics have the strongest impact due to the city's relatively early stage in urbanization, as the city has only recently experienced rapid growth in population and infrastructure. New neighborhoods are mostly being developed on the outskirts of the city, primarily replacing natural, semi-arid grassland. This is in contrast to the neighborhoods that have been long established in the central part of the city (e.g. Old Town), where much of the current UTC was planted decades ago.

Because Fort Collins' rapid growth only started in the 1990s, UTC is best described by morphological characteristics that are consistent with conditions that existed when many trees were planted, rather than the current social-demographic or lifestyle characteristics that are only beginning to develop. The importance of temporal trends has been seen in other studies, where correlation between UTC and social-demographic or lifestyle characteristics depends on the amount of time since urbanization (Boone et al. 2010; Troy et al. 2007; Lowry et al. 2012). In many cases, the physical development of the city is innately connected to the underlying social-demographic patterns (Williams et al. 2000), but these patterns are extremely dynamic over time.

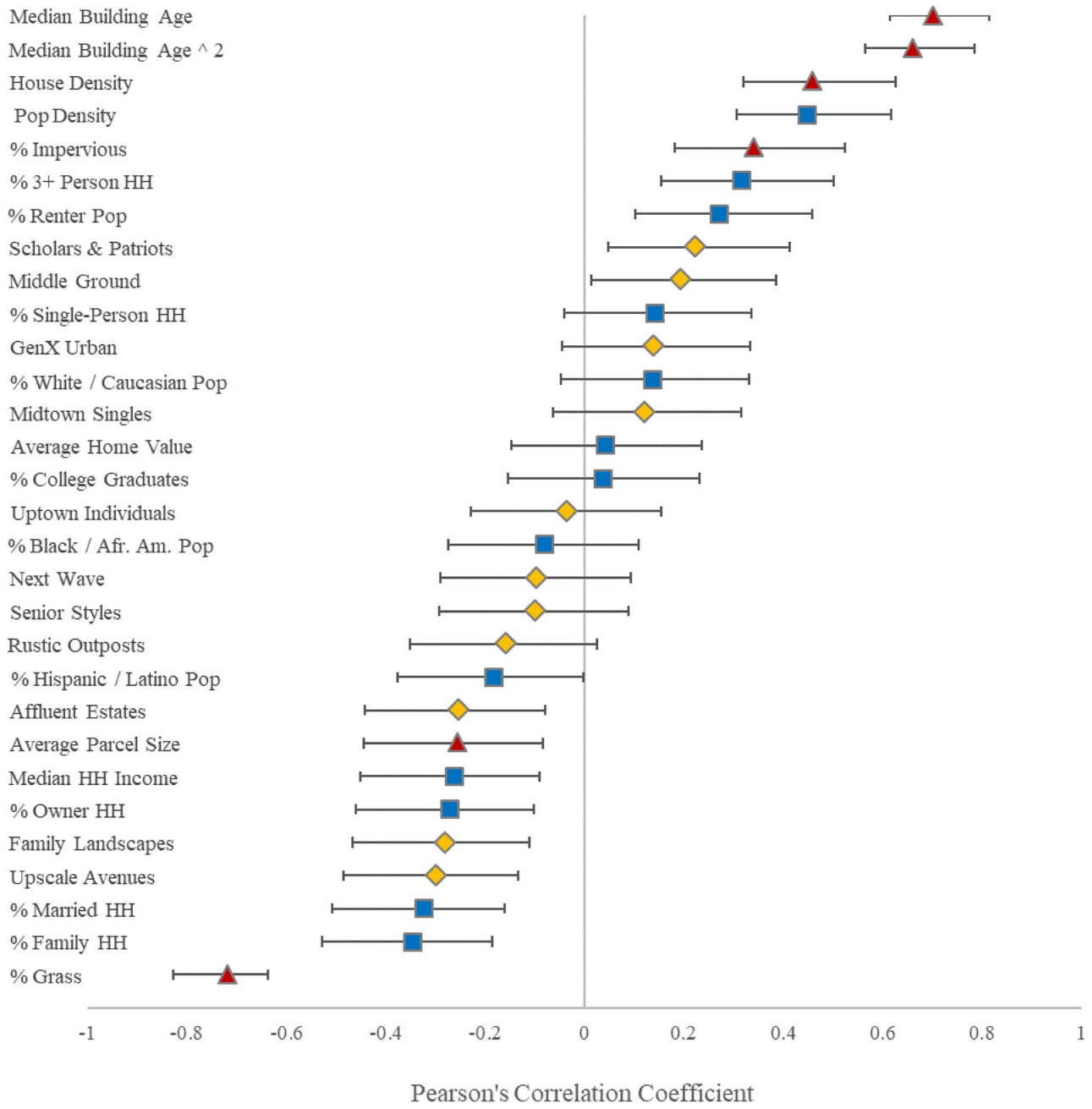

Fig. 2 Correlations between explanatory variables and percent tree cover within block groups. Red triangles represent variables belonging to the morphology subgroup, including land cover; blue squares represent social-demographic variables; and yellow diamonds represent lifestyle variables

Divergence of Fort Collins UTC predictors from larger, temperate cities

We found a significant and negative relationship between grass cover and tree cover, as might be expected given the local biome. Nowak et al. (1996) assessed the distribution of UTC in 58 U.S. cities and found UTC to be lower in cities situated in grasslands, which also tend to have more agricultural land. Nowak and Greenfield (2020) stated that in drier grasslands, unmanaged land will also not naturally regenerate with trees and will have lower UTC unless tree planting and watering programs are established. These findings may explain the inverse relationship we see between grass and tree cover. Because Fort Collins is still in the process of urbanizing, areas on the outer edge of the city have yet to be transformed from grassland and agricultural land to a

Table 4 Summary of spatial lag regression variables explaining Fort Collins Urban Tree Canopy. Impacts indicate the influence of a one unit increase of the variable on the percent tree cover for both the target block group (direct) and neighboring block groups (indirect)

Variable	Coefficient	Std. Error	*P* value	Impacts		
				Direct	**Indirect**	**Total**
Intercept	22.854	4.636	< 0.001			
House Density (ha^{-1})	0.414	0.085	< 0.001	0.430	0.296	0.726
% Grass Cover	-0.305	0.047	< 0.001	-0.317	-0.218	-0.536
Median Building Age	0.217	0.039	< 0.001	0.225	0.155	0.380
% Impervious Cover	-0.162	0.057	0.004	-0.168	-0.116	-0.284
% 3 + Person Households	0.147	0.068	0.030	0.152	0.105	0.258
% Renter Households	-0.113	0.022	< 0.001	-0.117	-0.081	-0.198
% Hispanic / Latino	-0.043	0.034	0.202	-0.044	-0.031	-0.075

more urbanized landscape that can accommodate a larger population, and it may take years before trees are fully established. This differs from most cities in temperate regions where natural tree cover is often being removed to make way for new development (Heilman et al. 2002; Hostetler et al. 2013; Bonney and He 2019).

We found that Fort Collins block groups with older houses were associated with greater tree cover. This is supported by findings in Raleigh, NC, but in contrast to Baltimore, MD (Bigsby et al. 2014). Additionally, Conway (2009) analyzed vegetation in Toronto, Canada and found that older houses had less overall vegetation than newer houses. We speculate that these contrasting results may be explained by the climate or biome of Fort Collins; this semi-arid ecosystem has few native tree species that mostly occupy riparian areas, resulting in a planted and heavily-managed UTC. Much of the vibrant UTC has long been planted and maintained throughout the oldest parts of the city, whereas the UTC in newer developments has been recently planted as the city undergoes rapid population growth.

We also found higher UTC in areas with with higher housing density, while other studies have found that areas with higher house density contain less tree cover. In a study by Iverson and Cook (2000) that took place in Chicago, IL, the authors found tree cover to be strongly and inversely related to house density. In analyzing 29 different suburbs of Chicago, the authors evaluated a wider range of housing densities than those found in Fort Collins. However, it is interesting that Iverson and Cook (2000) found that the highest tree cover occurred in regions with 24.7–37.0 houses per hectare, which broadly matches the higher end of Fort Collins' housing density of 0.6—38.8 houses per hectare. These similarities might point to common social preferences for tree cover within urbanizing areas. The nuanced finding within Fort Collins could be explained by the unique morphological development of the city, because housing density is highest in the oldest parts of the city where UTC has been created and maintained the longest. This contrasts with places like Chicago where the greatest density is no longer dominated by single-family housing.

The SAR model results revealed the only significant social-demographic characteristics for explaining the UTC distribution was the percentage of renter-occupied and 3 + person households. Previous work has suggested less UTC exists in areas with more disadvantaged populations, such as renters (see Riley and Gardiner 2020). The SAR model supports this in Fort Collins, suggesting that for every 10% more renter households, there was 1.1% less tree canopy.

However, we also found that the percent of 3 + person (non-family) households displayed a positive relationship to UTC, something we did not expect given its similarity to renters (see Fig. 2). The contrasting results between the rental population and 3 + person households may simply be explained by the fact that renters are not generally isolated to any particular region due to housing market constraints in recent years (Corona Insights 2019), whereas 3 + person households are often young, college students situated near Colorado State University and Old Town where there is a greater amount of tree cover. There has also been evidence of homeowners renting out portions of their home, such as a single room or a basement, resulting in more people per household. If this happens in neighborhoods with greater UTC, it could explain the positive relationship we are seeing with respect to 3 + person households.

Possible distributional inequities developing in Fort Collins

The SAR model indicated the percent of Hispanic / Latino population was associated with reduced UTC. Although the variable was not statistically significant ($p = 0.202$), removing the variable substantially increased the model AIC, supporting its potential importance in understanding the distribution of UTC. Examining the correlation coefficients associated of Fort Collins' racial and ethnic groups reveals a positive relationship between UTC and the population percentage who self-identified as white / Caucasian and negative relationships for block group population percentages for those self-identifying as Hispanic / Latino or black / African American (Fig. 2). Although not significant, there was a

difference in the coefficients for these three racial and ethnic communities in Fort Collins, which may indicate disparities developing within the city. Several studies have suggested that some disparities in UTC have reflected racial segregation (Flocks et al. 2011; Heynen 2003; Schwarz et al. 2015; Riley and Gardiner 2020). Fort Collins currently has low racial and ethnic diversity compared to larger, more mature cities in the US (see Table 1), yet based on our results, we still see potential distributional inequities that may be developing within the city.

Recommendations for future tree planting and maintenance

Studies on the distribution of UTC can have the power to inform future management decisions, indicating areas where we may want to prioritize tree planting and maintenance. We discuss planting and maintenance in the context of the "Three P's" framework introduced by Grove et al. (2006). This framework can assist in maximizing the benefits of UTC while minimizing the potential disservices, as it considers areas for *possible*, *preferable* and *potential* UTC. Following previous research on planting guidelines (Locke et al. 2010), this analysis indicates areas where planting is both possible and preferable to maximize Fort Collins' UTC.

Possible UTC includes areas where it is biophysically feasible to create and maintain UTC, which is shaped by the type of existing land cover (e.g. impervious vs. pervious cover). As Fort Collins continues to develop, more trees could be planted in recently urbanized areas dominated by grass, as these areas are currently associated with low UTC and high pervious cover, which is the most biophysically feasible land cover for tree planting. Conversely, impervious cover limits space for additional planting (see Nowak and Greenfield 2012; Coseo and Larsen 2019), and also limits the natural regeneration of trees (Nowak and Greenfield 2020), indicating maintenance is the preferred action to ensure adequate UTC is available in areas with high impervious cover. Maintenance will be especially important in impervious areas because of the offsetting effects tree shade has on the Urban Heat Island effect, a phenomenon that leads to higher temperatures in areas with more impervious cover (Zhou et al. 2017; Wang and Akbari 2016).

Extending beyond planting possibilities, cities considering preferable areas for increasing or maintaining UTC have the potential to reduce distributional inequities amongst communities (Flocks et al. 2011). We recommend areas with a greater percentage of minority-occupied block groups be a priority for planting to offset the identified early forming distributional inequity. Additionally, to prevent loss of existing UTC that could exacerbate possible inequities, maintenance should focus on areas vulnerable to future tree collapse from old age, or removal for pests and disease. For example, Fort Collins recently detected Emerald Ash Borer (EAB), an invasive pest that has decimated ash tree populations in other regions of the world (Herms and McCullough 2014), and it is expected that many public trees will be removed to help contain EAB spread. To prevent distributional inequities of UTC it is important to promote phased removal and replanting of public trees, otherwise these communities are at risk of becoming further underserved by the UTC.

There are many different contexts as to why distributional inequities appears in cities (Riley and Gardiner 2020; Nesbitt et al. 2019). We acknowledge that complex interactions take place between the social-demographic preferences of urban residents and the morphological development of cities that can influence UTC distribution. In Fort Collins, this is further complicated by the underlying semi-arid biome. These results should be framed within the context of local urban tree inventory data to understand the trajectory of UTC in newer neighborhoods. If these neighborhoods have the same number of planted trees as more mature neighborhoods, it is reasonable to assume that potential inequities are not attributable to social preferences or policy development, but rather to the slower process of ecosystem conversion; in which case, we simply need to allow more time for trees to establish.

The results of our study provide relevant information that can be used to guide future planning and development. The types of urban morphological patterns and social-demographic factors driving UTC in Fort Collins promotes ideas such as establishing zoning codes that require planting trees in new developments, targeting planting in areas with increased minority presence that are currently underserved by the UTC, and maintaining UTC in areas that will be susceptible to EAB.

Study limitations and future work

Most of our social-demographic variables were analyzed at the block-group scale. Due to Fort Collins's relatively low population density, block groups cover a larger area, and do not necessarily aid in distinguishing local neighborhood dynamics or fine resolution changes in socio-demographics. The lifestyle variables we included in our analyses were not evenly distributed in the City, with some categories having much more representation in the city than others, and this clouds our understanding of the relationship between lifestyle and UTC, if indeed there is an important one. Further, Homeowners Associations are particularly popular in the west, and there is reason to believe that they are having an impact on neighborhood level management practices in Fort Collins (Rasmussen et al. 2021). Although, we did not separate out public versus private lands in our analyses, these are studies that we aim to do in the future. This kind of information is important for developing policies to support homeowners as they deal with EAB in Fort Collins, as it is a matter that will

need strategic coordination between both public and private landowners.

Finally, since all of our land cover classes sum to 100% in each block group, there is an inherent correlation between each class and tree cover, and this needs to be considered when interpreting results. For the purpose of this study, we were mainly interested in the direction of these relationships, but further work can be done to understand their distribution and effects on one another. Future work can also expand on UTC relationships by comparing various spatiotemporal scales, as we expect different patterns to emerge under differing spatial and temporal conditions (see Locke et al. 2016). This work would greatly benefit by gathering unique household level data on social characteristics, which may require a more qualitative study using survey methods.

In Fort Collins, it will be especially valuable to consider legacy effects (see Troy et al. 2007; Bigsby et al. 2014), since the city has experienced rapid morphological and social change in a relatively short amount of time. We could also consider controlling for age in future analyses so we can isolate additional trends that may be temporally dependent. Additional research can be performed to compare Fort Collins to the neighboring city of Denver; since Denver is in a more mature urbanization stage, it may be valuable to investigate differing morphological, social-demographic and lifestyle influences on UTC between these cities with similar climates.

Conclusion

Our study revealed that UTC in Fort Collins was highly correlated with urban morphological variables, indicating that they are more important drivers of UTC than the social-demographic or lifestyle characteristics of residents at this time. Also, since Fort Collins is situated in the shortgrass steppe ecosystem, that does not support many native tree species, mature UTC was primarily found in the oldest parts of the city with the highest population density. Fort Collins' rapid population growth, beginning in the 1990s, prompted the need to accommodate more residents and the city continued to expand outward. These areas tend to have less UTC, and therefore, as the city continues to grow, the newly developed neighborhoods on the outer edges of the city will need to plant trees in order to gain UTC benefits in the future. Although previous research in Fort Collins has shown that the benefits provided by UTC may often outweigh the water costs associated with trees in residential neighborhoods, the potential tradeoffs associated with water should be considered in these areas as well.

Fort Collins' unique UTC patterns are likely a function of its development stage, climate, and native biome. It is a relatively young community in a semi-arid climate that manifested UTC patterns diverging from previous studies in large temperate cities. We provide valuable information that can add to the sphere of research surrounding UTC, and our results can facilitate urban planning and development to maximize the benefits provided by UTC and to minimize distributional inequities experienced by urban residents. To better understand these relationships, it will be important to cross compare UTC in semi-arid cities over time.

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