THESIS

CLIMATE FORECASTING, CLIMATE-RESISTANT TREE SPECIES SELECTION, AND URBAN CANOPY PLANNING FOR A SMALL, SEMI-ARID CITY

Submitted by

Natalie S Buchholz

Graduate Degree Program in Ecology

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2023

Master's Committee:

Advisor: Julia Klein

Randall Boone
Troy Ocheltree

ABSTRACT

CLIMATE FORECASTING, CLIMATE-RESISTANT TREE SPECIES SELECTION, AND URBAN CANOPY EQUITY IN A SMALL, SEMI-ARID CITY

Globally, there is an increasing shift from rural to urban living, with major implications for the ecosystem services provided by these ecological systems and profound effects on the human communities that continue to migrate to them. Urban canopies and the development of green spaces in the urban environment can mitigate some of the negative effects of urban living such as high Urban Heat Indices (UHI), poor air quality, loss of emotional support from nature, and loss of sense of place. However, the poleward shift of climate envelopes due to climate change will eventually lead to urban canopy collapses as street trees become less suited to their environment. In chapter one of this thesis, I explore this shift and climate-change resistant tree species selections by using WorldClim's current (1971-2000), SSP126 (low emissions) and SSP585 (high emissions) scenarios to generate climate envelope projections for the City of Fort Collins, Colorado in the years 2061-2080. I collected recommended street tree lists from cities that currently exhibit future climate conditions in Fort Collins (hereafter, reference cities) and compared them to the current city of Fort Collins' recommended street tree list. I identified 15 shade trees that have already undergone testing by CSU arborists and are appropriate for immediate planting in Fort Collins, Colorado – these 15 shade tree species comprise the Future Fort Collins Recommended Street Tree list. I identified an additional 21 shade tree species that still require CSU arborist testing for planting suitability – these 21 shade tree species comprise

the Future Fort Collins Recommended Street Tree-Test list. The Future Fort Collins Recommended Street Tree and Future Fort Collins Recommended Street Tree-Test lists will inform street tree diversity and planting strategies for the City of Fort Collins, CO, and provide a brief list of species that need further suitability testing by foresters and arborists along the Front Range.

Chapter two of this thesis aims to address current canopy inequities in Fort Collins, Colorado, by examining patterns in the city's overall land cover distribution, as well as the built environments and policies that limit canopy expansion. Here I explore canopy and land cover in four census blocks that are at least 25% Hispanic and have a median household income of less than $40k per year. I further dissect these four census blocks into smaller study areas based on zoning type as designated by the City of Fort Collins and Larimer County Assessor's Office. Using a combination of satellite observation and I-Tree canopy analyses I hope to, 1) identify patterns in land and canopy cover across zoning types, and 2) identify factors in the built environment and written policy that limit urban canopy growth in the City of Fort Collins, Colorado. Results will inform canopy care and planting strategies as the city moves to create its first Urban Forest Strategic Plan in the coming years.

ACKNOWLEDGEMENTS

The following studies were funded by The City of Fort Collins through the Forestry and Parks and Recreation departments.

I would like to thank my advisor, Julia Klein, and committee members, Troy Ocheltree and Randall Boone, as well as Kendra Boot and Ralph Zentz from the Fort Collins Forestry Department for their expertise, input, and guidance throughout my thesis research and writing process. This thesis would not have been possible without your assistance and mentorship; I am forever grateful.

I would also like to thank Jim Klett for providing information on the formation of the Front Range Tree Recommendation list, and for his advice on narrowing down my initial pool of resistant species.

I acknowledge the World Climate Research Program, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. I thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF.

DEDICATION

This thesis is dedicated to my parents and sibling, Pam, Jim, and Izzy Buchholz, as well as my partner, Jack Huun. I could not have made it here without you. Thank you for believing in me, pushing me, and supporting me through this daunting process. I am so grateful to you.

This thesis is also dedicated to the children and future generations of Fort Collins, Colorado. May the trees shade and protect you in our rapidly changing world.

TABLE OF CONTENTS

CHAPTER 1: FUTURE CLIMATE PROJECTIONS AND CLIMATE-CHANGE-RESISTANT STREET TREE SELECTION IN FORT COLLINS, COLORADO

1.1 Introduction

1.1.1 Forests and Climate Change

Ecological state factors, such as climate, soil formation and type, topographic features, and biotic factors, determine the range in which different species can occur. Of these state factors, climate is the major controller of species distributions and ecosystem processes (Williams and Jackson 2007). Each species has a unique set of climatic conditions in which it can persist; this combination of climatic tolerances is known as a climate envelope. These climate conditions include light, temperature, rainfall, soil moisture content, and humidity (Burke et al. 2019, Hijmans and Graham 2006, Iverson et al. 2007, Lawing and Polly 2011, McKenney et al. 2007, Notaro et al. 2012). The Climate Envelope Model (CEM) uses this concept of species-specific climate tolerances to define the current, potential, future, or historical range of a species (Burke et al. 2019, Hijmans and Graham 2006, Iverson et al. 2007, Lawing and Polly 2011, McKenney et al. 2007, Notaro et al. 2012). By identifying the range of climate conditions under which a species can live, researchers can locate areas of interest for species conservation, map the likely spread of invasive species, and predict how species distribution might shift under different climate conditions (Burke et al. 2019, Iverson et al. 2007, Lloret et al. 2021, McKenney et al. 2007, Notaro et al. 2012, Pickett et al. 2008, Williams and Jackson 2007).

Another method, known as Space for Time substitution (SFT), allows ecologists to draw conclusions on long-term ecosystem changes by extrapolating temporal trends from a series of different aged sites (Pickett 2008). SFT substitution is used in the field of ecology for

interpreting the stages of seres in a successional chrono-sequence, for climate change studies, and in areas where long-term studies are impractical or impossible (Pickett 2008, Blois et al. 2013, Wogan and Wang 2017). The use of an SFT assumes that spatial and temporal variation are similar, in other words, we assume that the observed spatial phenomena are applicable across time and space. A common example of SFT use is in interpreting the successional stage of a site after a disturbance. If the site's disturbance were a forest fire, one would expect the affected area to recover like other forest fire sites, especially if those sites occur in the same ecosystem. With this assumption in mind, one can observe forest-fire recovery areas five-, ten-, fifteen-, and twenty-years post-fire to form expectations for the recovery of a recently burned forest site.

SFTs can also be used for predicting climate-change effects on biodiversity. Blois et al. (2017) compared pollen data from the Late Quaternary and Holocene to results generated from "Space for Time" and "Time for Time" models to test their capacity for predicting plant assemblages. The research team found that SFTs were 72% as accurate as the Time for Time models for the Late Quaternary test period. They also found that the models performed more poorly during the Holocene period, suggesting that SFTs may be less accurate during periods of rapid climate fluctuations. Despite this latter finding, the team still supports the use of SFTs for predicting shifts in biodiversity under climate change (Blois et al. 2017). Climate change studies also use natural climate gradients across space (i.e., along an elevational gradient or across landscapes that differ due to climate) to explore how a given ecosystem may shift over time with climate change. The assumption here is that species and ecosystem changes over time will follow species/ecosystem-climate relationships that currently exist over space (Dunne et al. 2004).

In support of the use of SFTs in the face of climate change, ecologists have long documented the relationship between climate change and shifting climate zones across geologic

time. From a paleoclimate perspective, climate zones typically shift towards the equator in climate-cooling scenarios and shift poleward during climate-warming scenarios. With ongoing patterns of increasing global temperatures due to anthropogenic climate change, climate zones are expected to shift poleward in the coming century (Brandt et al. 2016, Burley et al. 2019, Lloret et al. 2021, McKenney et al. 2007, Yang 2008). An example of this expected shift can be seen in figure 1.1, which illustrates the recent past distribution of forest types (1961-1990) and projected changes to their distribution (2070-2100) for the eastern half of the United States (Karl et al. 2009). Note the major shift in forest types; for instance, examine the expected shift from predominately Maple-Beech-Birch Forest to Oak-Hickory Forest in New York, New Hampshire, Vermont, and portions of Maine and Pennsylvania.

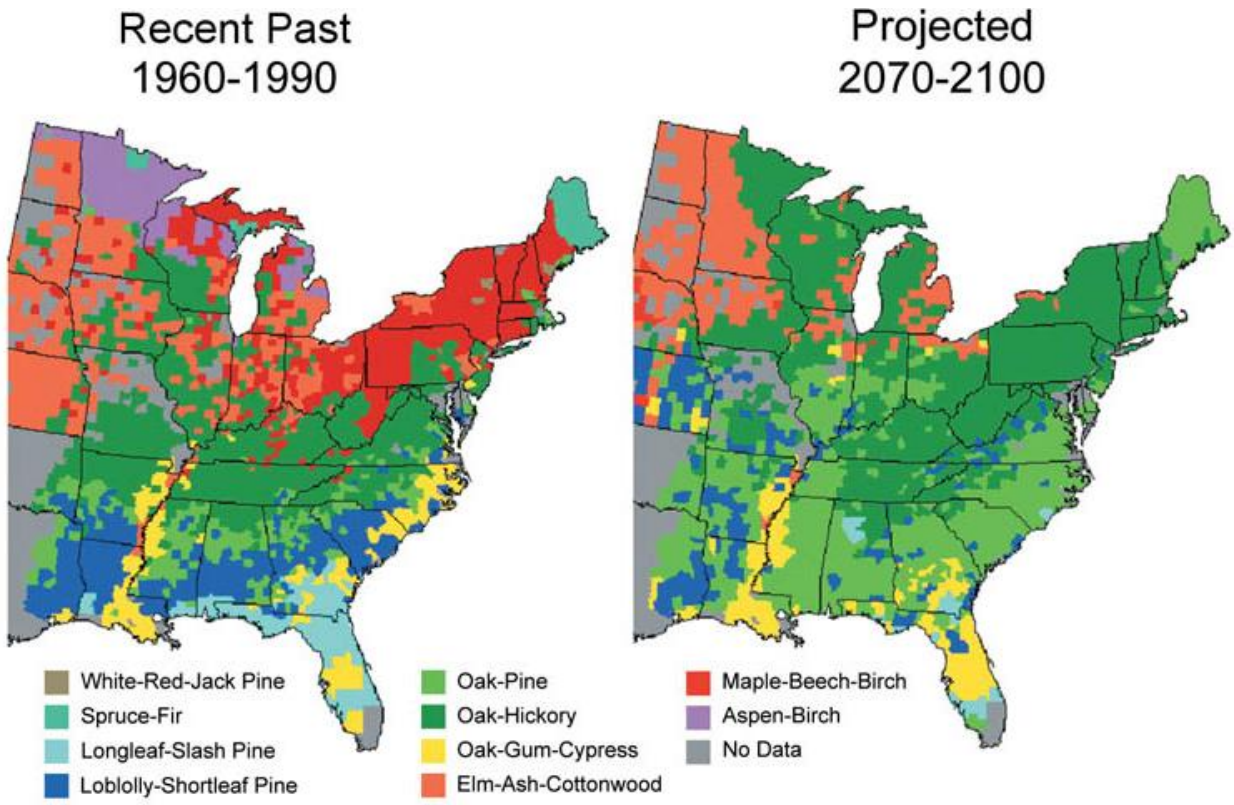

Figure 1.1: Recent past (1960-1990) and projected future (2070-2100) distributions of forest types in the midwestern to eastern United States. Source: Karl et al. 2009.

Iverson and colleagues' (2005) review on climate change and species distribution shift noted that the typical migration rate of most plant species (about 50km per century) is not likely to keep up with the current rate of climate change. For example, one study assessed climate-change driven shifts to the climate envelopes of 130 different eastern North American trees and found that over a quarter of species investigated had a poleward shift of more than 400 kilometers (Iverson et al. 2008). Another study which focused on 176 species in urban forests in Australia found that by 2070, "climatically suitable habitat is predicted to decline for 73% of the species assessed. For 18% of these species, climatically suitable area is predicted to be more than halved (Burley et al. 2019)." This leads ecologists to a controversial and dichotomous decision: Do we introduce species to their future climate extents ahead of their expected shift, or do we let nature take its course knowing that this shift will likely cause extensive ecosystem collapse?

The purposeful introduction of species to new extents is a controversial topic across the broader field of ecology (Simberloff et al. 2005). On one hand, introduction into new areas could prevent the extinction of climate-sensitive species and help ease the transition to more climatically suitable zones. On the other hand, the introduction of a new species could set off a chain reaction (such as a trophic cascade) by disturbing ecosystem distributions in the existing species assemblage (Walsh et al. 2016). However, experts in the field of urban forestry and urban ecology generally agree that introducing new tree species to urban environments poses less of an ecological threat to biodiversity than the introduction of non-native tree species to natural environments. This is particularly true of urban environments whose native ecosystem typically features low canopy coverage (such as this project's study area of Fort Collins, CO, which resides in a semi-arid short-grass steppe ecosystem). In such environments, most of the urban

canopy cover already consists of nonnative species (Brandt et al. 2016, Burley et al. 2019, Lloret et al. 2021, McKenney et al. 2007, Yang 2008).

1.1.2 The Importance of Urban Forests

Urban forests across the globe provide critical ecosystem services to urban areas. An urban forest (or urban canopy) is defined as all publicly and privately owned trees in an urban area (see table 1.1.2) (Nowak et al. 2001). Urban tree canopy cover provides protection from elements such as wind, heat, and noise pollution. For example, urban canopy cover has been shown to reduce the Urban Heat Island effect (UHI), which is a phenomenon where urban environments feature higher ground temperatures than surrounding rural areas. UHI is caused by high rates of impermeable surfaces (such as buildings, sidewalks, and roads) which absorb solar radiation and emit infrared radiation at high rates, increasing surface temperatures (Grimm 2008, Pickett 2008 & 2011, and Schell 2020). UHI can raise ambient air temperatures from 1ºC to 10ºC, which is known to increase the formation rate of ground level ozone.

Table 1.1.2: Common urban forestry terms and their definitions. These terms will be used throughout the study.

Term	Definition
Urban Canopy or Urban Forest	All publicly and privately owned tree canopy in an urban area. May be reported as a percentage or acreage of cover for a specific area.
Public Canopy	Canopy owned and maintained by a local municipality. Ex: Park trees and street trees.
Private Canopy	Canopy owned and maintained by private landowners.
Street Tree	A tree planted in the right of way along streets. A right of way is a property easement, typically located in the green strip between a street and public sidewalk.
Shade Tree	A tall tree with a distinct elevated crown that provides ample shade. Shade trees are typically used as street and park trees.

Canopy cover can effectively reduce UHI by shading impermeable surfaces and through evapotranspiration (the process by which plants emit water vapor into the atmosphere) which cools the surrounding air (Pickett 2011). The presence of street trees (see table 1.1.2) is known to reduce local pollutants, such as particulate matter, carbon dioxide, and ground level ozone, thus reducing rates of air-pollutant agitated illnesses like asthma (Lee and Maheswaran 2010, Schell et al. 2020). Street trees have also been shown to increase the walkability of urban areas, leading to a decrease in cardiovascular disease and an increase in overall health in urban populations (Figueredo et al. 2016). In a similar vein, street trees can increase traffic safety by adding visual inputs in a driver's peripheral vision, reducing the speed of traffic and the frequency car crashes by 5% to 20% (Ewing and Dumbaugh 2009).

Trees provide critical cultural ecosystem services and support human well-being in multiple ways. For instance, trees support and create a sense of place. The shade cover of a large tree provides ample space for community gatherings, safety for children to play, sites for memorial dedications, and aesthetic value that enriches the environment (Cross 2001). High rates of canopy cover have also been shown to reduce rates of mental illness and emotional stress, as well as boost the rate of recovery from such ailments (Tsai et al. 2018).

1.1.3. The Changing Urban Canopy in the City of Fort Collins, CO

The City of Fort Collins, Colorado is situated on the Front Range of the Colorado Rocky Mountains in a semi-arid climate. The city is rapidly growing with an increase of 14,000 residents between 2011 and 2019 (Fort Collins City Plan 2019), and a current estimated population of 170,430 people (City of Fort Collins 2023). The city has accounted for this continued growth with its "Fort Collins City Plan," which was released and adopted in April of

2019. A year after the release of the city plan, Emerald Ash Borer *(Agrilus planipennis,* also known as EAB) was detected just outside of city limits. EAB is an extremely destructive invasive pest that infiltrates the xylem and phloem (vascular tissues) of ash species (*Fraxinus spp.*), causing tree mortality within two to four years. The discovery of EAB in Fort Collins, Colorado poses a serious threat to the city's urban canopy because approximately 1/3 of its canopy is made up of ash tree species (City of Fort Collins Forestry 2023). With the ongoing threat of EAB and projected changes to local climate, the city's forestry staff has begun to take steps towards the creation of an Urban Forest Strategic Plan to ensure the longevity of its urban canopy.

In this chapter, I combine climate envelope modeling and space for time substitution to explore how the climate envelope of Fort Collins in 2061-2080 is projected to differ from the current climate envelope. I then use this information to investigate which species of shade trees would be climate-change resistant under the projected climate scenarios (low emission and high emission pathways). The main question my work seeks to address is: Which street-tree species should be selected to prevent climate-change-induced urban canopy collapse in Fort Collins, Colorado in the next fifty years (2061-2080)? The findings from this chapter aim to help the City of Fort Collins plan for the longevity of its urban canopy and illustrate a novel way to help other cities plan and maintain urban canopies in the face of climate change.

1.2 Methods

For this research study, I introduce a novel approach to selecting climate-change resistant tree species for use in the urban canopy of Fort Collins, Colorado by applying the climate envelope concept to the city of interest. I first extracted city-specific data from WorldClim's

BIOCLIM databases for the Earth's "current" climate scenario (actual climate data from the years 1970-2000, serves as my baseline scenario), and two projected climate scenarios under Shared Socioeconomic Pathways 1 and 5 (reduced fossil fuel emissions and increased fossil fuel emissions, respectively) for the years 2061-2080.

To model climate changeresearchers make assumptions about future greenhouse gas emissions. These emissions are based on scenarios or 'stories' of different plausible pathways of socio-economic and technological development (Riahi et al. 2016). The two future emissions scenario pathways used in this study are from the WorldClim v.2 database which as based off Shared Socio-economic Pathways (SSP) 1 and 5. These pathways were generated from downscaled future climate projections of CMIP6 (Coupled Model Intercomparison Project number 6) from the Beijing Climate Center (Zhang et al. 2019). Both SSP models consider climate projections for the years 2061-2080 and are at a 2.5-minute spatial resolution. The SSPs, which represent different climate mitigation and adaptation paths, were created by the Intergovernmental Panel on Climate Change (IPCC) (Riahi et al. 2016).

There are five total SSPs; however, this study will only consider SSP1 and SSP5. SSP1 is the "sustainability" pathway, which features few challenges to mitigation and adaptation, as well as the rapid development of innovative technologies. SSP1 assumes that society will make every effort possible to reduce emissions. SSP5, or the "fossil-fueled development" pathway, has many challenges for mitigation (due to reliance on fossil fuels) and challenges toward adaptation of green technology (due to path dependency and rapid development of fossil fuel technology) (Riahi et al. 2016). SSP5 assumes that society will further increase its dependency on and use of fossil fuels, thus dramatically increasing carbon emissions. SSP's 2-4 are more intermediate pathways that assume different combinations of new green technology and continued fossil fuel

use. For the purposes of this study we will be using SSP1 and SSP5 as our reference pathways (referred to as SSP126 and SSP585 in the WorldClim and BIOCLIM databases, respectively) in order to capture the breadth of variation across the five climate scenarios.

The collected data identifies the current and potential future climate envelope extents for the City of Fort Collins by defining the observed range of average precipitation (annually, and warmest and coldest quarters) and temperature (annually, and warmest and coldest months) within the city across the three climate scenarios. The observed ranges from SSP1 and SSP5 were then projected onto a raster layer containing data from the current climate scenario to identify areas in the United States where these climates ranges currently exist. By doing so, I was able to locate cities that currently feature the climate conditions expected for Fort Collins in 2070 under a low-emission and high-emission pathway. These reference cities have publicly available recommended street tree lists, allowing me to identify tree species with high potential for surviving Fort Collins, CO's future climate conditions. This reference city analysis provides an initial pool of 141 species which was further refined until I generated my final two recommendation lists: first, a list of 15 shade-tree species that have been proven suitable for Fort Collins, but are not currently planted; and second, a list of 21 shade-tree species that may be appropriate for the city but require further assessment.

1.2.1 Study Area and Recommended Tree Lists

The City of Fort Collins, Colorado lies nestled in the front range of the Rocky Mountains within the Cache la Poudre River watershed. At an elevation of 5,000 feet above sea level, residents of Fort Collins experience four full seasons while enjoying an average of 300 days (about 10 months) of sunshine. The city resides within a semi-arid short grass steppe ecosystem,

receiving an average of 14.5 inches (368mm) of precipitation a year. The warmest month of the year is typically July, with average highs of 30ºC and average lows of 13.8ºC. The coldest month of the year is typically January, with average highs of 5.5ºC and average lows of -10ºC (Fort Collins Facts 2023).

The City of Fort Collins' Forestry Department runs a rigorous program complete with city foresters who care for publicly owned trees, neighborhood street tree planting and care programs, a self-guided tree tour of notable and historical trees in the city, free tree selection and care guides, and a community-based Urban Forest Ambassador program (Fort Collins Forestry 2023). Fort Collins' provides a recommended street tree list that is publicly accessible and details information on 21 shade-tree species that forestry staff has deemed appropriate for use in public parks and within public right-of-way areas (the space between a road and a sidewalk where street trees are typically planted) and are known to be suitable to local climate (Fort Collins Forestry 2023).

Many cities across the world generate their own recommended street tree lists to inform citizens of appropriate tree species for the area. These lists typically contain information on each species' landscaping use (street tree, ornamental, shade-tree, fruiting tree, etc.), water use intensity, shade, heat, and cold tolerance, soil preferences and tolerance, and any relevant planting considerations (such as potential pests, and level of mess created by tree leaves, flowers, seeds, and pollen). Some counties and regions also create tree planting guides to make general recommendations for a greater area. One such guide, the Front Range Tree Recommendation List, was created by local forestry, arboriculture, and nursery experts along the front range of Colorado, including contributors from Colorado State University, and the Colorado State Forest Service. This list is intended to inform local municipalities and citizens of suitable tree species

selections for the area and features suitability ratings ranging from A-D, with A being highly recommended, B being conditionally recommended (only certain landscape uses, shade preferences, or soil types), C being unproven/untested, and D being not recommended. The suitability rating for each species on the Front Range Tree Recommendation List was designated by consensus by the local experts who created the list (Barry et al. 2010).

Another local list considered by this study is the Colorado State University Arboretum Test List, which was generated by foresters and arborists at the Colorado State Forest Service and Colorado State University. Tree species appearing on this list are either currently being, or have been, tested in Colorado State University-affiliated arboretums for local planting suitability. Each tested species receives a rating of recommended, conditionally recommended (only certain cultivars or for specific planting situations), or not recommended.

1.2.2 Creation of Climate Envelope Models

For this study, six bioclimatic variables were sourced from WorldClim's historical and future climate projections database (Fick and Hijmans 2017). These six variables were annual mean temperature (BIO1), maximum temperature of the warmest month (BIO5), minimum temperature of the coldest month (BIO6), mean annual precipitation (BIO12), precipitation of the warmest quarter (BIO18), and precipitation of the coldest quarter (BIO19). These six variables help to define an organism's "climate envelope," or the set of conditions under which a specific species can survive. This specific set of six variables have been used to define climate envelopes in previously conducted tree-survivorship and climate change research (Yang 2009, McKenney et al. 2007). Previous studies using BIOCLIM variables have eliminated the use of variables BIO8 (mean temperature of the wettest quarter), BIO9 (mean temperature of the driest quarter),

BIO18 (precipitation of the warmest quarter), and BIO19 (precipitation of the coldest quarter) due to spatial discontinuities attributed to the interactive nature of these four variables (Booth 2022, Escobar et al. 2014). However, our study will continue to use BIO18 and BIO19 because no abnormalities in distribution were noted by teams conducting climate envelope research in the same study extent (Burke et al. 2019). Unlike past research studies, which used bioclimatic indicators to predict species extent, these six indicators will be used to project the extent of the City of Fort Collins, Colorado's recent historical (1970-2000) and expected future (2061-2080) climate envelopes in ArcGIS Desktop (v. 10.6).

To generate current and future climate envelope models for the City of Fort Collins, the recent historical (1970-2000) and future climate models (SSP126 and SSP585) were downloaded from WorldClim at a 2.5-minute spatial resolution and brought into ArcGIS Desktop (version 10.6). For each climate scenario, an area of interest (AOI) encompassing the continental United States and a portion of Central America, and the city limits of Fort Collins, Colorado were uploaded onto the active map (City of Fort Collins City Limits 2018). All bioclimatic indicators from the current baseline and future climate scenarios were first clipped to the AOI, and then again to the city limits. By clipping to the city limits, the researcher was able to isolate a 5x5 pixel block (1 pixel = 2.5-degree-minutes) of bioclimatic indicator data specific to the city. AOI clips were saved and set aside to be used later in analysis (see "Z-scores" below).

Once the 5x5 pixel block covering Fort Collins was isolated, each of the six chosen bands representing a different bioclimatic indicator were isolated from the original raster stack provided by WorldClim. Each band was added to the active map and renamed "climate scenario_startyear_Clip_bioclimatic indicator." For example, band 1 refers to the bioclimatic indicator Annual Mean Temperature and was labeled "SSP126_2061_Clip_AnnMeanTemp" for

the low-emissions future climate model. Values from all 25 pixels were recorded in Microsoft Excel for each of the six bioclimatic indicators across the three models. Excel was then used to generate means for each variable across the three scenarios.

These means were then used to calculate z-score raster layers for each bioclimatic indicator. A Z-score is a commonly used method in statistics that creates a standardized scale to measure how many standard deviations a specific value is away from the mean of that variable (see figure 1.2.2). Because an individual z-score represents a standard deviation distance from that variable's mean, we can compare z-scores of different variables on a single, standardized scale. The Z-score is imperative to building my climate envelope models because it allows me to create a single scale from which all my variables can be compared. For instance, a Z-score of +1 for a variable whose mean is 100 would be equal to 134, while a z-score of +1 for a variable whose mean is 50 would be equal to 69. Both have equal z-scores but differing variable values. The use of Z-scores will allow me to create a single raster layer that highlights all values within a particular range of Z-scores (-0.25 to +0.25), representing my accepted range of climate variability and forming my climate envelopes.

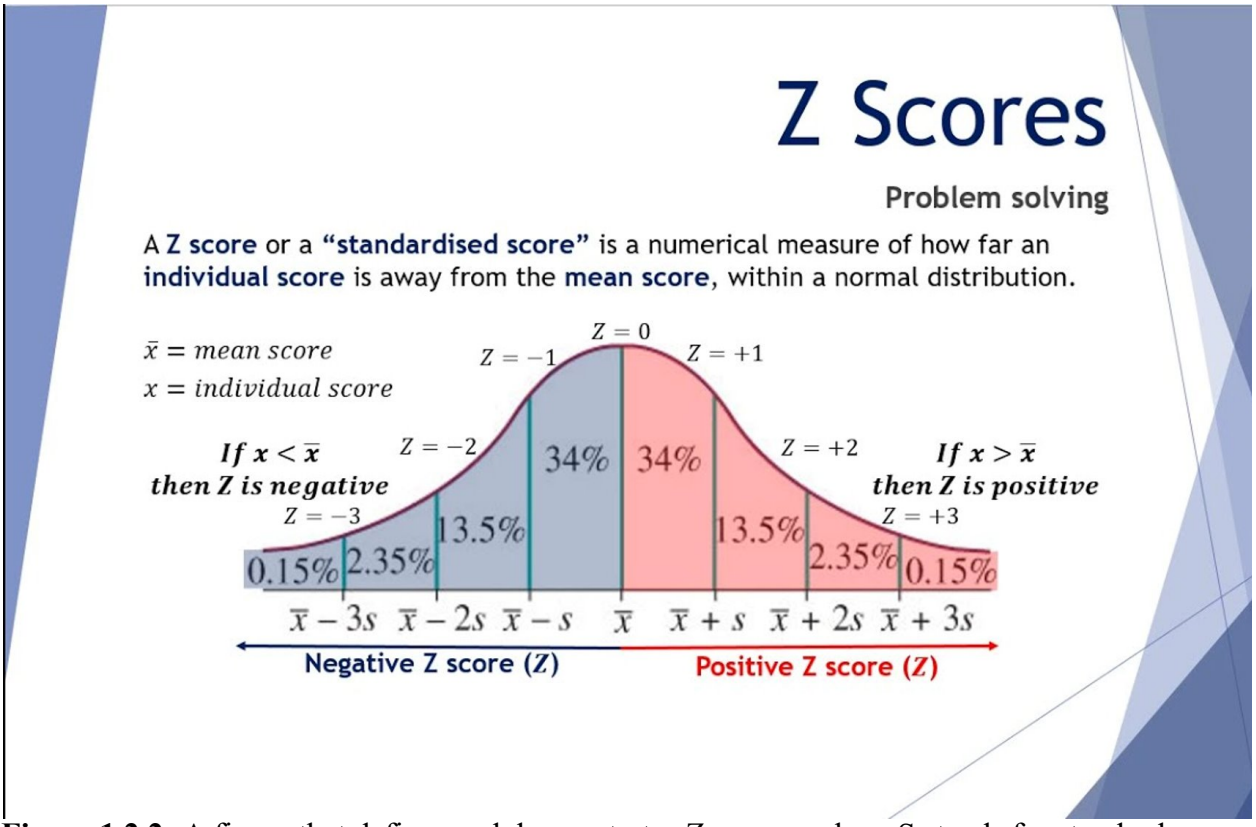

Figure 1.2.2: A figure that defines and demonstrates Z-scores, where S stands for standard deviation. Image credit: Juddy Productions' Educational Resources.

Once all the bioclimatic indicator variables' means were collected, I was able to create z-score raster layers for each bioclimatic indicator with a z-score of 0 centered on Fort Collins, Colorado using the following formula:

$$Zi = \frac{\text{"Fort Collins Indicator Mean"i - "Overall Indicator Mean"i)}}{\text{"Indicator Standard Deviation"i}}$$

Formula 1.2.2: calculating z-score layers of each bioclimatic indicator.

Where “Fort Collins Indicator Mean” refers to the bioclimatic indicators’ mean within Fort Collins’ city limits, “Overall Indicator Mean” refers to the bioclimatic indicators’ mean within the larger area of interest, and “Indicator Standard Deviation” refers to the bioclimatic indicators’ standard deviation across the larger area of interest. The same formula was entered into the Spatial Analysis tool, Map Algebra, in ArcMap (ver. 10.6) to generate a “z-score layer” for each bioclimatic indicator. This effectively retrained each bioclimatic indicator layer so a z-score of 0 would represent the City of Fort Collins, Colorado.

Once all 18 z-score layers were created (one for each of the six bioclimatic indicators across the three models – the baseline and the low and high emission scenarios), three, six-dimensional z-score models were generated, one for each climate scenario (current baseline, future low-emissions, and future high-emissions). These six-dimensional z-score models train all six bioclimatic indicator means to a single statistical zero using the following formula in Raster Calculator:

```
SQUAREROOT ( ( "indicator1" - (indicator1 zscore)) * ("indicator1" - (indicator1 zscore)) +
        ("indicator2" - (indicator2 zscore)) * ("indicator2" - (indicator2 zscore)) +
        (“indicator6" - (indicator6 zscore)) * ("indicator6" - (indicator6 zscore)) +
        ("indicator12" - (indicator12 zscore)) * ("indicator12" - (indicator12 zscore)) +
        ("indicator18" - (indicator18 zscore)) * ("indicator18" - (indicator18 zscore)) +
        ("indicator19" - (indicator19 zscore)) * ("indicator19" - (indicator19 zscore)) )
```

Formula 2: Raster Calculator code for generating a six-dimensional z-score raster layer in Raster Calculator on ArcDesktop.

Where each ‘“indicator”’ (ex: “indicator1”) is the name of that indicator’s raster layer on the active map and “indicator zscore” is the z-score value for that indicator as described in formula 1. Formula 2 was used for each of the three models: current baseline scenario (1971-2000), future low-emissions scenario SSP126 (2061-2080), and future high-emissions scenario SSP585 (2061-2080), thus generating a six-dimensional z-score layer for each climate scenario. Like the z-score layers created using formula 1, the six-dimensional z-score layers generated with formula 2 “fixes” the statistical zero to Fort Collins, Colorado. This fixation was tested using the following CON statement in Raster Calculator:

CON (“6DLayer” <= (zvalue))

Formula 3: CON statement used in Raster Calculator to test fixed zero in new six-dimensional z-score layers.

Where ‘“6DLayer”’ is the six-dimensional z-score layer for that climate scenario, and “zvalue” is the z-score (or standard deviation from z’s zero) being tested. This CON statement will highlight all z-score values less than or equal to the z-score of interest. This allows us to test for proper zero fixation by using a small z-score to see if it highlights Fort Collins, Colorado, and a small amount of surrounding area (see proof of concept).

The six-dimensional z-score layers from the two future climate-scenarios (SSP126 for the low-emissions scenario, and SSP585 for the high-emissions scenario) were added to the current baseline-scenario map. A CON statement (formula 3) with a z-score value of +/-0.25 was applied to both future climate-scenario’s six-dimensional z-score layers. This application of both future scenarios’ six-dimensional z-score layers allowed me to project the current extent of expected

future climate envelopes for Fort Collins, Colorado onto the AOI. Names of cities residing within the highlighted areas were recorded.

1.2.3 Proof of Concept

To test my approach, I first generated a model that illustrates the extent of Fort Collins' current climate envelope. I considered the test successful when this baseline climate envelope model highlighted the city of Fort Collins and a portion of the surrounding area (Z = -0.25 and +0.25). Formation of the baseline climate enveloped indicated that the z-score layers and subsequent multi-layer z-score raster (which combined all six of the selected bioclimatic z-score layers) were successfully trained to the City of Fort Collins, allowing bioclimatic indicator means for the city to act as "zero" on their respective Z-score scales.

With the city trained to zero on a z-score scale within our multi-layer z-score raster, I used a CON statement in Raster Calculator to highlight all scenarios that fall within a certain distance from the standardized mean (or standard deviation). This standard deviation represents the accepted limits of the defined baseline climate envelope. For my research study, the baseline and two future scenarios used a standard deviation of 0.25 which I felt was large enough to encompass a city's climate envelope, but specific enough that it would limit the extent of my estimated future climate envelopes. When the statement (CON ("combo-z" ≤0.25)) is entered in the baseline scenario (current climate), the highlighted area on the map covers the majority of the City of Fort Collins, and some surrounding areas (see map 1.3.1). I considered this a successful test of my novel approach and applied the same treatment to my two future scenario datasets.

This application of climate envelope modeling to future projections is what makes my approach novel. Previous climate envelope studies have focused on predicting the current extent

of species, using species specific information to define the parameters of their climate envelope. My research treats the City of Fort Collins, Colorado as our study organism, identifying current baseline climate conditions and estimated future conditions to determine how much the city's climate is expected to shift by 2061-2080, and uses a space for time approach by identifying reference cities and their respective recommended tree species lists.

1.2.4 Identification of Reference Cities

Once I verified my proof of concept and added the two future climate-envelope projections to the current map, I was able to begin analysis and data collection to answer my main research question about shade-tree species' resistance to climate change. To identify reference cities, I noted all the cities that fell within the projected low and high future climate envelopes and then downloaded their recommended street tree lists (RST). Some of the reference cities deferred to the Front Range Tree Recommendation List and some reference cities did not provide an RST. I compiled reference cities that did provide RSTs, and the species listed on those RSTs were then compiled into a single master list in excel which detailed tree species (common and scientific name), recommended cultivars, the city list(s) that each species/cultivar appeared on, and whether each species also appeared on the current RST for Fort Collins, Colorado. This list became my Initial Pool of Resistant Species for consideration.

I then removed non-shade providing tree species from my Initial Pool of Resistant Species, because the city wants to plant large, shade providing trees for public street tree planting, public parks, and shade landscaping. I then compared the remaining pool of species to the Front Range Tree Recommendation list. Trees in my Initial Pool of Resistant Species that did

not appear on the Front Range Tree Recommendation list were then searched for in the CSU-Arboretum Test List, and their suitability rating was recorded.

My findings from comparing my Initial Pool of Resistant Species to the Front Range Tree Recommendation list and CSU Arboretum Test list allowed me to generate my final products: first, the Future Fort Collins RST list, and second, the Future Fort Collins RST Test list, both of which consist of a subset of species appearing in my initial pool of resistant species (see figure 1.2.4). The Future Fort Collins Recommended Street Tree List is made up of species that do not appear on Fort Collins *current* Recommended Street Tree List but are endorsed by the CSU-Arboretum Test List and/or the Front Range Tree Recommendation List. The Future Fort Collins Recommended Street Tree List is intended to inform Fort Collins' forestry staff of climate-change-resistant tree species that are not currently planted by the city and whose local survivability has been confirmed by expert arborists. The Future Fort Collins RST also provides the following information on each species: common and scientific name, recommended cultivars (if any), which "reference city(s)" RSTs that species appeared on. The Future Fort Collins RST list can be seen in table 1.3.3a.

The Future Fort Collins RST-Test list is made up of shade-tree species that either, 1) had a C rating (unproven/untested) on the Front Range Tree Recommendation list, or 2) did not appear on the Front Range Tree Recommendation list, Fort Collins' current RST, or the CSU-Arboretum Test list. Species on the Future Fort Collins RST-Test list will be recommended for survivability and suitability testing in Colorado State University's test arboretums. Once species have been tested by Colorado State University and Colorado State Forest Service arborists, they can be moved onto the Future Fort Collins RST list or designated as unsuitable for planting in Fort Collins, Colorado. The Future Fort Collins RST-Test list can be seen in table 1.3.3b.

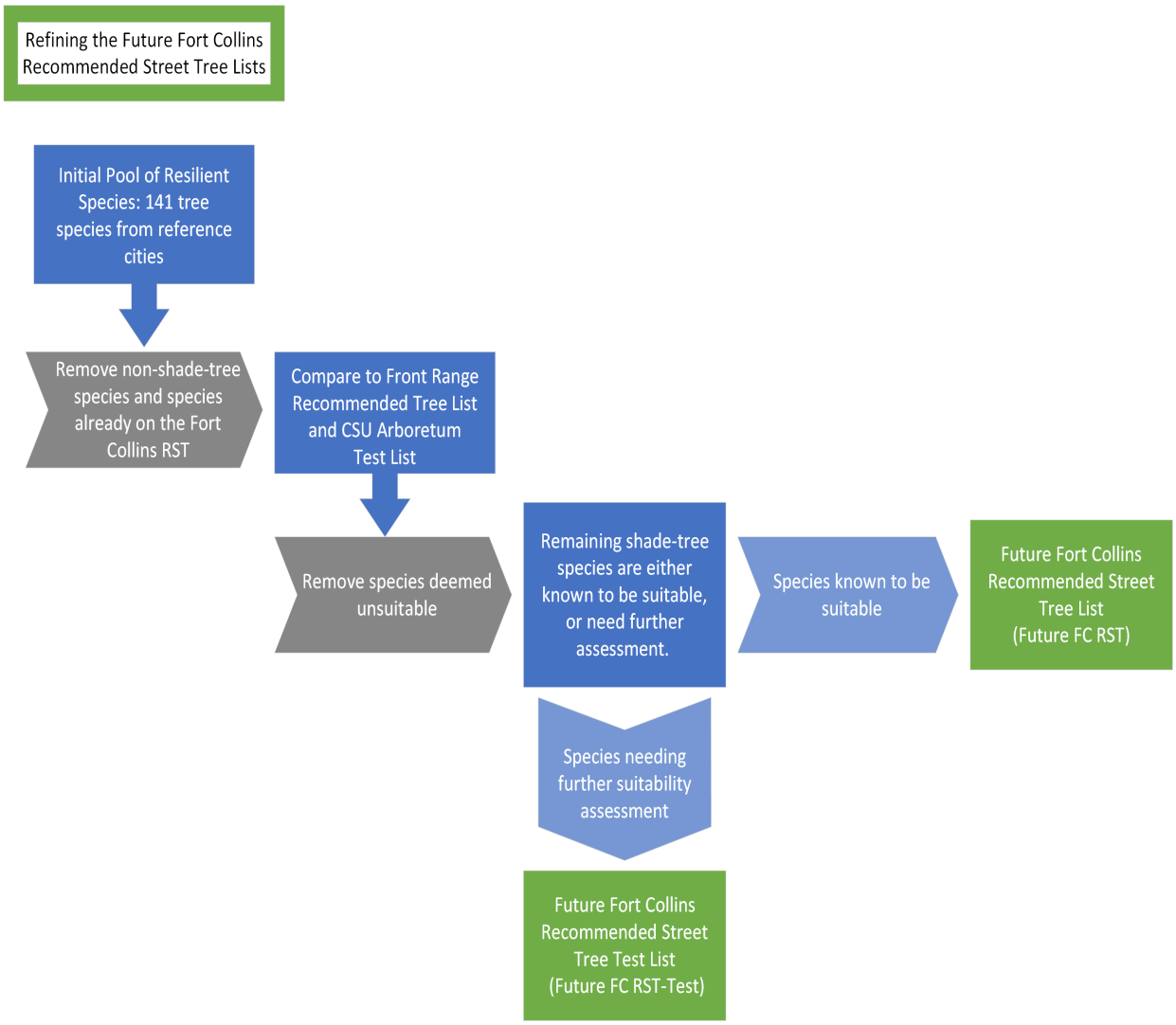

Figure 1.2.4: A flowchart illustrating the process of sorting the Initial Resistant Species Pool into the Future Fort Collins RST and Future Fort Collins RST-Test lists by removing non-shade, redundant, and known-to-be unsuitable tree species, and then further refining the lists by species immediately implementable (Future Fort Collins Recommended Street Trees) and those needing further assessment (Future Fort Collins Recommended Street Trees-Test).

1.3 Results

1.3.1 Proof of Concept and Current Climate Extent

The baseline climate envelope model for Fort Collins, Colorado is depicted in figure 1.3.1. This illustrates the six-dimensional z-score layers were in fact trained to Fort Collins and highlights areas that currently feature climates similar to Fort Collins.

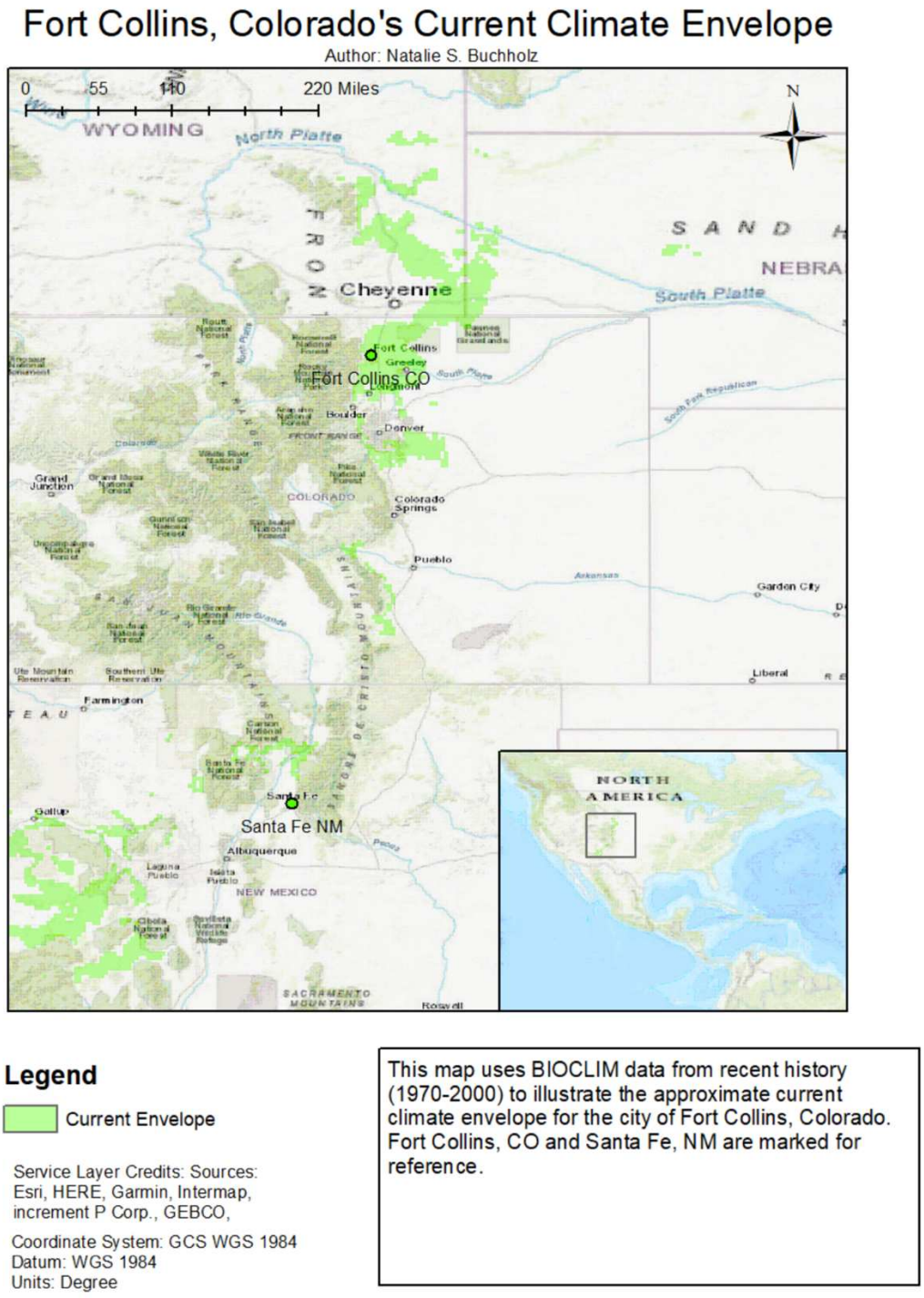

Figure 1.3.1: Fort Collins, Colorado's current climate envelope extent. The climate envelope (shown in green) includes Fort Collins, Colorado and surrounding areas including portions of southeast Wyoming and western Nebraska. Similar climates can also be found surrounding the Denver Metro area, south central Colorado, North of Santa Fe, NM, and in western New Mexico.

When viewing the current climate envelope model as seen in Figure 1.3.1, we also observe that the climate envelope stretches to areas far beyond Fort Collins, Colorado. Portions of this climate envelope also persist in southeast Wyoming and western Nebraska, surrounding the Denver Metro area and the front range of south-central Colorado, just north of Santa Fe, NM, and in the plains of western New Mexico.

1.3.2 Projecting Current Extents of Future Climates

After completing the proof of concept, the future Bioclimatic indicators' 6-dimensional z-score layers for both the low (SSP126) and high-emissions (SSP585) scenarios were added to the current map. This created a projection of the current extent of the future climates expected for Fort Collins in 2061-2080. We can see these extents in Figure 1.3.2, where the low-emissions scenario (SSP126) is shown in yellow, and the high-emissions scenario (SSP585) is shown in pink. Areas of overlap, shown in orange, indicate the current extent of future climates in between the low and high emissions scenarios.

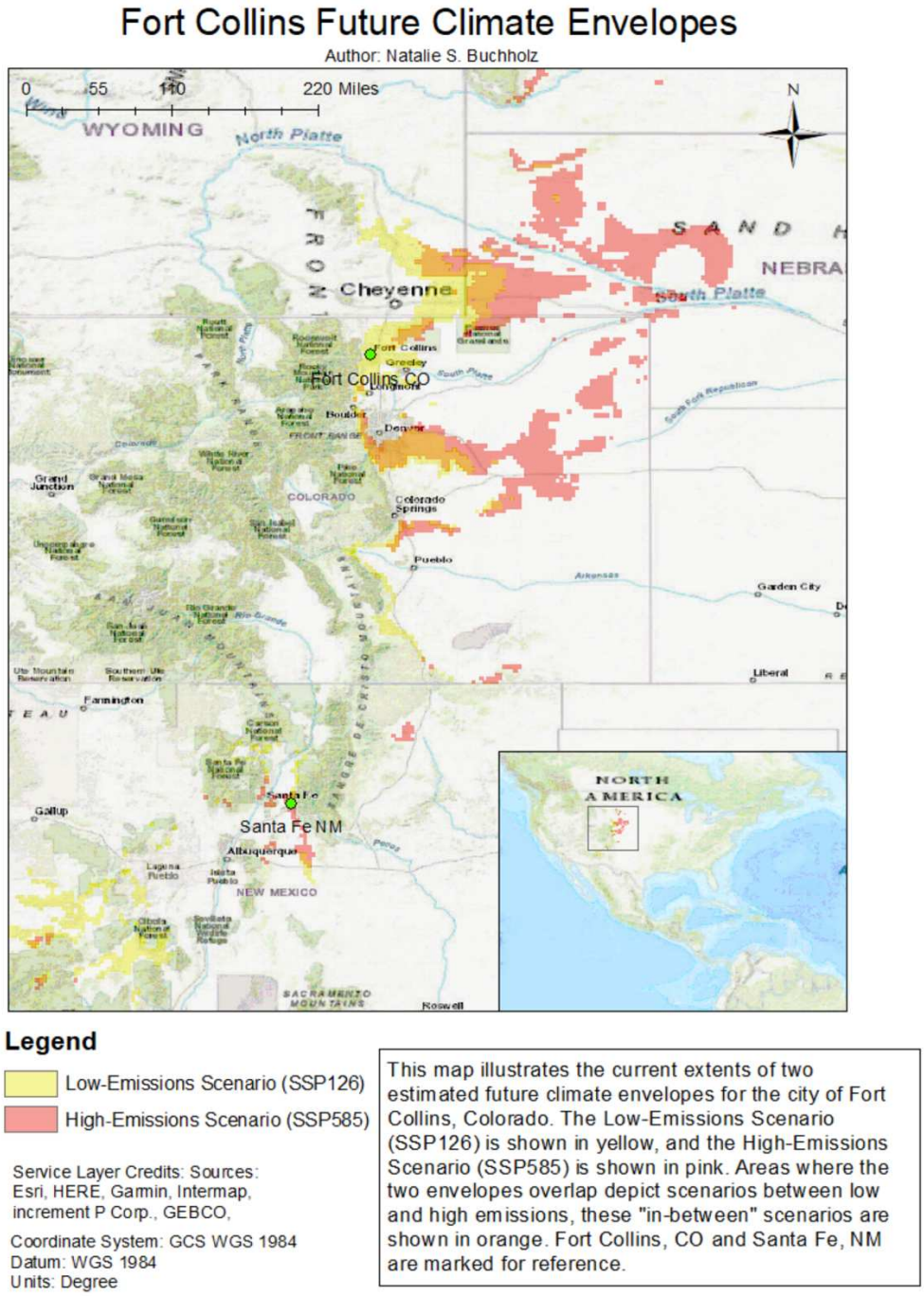

Figure 1.3.2: This map layout details the current extent of future climates projected to be experienced in Fort Collins, Colorado in 2061-2080. The Low-Emissions Scenario (SSP126) is shown in yellow, and the High-Emissions Scenario (SSP585) is shown in pink. Areas of overlap, shown in orange, indicate the current extent of future climates in between the high and low emission scenarios. I examined these extents and recorded the name of any cities within them to build the initial list of potential tree species.

Figure 1.3.2 shows that current extents of future climates occur in the areas directly surrounding the city of Fort Collins, Colorado, the Denver Metro area, and extend into areas in the neighboring states of New Mexico, Nebraska, and Wyoming. Cities existing within these current extents of future climates were recorded and then further refined by availability of city-specific tree recommendation lists, thus creating one concise list of reference cities (see table 1.3.2). The current extents of future climates in Nebraska and Wyoming occur over large agricultural areas that are either unincorporated or belong to smaller towns without a forestry department. Because of this, there were not any cities with RSTs in Nebraska or Wyoming that could be included in the reference cities list (table 1.3.2).

Table 1.3.2: A list of final reference cities, their states, and straight-line distances from Fort Collins, Colorado.

Reference City	State	Distance from Fort Collins, CO (straight-line)
Aurora	Colorado	~60 miles south
Castle Pines	Colorado	~78 miles south
Castle Rock	Colorado	~85 miles south
Centennial	Colorado	~70 miles southeast
Littleton	Colorado	~67 miles south
Parker	Colorado	~76 miles southeast
Santa Fe	New Mexico	~342 miles southwest
Superior	Colorado	~44 miles south

There was a total of 8 reference cities, 7 of which occurred within the state of Colorado, with the remaining city appearing in New Mexico. Most reference cities reside within or just south of the Denver Metro area of Colorado. These cities are Aurora, Castle Pines, Castle Rock, Centennial, Littleton, and Parker, Colorado. The reference city of Superior, Colorado can be found just northwest of the Denver Metro area and is the northernmost city examined. Finally, the only out-of-state and southernmost reference city was Santa Fe, New Mexico.

1.3.3 Climate-Change-Resistant Tree Species Selection

The initial pool of resistant species totaled 141 tree species. I reduced that pool to 36 species by removing non-shade trees and species that already appear on Fort Collins' Recommended Street Tree list. These 36 species were then sorted into one of two lists, the Future Fort Collins Recommended Street Tree List (see table 1.3.3a) and the Future Fort Collins Recommended Street Tree-Test List (see table 1.3.3b).

The Future Fort Collins Recommended Street Tree List is composed of 15 shade-tree species that are suitable for immediate addition to the city of Fort Collins' urban canopy and recommended street tree list (see table 1.3.3a). Of these 15 species, 10 appeared on Santa Fe, NM's recommended street tree list. The remaining 5 species all appear on recommended street tree lists from reference cities in the Denver Metro area. Cities closer to Fort Collins (like those in the Denver Metro Area) are more likely to have species in common on their RSTs than cities further away (like Santa Fe, NM). This is the likely explanation for why more species used by cities outside of Colorado were recommended than species currently used by cities within Colorado.

Table 1.3.3a: The Future Fort Collins Recommended Street Tree List. This list names 15 climate-change resistant shade tree species deemed appropriate for immediate planting in Fort Collins, Colorado.

Common Name	Scientific Name	Cultivars	Reference City
Shantung Maple	Acer truncatum		Santa Fe, NM
Amur Corktree	Amurense	Male cultivars only	Centennial, CO
American Smoke Tree	Cotinus obovatus		Santa Fe, NM
Crusader Hawthorn	Crataegus Crus-Galli	Crusader	Castle Pines, CO
Arizona Cypress	Cupressus arizonica		Santa Fe, NM
Hardy Rubber Tree	Eucommia ulmoides		Santa Fe, NM
Douglas Fir	Pseudotsuga menziesii	Glauca, Fastigiata, Pendula	Castle Pines, Castle Rock, Parker, CO
Jujube	Ziziphus jujuba		Santa Fe, NM
Mongolian Linden	Tilia mongolica	Harvest Gold	Castle Rock, CO
Native Hawthorn	Crataegus succulenta	Macrantha	Castle Pines, CO
Winterberry Euonymus	Euonymus bungeana	North Platte, Pink Lady, Verona	Santa Fe, NM
Sargent Cherry	Prunus sargentii	Pink Flair	Santa Fe, NM
Higan Cherry	Prunus subhirtella	Pisnshazam, Pendula Plena Rosea, Pink Snow Showers, Weeping Higan	Santa Fe, NM
Osage Orange	Maclura pomifera	White Shield (low-thorn count)	Santa Fe, NM
Oak Hybrids	Quercus x	x bimundorum Midwest, x macdanielli Clemons	Santa Fe, NM

The Future Fort Collins Recommended Street Tree-Test List is composed of 21 shade-tree species that are untested or unproven for planting suitability in Fort Collins, Colorado (see table 1.3.3b). Of these 21 species, 17 appeared on Santa Fe, New Mexico's recommended street tree list, 2 appear on both Santa Fe's recommended street tree list and recommended street tree lists from the Denver Metro area, and 6 appear only on recommended street tree lists from

reference cities in the Denver Metro area. Like species appearing on the Future Fort Collins Recommended Street Tree List, it is most likely that the higher number of recommended species from Santa Fe is due to differences in distance from Fort Collins, Colorado. The trees appearing on this list are recommended for further suitability analysis and testing before adding them to Fort Collins' urban canopy and recommended street tree list.

Table 1.3.3b: The Future Fort Collins Recommended Street Tree-Test List. Trees appearing on this list are recommended for further suitability evaluation by Colorado State University arborists in CSU test arboretums. If a species is deemed suitable for the city of Fort Collins, Colorado, they will be added to the Climate-Change-Resistant Trees list and recommended to the city for planting.

Common Name	Scientific Name	Cultivars	Reference City
Sensation Boxelder	Acer negundo	Sensation	Littleton, CO, Santa Fe, NM
Texas Madrone	Arbutus texana		Santa Fe, NM
Desert Willow	Chilopsis linearis		Santa Fe, NM
Yellowwood	Cladrastis kentukea		Santa Fe, NM
Lavalle Hawthorn	Crataegus x lavellei		Santa Fe, NM
Amur Maackia	Maackia amurensis		Santa Fe, NM
Illinois Everbearing Mulberry	Morus rubra	Illinois everbearing	Santa Fe, NM
Lacebark Pine	Pinus bungeana		Parker CO, Santa Fe, NM
Swiss Stone Pine	Pinus cembra		Santa Fe, NM
Single-leaf Piñon	Pinus monophylla		Santa Fe, NM
Chinese Pistache	Pistacia chinensis		Santa Fe, NM
Sycamore	Platanus occidentalis		Parker, CO
Lanceleaf Cottonwood	Populus acuminata		Castle Pines, Castle Rock, CO
European Plum	Prunus domestica		Santa Fe, NM
Oriental Fruiting Pear	Pyrus pyrifolia		Santa Fe, NM
Southern Red Oak	Quercus falcata		Littleton, CO
Escarment Live Oak	Quercus fusiformis		Santa Fe, NM
New Mexican Locust	Robinia noemexicana		Castle Rock, CO
Lacebark Elm	Ulmus parvifolia		Santa Fe, NM
Yellowhorn	Xanthoceras sorbifolium	Clear Creek	Santa Fe, NM
Japanese Zelkova	Zelkova serrata	Musashino, Green Vase, Village Green	Santa Fe, NM

1.4: Discussion

1.4.1 Current Climate Envelope and Current Extents of Future Climates

The baseline climate envelope can be seen in Figure 1.3.1. Here we observe that Fort Collins' current climate envelope surrounds the city of Fort Collins, but also extends to areas both within and outside of the state of Colorado. The current climate envelope for Fort Collins persists in the Denver Metro Area and south-central Colorado, western Nebraska, southeastern Wyoming, the western plains of New Mexico, and just north of Santa Fe, NM.

1.4.2 Climate-Change Resistant Tree Species Selections

The two lists of climate-change resistant tree species, the Future Fort Collins Recommended Street Tree List and Future Fort Collins Recommended Street Tree-Test List are the major products of this study. First, the Future Fort Collins Recommended Street Tree List details 15 shade tree species that my study deemed appropriate for street tree use in Fort Collins but are not included in the city's current recommended street tree list (see table 1.3.3a). I strongly recommend that the species on this list be considered for addition to Fort Collins, Colorado's Recommended Street Tree List and that foresters work with local nurseries to have these species and cultivars carried and available for both public and private landowners.

The Future Fort Collins Recommended Street Tree-Test List is the second of two products created by this study. This list details 21 additional shade tree species that may be suitable for street tree planting in Fort Collins but require additional testing. I recommend that the City of Fort Collins Forestry Department, in conjunction with Colorado State University and Colorado State Forest Service arborists, begin suitability testing on these 21 species as soon as

possible. Ideally, these 21 shade trees would be immediately added to the CSU test arboretums to be observed and, hopefully, approved for local use in the next few years.

The purpose of both lists is to supplement the current Fort Collins Recommended Street Tree List, giving local foresters options for diversification. Increasing urban canopy biodiversity should be an overall long-term goal for municipalities of all sizes to safeguard against catastrophic canopy loss from species-specific failures. Urban canopy collapses become increasingly likely as tree species richness decreases, particularly if some species are more prevalent than others and occur in groups. For instance, the current canopy collapse in Fort Collins was brought on by the Emerald Ash Borer, but the magnitude of collapse could have been reduced had there been a greater diversity of species in the municipality and had ash trees not become such a large portion of total canopy cover (estimated 1/3 of total urban canopy cover in Fort Collins, Colorado).

As the city continues to inoculate, remove, and replace its' ash tree population, foresters should consider boosting local canopy biodiversity by including the species identified on the Future Fort Collins Recommended Street Tree List and verifying the local suitability of species identified on the Future Fort Collins Recommended Street Tree-Test List. Species occurring on both lists should be considered for addition to the Front Range Tree Recommendation list so that municipalities across the Front Range may also contemplate them for local use.

1.4.3 Using multi-method approaches to link science with society

This is the first study, to my knowledge, that combines climate envelope modeling and space for time substitution with urban canopy management in the face of climate change and disease-related urban canopy collapse. The study is unique in that it draws on multiple sources of

evidence – from climate envelope modeling, space-for-time substitutions, tree tolerance studies from the Colorado State University Test Arboretums, and expert knowledge from city foresters in Fort Collins, Colorado and reference cities like Santa Fe, New Mexico. This work is an example of how multi-method approaches are required for addressing critical sustainability challenges, and how a transdisciplinary approach, where scientists work with and for society, can be the most effective means of moving forward.

1.4.4 Limitations

This study has limitations that impact the accuracy of my current and predicted future climate envelopes. The current climate envelope model relies on historical climate data from the years 1971-2000 because it was the most recent available historical dataset produced by WorldClim at the time of this study. In the future, I would like to improve the accuracy of my study by reproducing it with the 2001-2020 historical climate dataset when it becomes available. A comparison of the 1971-2000 dataset and 2001-2020 dataset could also reveal key information into the current rate of climate change along the Front Range of Colorado.

1.4.5 Recommendations for Future Work

When determining my methods for this study, I decided to use only two of the five available Shared Socio-economic Pathways (SSPs). I made this decision under the assumption that areas of overlap between the lowest emission (SSP1) and highest emission (SSP5) pathways would reveal the current extent of more intermediate pathways (SSPs 2, 3, and 4). However, it is

entirely possible that this is not true, or that the extents of the intermediate pathways surpass that of SSP1 and/or SSP5. Future research should include the other three SSPs to bolster findings.

Additionally, my area of interest only included the continental United States and a portion of Mexico (to the southern extent of the Florida peninsula). I chose this area of interest to manage the size of my dataset and limit the time spent running geoprocessing tools. However, it is highly likely that with a global area of interest I would have revealed additional areas with current climates like what is expected for Fort Collins in the next fifty years. This increase in current extents of future climates would have likely produced additional reference cities with RSTs, thus causing an increase in the number of tree species appearing on my initial pool of resistant species. In a similar vein, this study only considered shade tree species appearing on RSTs. A larger initial pool of resistant species could have been collected had I considered native species from the current extents of future climates and included non-shade tree species (shrubs, ornamentals, non-shade conifers, fruiting trees, etc.). If I were to perform a similar study in the future, I would consider a global area of interest, native species, and non-shade trees to further increase Fort Collins, Colorado's canopy biodiversity.

This study presents projected climate change at an extremely local level, specifically for the City of Fort Collins, Colorado. Due to its scale and the unique nature of mountain/foot of the mountain ecosystems, this study should not be extrapolated to make general conclusions about the Front Range region of the Rocky Mountains. Instead, this study should be replicated for other Front Range Colorado cities such as Boulder, Golden, Longmont, Loveland, and Lyons. As additional Front Range climate envelopes and current extents of future climates are explored, we can make more informed conclusions about how climate is likely to shift across a larger region and begin planning for appropriate mitigation and adaptation strategies.

In a similar vein, this study should be replicated outside of the Front Range region of Colorado. This study's methods were intended to be adaptable to any ecosystem, any size city or study area, and any region of the world. Continuing to replicate this study across the globe will give us a larger picture of how climate change will impact both native and urban ecosystems, with additional methods for determining climate-change resistant tree species selections for use in urban systems. As additional historical datasets become available (for example, the 2001-2020 dataset was not available at the time of this study) this study should be repeated to examine the actual rate of climate change between historical datasets as well as the projected rate of climate change between historical and projected datasets.

1.5: Conclusion

This study demonstrates that combining climate envelope modeling methods and space for time substitution approaches can effectively locate near-future climate analogs for urban ecosystems (50-100 years in the future). An understanding of which cities and regions currently represent an urban area's potential future climate allows researchers and local policy makers to make informed decisions about near-future impacts of climate change. Climate analogs (referred to as "reference cities" in this study) can inform decisions for many topics such as water use and maintenance, preparation for changes to precipitation patterns like drought and flood mitigation, UHI mitigation and more.

This study used identified climate analogs under low and high emissions scenarios to determine appropriate climate-change-resistant street tree selections for the city of Fort Collins, Colorado. The use of climate analogs for this purpose represents a faster method for street tree species selection than the typical climate envelope method, which generates a climate envelope

for each potential species that would then be used to see if their range overlaps with the area of interest. By using a climate analog, researchers can more efficiently identify species that occur in the region instead of researching species that may occur there, and then mapping their potential range under climate change.

CH 1 REFERENCES

Barry, G. et al. Front Range Tree Recommendation List. (2010).

Blois, J. L., Williams, J. W., Fitzpatrick, M. C., Jackson, S. T. & Ferrier, S. Space can substitute for time in predicting climate-change effects on Biodiversity. Proceedings of the National Academy of Sciences 110, 9374–9379 (2013).

City of Fort Collins. City Limits. City of Fort Collins: Fort Collins Geospatial Information Services, April 24, 2018.

Cross, Jennifer E. 2001. "What is Sense of Place?" Prepared for the 12th Headwaters Conference, Western State College, Department of Sociology, Colorado State University. https://mountainscholar.org/bitstream/handle/10217/180311/FACFSOLO_Cross_2001_Headwaters%20XII_Sense%20of%20Place.pdf?sequence=4&isAllowed=y

Dunne, J. A., Saleska, S. R., Fischer, M. L. & Harte, J. Integrating experimental and gradient methods in Ecological Climate Change Research. Ecology 85, 904–916 (2004).

Ewing, R. & Dumbaugh, E. The built environment and traffic safety. Journal of Planning Literature 23, 347–367 (2009).

Fick, S. E. & Hijmans, R. J. WorldClim 2: New 1-km spatial resolution climate surfaces for Global Land Areas. International Journal of Climatology 37, 4302–4315 (2017).

Figueiredo, R., Gonçalves, A. B. & Ramos, I. L. Service areas of local urban green spaces: An explorative approach in Arroios, Lisbon. ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences III-4/W1, 111–116 (2016).

Fort Collins facts || visitor 2023 Fort Collins Facts - City of Fort Collins. Available at: https://www.fcgov.com/visitor/fcfacts.php.

Fort Collins Forestry 2023 City of Fort Collins. Available at: https://www.fcgov.com/forestry/.

Iverson, L. R., Prasad, A. M., Matthews, S. N. & Peters, M. Estimating potential habitat for 134 eastern us tree species under six climate scenarios. Forest Ecology and Management 254, 390–406 (2008).

Karl, T.R., J.M. Melillo, and T.C. Peterson (eds.) 2009. "Climate Change Impacts by Sectors: Ecosystems." United States Global Change Research Program. Cambridge University Press, New York, NY, USA.

Lloret, F. & Batllori, E. Climate-induced global forest shifts due to heatwave-drought. Ecosystem Collapse and Climate Change 155–186 (2021). doi:10.1007/978-3-030-71330-0_7

Neilson, R.P. et al. Forecasting regional to global plant migration in response to climate change. BioScience 55, 749 (2005).

Nowak, D. J., Noble, M. H., Sisinni, S. M. & Dwyer, J. F. People and Trees: Assessing the US Urban Forest Resource. Journal of Forestry 99, 37–42 (2001).

Notaro, M., Mauss, A. & Williams, J. W. Projected vegetation changes for the American Southwest: Combined Dynamic Modeling and Bioclimatic-envelope approach. Ecological Applications 22, 1365–1388 (2012).

Pickett, S. T. A. in Long Term Studies in Ecology (ed. Gene, L. E.) 110–135 (Springer, 1989).

Riahi, K. et al. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change 42, 153–168 (2017).

Schell, C. J. et al. The ecological and evolutionary consequences of systemic racism in Urban Environments. Science 369, (2020).

Simberloff, D., Parker, I. M. & Windle, P. N. Introduced species policy, management, and future research needs. Frontiers in Ecology and the Environment 3, 12–20 (2005).

Tsai, W.-L. et al. Relationships between characteristics of urban green land cover and mental health in U.S. metropolitan areas. International Journal of Environmental Research and Public Health 15, 340 (2018).

Walsh, J. R., Carpenter, S. R. & Vander Zanden, M. J. Invasive species triggers a massive loss of ecosystem services through a trophic cascade. Proceedings of the National Academy of Sciences 113, 4081–4085 (2016).

Williams, J. W., Jackson, S. T. & Kutzbach, J. E. Projected distributions of novel and disappearing climates by 2100 AD. Proceedings of the National Academy of Sciences 104, 5738–5742 (2007).

Williams, J. W. & Jackson, S. T. Novel climates, no-analog communities, and ecological surprises. Frontiers in Ecology and the Environment 5, 475–482 (2007).

Wogan, G. O. U. & Wang, I. J. The value of space-for-time substitution for studying fine-scale microevolutionary processes. Ecography 41, 1456–1468 (2017).

Zhang, Fang; Wu, Tongwen; Shi, Xueli; Li, Jianglong; Chu, Min; Liu, Qianxia; Yan, Jinghui; Ma, Qiang; Wei, Min (2019). BCC BCC-CSM2MR model output prepared for CMIP6 C4MIP. Version 20220201[1].Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.1723

CHAPTER 2: AN EXPLORATION OF CANOPY COVER IN FOUR LOW-INCOME AND HIGH HISPANIC-IDENTIFYING CENSUS BLOCKS IN FORT COLLINS, COLORADO

2.1 Introduction

2.1.1 Benefits of Canopy Cover

Health and Social Benefits

Canopy cover in urban ecosystems has multiple positive impacts on humans, including physical and mental health benefits. Urban canopy cover improves cardiovascular and physical health by increasing the "walkability" of urban areas, naturally encouraging outdoor activity (Figueiredo et al. 2016). Trees in urban settings also provide the critical ecosystem service of scrubbing pollutants like particulate matter, ground level ozone, and carbon dioxide from the atmosphere, improving local air quality. This aids in the local reduction of lung diseases and reduces asthma related hospitalizations (Lee and Maheswaran 2010, Selmi et al. 2016).

In terms of emotional health, patches of forest in the built environment, such as urban canopies, have been shown to reduce rates of stress, mental fatigue, and depression, and is known to decrease recovery times from mental and emotional stress (Tsai et al. 2018). Additionally, trees generate local place attachment, defined by Setha Low as, "the symbolic relationship formed by people giving culturally shared emotional/affective meanings to a particular space or piece of land that provides the basis for the individual's and group's understanding of and relation to the environment (Cross 2001)." In this light, trees increase sense of place by providing protective shade, sheltered areas for children to play, creating landmarks on the landscape, and generating space for community gatherings.

In addition to boosting physical, mental, and emotional health, and place building capabilities, tree cover around buildings has been shown to reduce the cost of homeownership and increase the overall value of properties. Positioning trees around a home reduces the amount of solar radiation reaching and heating the home during summer months and insulates the home from cold winds in the winter (Huang et al. 1990). One early study conducted in 1986 found that the proper placement of three trees around a home reduced annual energy costs by $100 to $250, equivalent to reducing household energy use by about 20%-25% at the time (Heisler 1986).

Water Benefits

Canopies provide critical ecosystem services that protect the local environment and keep urban areas livable for humans. Urban canopies prevent a phenomenon known as "urban stream syndrome," which is the continuous degradation of urban streams and bodies of water caused by chemical and stormwater runoff. Urban stream syndrome causes elevated levels of pollutants and nutrients, which can lead to harmful algal blooms and hypoxic conditions, as well as changes to local biodiversity and increased hydrologic flashiness (Pickett et al. 2011). Canopy coverage, especially in riparian areas, can help mitigate urban stream syndrome by reducing storm runoff, absorbing contaminant and nutrient runoff, and holding fragile topsoil in place.

Canopies also reduce flood risk by decreasing stormwater runoff. For instance, a study conducted in Dayton, Ohio found that the city's existing canopy cover (22%) reduced storm runoff by about 7%. This same study modeled the impact of additional tree cover on storm runoff and found that increasing the city of Dayton's tree cover by 7% would reduce stormwater runoff by another 5%, a total stormwater runoff reduction of 12% from canopy cover (Sanders 1986).

Urban Heat Island Effect (UHI) Reduction

The Urban Heat Island Effect (UHI) is the tendency for urban areas to have higher land surface temperatures than surrounding rural areas. Impervious surfaces, especially dark surfaces like blacktop, absorb solar radiation and remit it as infrared radiation, increasing local near-surface temperatures and raising UHI index (Grimm et al 2008, Imhoff et al. 2010, Nowak and Dwyer 2007). One study examining the impact of UHI on 38 different cities in the United States found that 70% of land surface temperature anomalies were caused by impervious surfaces and that the yearly average heat difference of 2.9ºC between urban and surrounding rural land can be directly attributed to impervious surface cover (Imhoff et al. 2010).

High Urban Heat Islands are correlated with increased rates of ground ozone formation, which occurs more rapidly in high surface temperature conditions. Heightened rates of ground level ozone are known to increase occurrences of asthma attacks and hospitalizations because ozone is a major lung irritant (Lee and Maheswaran 2010, Selmi et al. 2016). High Urban Heat Islands are also correlated with increased heat-related illnesses, hospitalizations, and deaths (Schell et al. 2020) and increased building cooling costs. The local cooling capacity of trees includes cloud seeding, local atmospheric cooling effects from evapotranspiration (the process by which plants release water vapor into the atmosphere), and the production of shade. Direct shading prevents solar radiation from being absorbed and remitted by impervious surfaces, while evapotranspiration cools the surrounding air, making urban canopies an extremely effective tool in combatting UHI.

2.1.2 Canopy Equity

Canopy Equity and Drivers of Canopy Inequity

For the purposes of this study, the term "canopy equity" will be defined as the equitable distribution of tree canopy and its benefits across an urban area, while "canopy inequity" will be defined as the inequitable distribution of tree canopy and its benefits across an urban area (American Forests "About Tree Equity" 2021). While it is a goal for most municipalities to generate and maintain canopy coverage, there are common drivers of canopy inequity that must first be addressed. The distribution of wealth across the landscape, and historical racial redlining practices are two major examples of barriers to canopy equity.

Neighborhood wealth is known to be positively correlated with relatively high rates of canopy cover and availability of greenspace. This phenomenon, known as the luxury effect, creates a positive feedback loop where wealthier neighborhoods establish expensive landscaping (including trees) which increases the value of local properties and thereby increases the overall wealth of local property owners; further augmenting their financial ability to manipulate the local environment (Schell 2020). Because of the luxury effect, wealthier neighborhoods are typically characterized by relatively high rates of greenspace and canopy cover, relatively low rates of impervious surfaces, and a relatively high occurrence of right of way space that supports local street tree programs. It has also been noted in the literature that residents of low-income neighborhoods may strategically avoid increasing canopy cover to avoid gentrification and rent hikes in the long term (Shwarz 2015).

The historical and ongoing impacts of redlining and housing discrimination further drives the luxury effect. Redlining, a practice of racial discrimination that restricted housing opportunities and home loan availability for minority groups, began as the Home-Owner's Loan

Corporation's (HOLC) response to the housing assistance boom of the 1930's and 1940's. HOLC sought to create a system of categorizing neighborhoods into ranks based on the creditworthiness of that neighborhood's residents. HOLC's racially biased investment and loan plans systematically zoned urban areas on a scale of red to green, with the most unfavorable communities coded red and reserved for minority housing and the most favorable communities coded green and reserved solely for the white middle and upper class. This effectively blocked African Americans, Jews, and Asian Americans from receiving home loans and accruing generational wealth through homeownership. Additionally, HOLC frequently undervalued older homes, which were typically located in the inner city and owned by minorities (Rheingold et al. 2001).

Because of the history of housing segregation through redlining, neighborhood racial composition is thought to be an even better predictor of urban ecological patterns than wealth (Schell et al. 2020). High minority status neighborhoods are typically characterized by relatively high rates of impervious surfaces, relatively low rates of canopy cover and greenspace, and relatively low occurrences of green right of way space (Schwarz et al. 2015). The heightened rates of impervious surfaces in inner-city and historically redlined neighborhoods significantly impacts local Urban Heat Island indexes; so much so that a recent study on urban thermal inequities across racial groups in 20 U.S. cities found that African Americans have a 52% higher chance of inhabiting urban areas with high exposure to heat risks than their white counterparts (Mitchell and Chakraborty 2018).

Assessing Canopy Equity: American Forests' Tree Equity Score

Measuring and assessing canopy equity in an urban area is a challenging task. Because humans are ecosystem engineers with social dynamics that complicate how we experience and build our environment, social considerations must be made when attempting to address canopy equity concerns. Factors like income level, population density, employment rate, age, and ethnicity impact whether the citizens of a neighborhood can afford to increase canopy cover on private property without assistance from the municipality (McPherson et al. 1997, Mitchel and Chakraborty 2018, Pickett et al. 2011, Schell 2020, Schwarz et al. 2015, Wilson 2020). Including these factors in attempts to measure how equitably canopy cover is distributed is crucial in planning and budgeting for improvements to urban canopies. By understanding which areas of the city will need more assistance and attention from the forestry department, we can effectively plan to increase canopy equity across the city.

A common solution to this problem is to use a measure called a Tree Equity Score (TES). A TES measures canopy coverage within a census block or census block group and multiplies it by quantifiable social factors (population density, income employment rates, race, age, and ethnicity) and UHI to assign each census block a score out of 100. Tree Equity Scores are relative to the city or municipality being examined, with the census block with the highest canopy coverage and greatest social ability to improve canopy cover receiving a score of 100. This allows foresters to compare canopy coverage and equity concerns across their municipality and quickly determine which areas are in greatest need of assistance.

Researchers can determine the relative weight of each social factor to design their own TES, or they can use a pre-existing TES database with set social factor weights to quickly

explore canopy equity concerns. The TES score and canopy cover analyses I will be comparing my results to comes from the American Forests organization. American Forests was the first national organization in the United States founded for the purpose of protecting, preserving, and planting trees. To help increase canopy equity on a large scale, American Forests released a United States TES database in 2022 that is now available to the public. This database gives TES scores to urban areas representing about 70% of the United States population and is the first nation-wide TES database in existence (American Forests "About Tree Equity" 2021).

2.1.3 Study Area and Research Questions

The City of Fort Collins, Colorado lies nestled in the front range of the Rocky Mountains within the Cache la Poudre River watershed. At an elevation of 5,000 feet (1,524 meters) above sea level, residents of Fort Collins experience four full seasons while enjoying an average of 300 days (about 10 months) of sunshine. The city resides within a semi-arid short grass steppe ecosystem, receiving an average of 14.5 inches (368 mm) of precipitation a year. The warmest month of the year is typically July, with average highs of 30ºC and average lows of 13.8ºC. The coldest month of the year is typically January, with average highs of 5.5ºC and average lows of -10ºC (City of Fort Collins 2023).

The City of Fort Collins' Forestry Department runs a rigorous program complete with city foresters who care for publicly owned trees, neighborhood street tree planting and care programs, a self-guided tree tour of notable and historical trees in the city, free tree selection and care guides, and a community-based Urban Forest Ambassador program (City of Fort Collins Forestry 2023). Fort Collins' provides a recommended street tree list that is publicly accessible and details information on 21 shade-tree species that forestry staff has deemed appropriate for

use in public parks and within the public right-of-way (the space between a road and a sidewalk where street trees are typically planted) and are known to be suitable to local climate (Fort Collins Forestry 2023).

The city is rapidly growing with an increase of 14,000 residents between 2011 and 2019 (Fort Collins City Plan 2019), and a current estimated population of 170,430 people (City of Fort Collins, 2023). The city has accounted for this continued growth with its "Fort Collins City Plan," which was released and adopted in April of 2019. A year after the release of the city plan, Emerald Ash Borer (*Agrilus planipennis,* also known as EAB) was detected along the northern extent of the city, in the Hickory Village and North College Manufactured Home Parks. EAB is an extremely destructive invasive pest that infiltrates the xylem and phloem (vascular tissues) of ash species (*Fraxinus spp.*), causing tree mortality within two to four years. The discovery of EAB in Fort Collins, Colorado poses a serious threat to the city's urban canopy because an estimated 1/3 of its canopy is made up of ash tree species (City of Fort Collins Forestry 2023).

The following study seeks to explore the current extent of urban canopy coverage and potential concerns for canopy equity in Fort Collins, Colorado. To investigate concerns for canopy equity, I will examine canopy distribution within the city's census blocks that are characterized by a low-income earning population (<$40,000 per year) with a high rate of Hispanic identifying (>25%) persons. This study will split census blocks into distinct and separate study areas based on city zoning and available parcel information from the Larimer County Assessor's Office. These study areas will then undergo a land cover assessment using i-Tree canopy from the i-Tree toolset, a free, open access land cover assessment tool, and additional satellite observations will be used to further understand drivers of canopy cover.

Specifically, this study seeks to answer the following research questions: First, are there any identifiable land cover distribution patterns across zoning types in the City of Fort Collins (such as differences between commercial areas and neighborhoods)? Second, what factors, if any, exist in the examined areas that could limit urban forest policy and potential canopy growth? Third, and finally, how does my analysis of land cover distribution at a finer scale compare to existing census block level analyses, like American Forest's Tree Equity Score? I hope that by addressing these spatial questions I can identify areas in the selected census blocks that need additional attention from the city's forestry department and make general recommendations to increase overall canopy cover and tree equity in Fort Collins, Colorado.

2.2 Methods

Census Block Selection and Land Cover Analysis

To explore my research questions, I first needed to determine areas of interest within the City of Fort Collins, Colorado. Forestry staff from the city indicated that they would prefer analyses of areas that are low income with high Hispanic populations. City forestry staff had previously conducted a Kernel Density estimate of dead and poor condition trees (including untreated ash trees) overlain with canopy cover and demographic information (see figure 2.2). This map also highlights four census blocks with a population of at least 25% Hispanic identifying persons and an average household income of less than $40k per year. Because of the city's interest in low income/highly Hispanic populated areas, these four census blocks (CB#8069009021, CB#80690010071, CB#80690013041, and CB#80690013042) were chosen for further analysis.

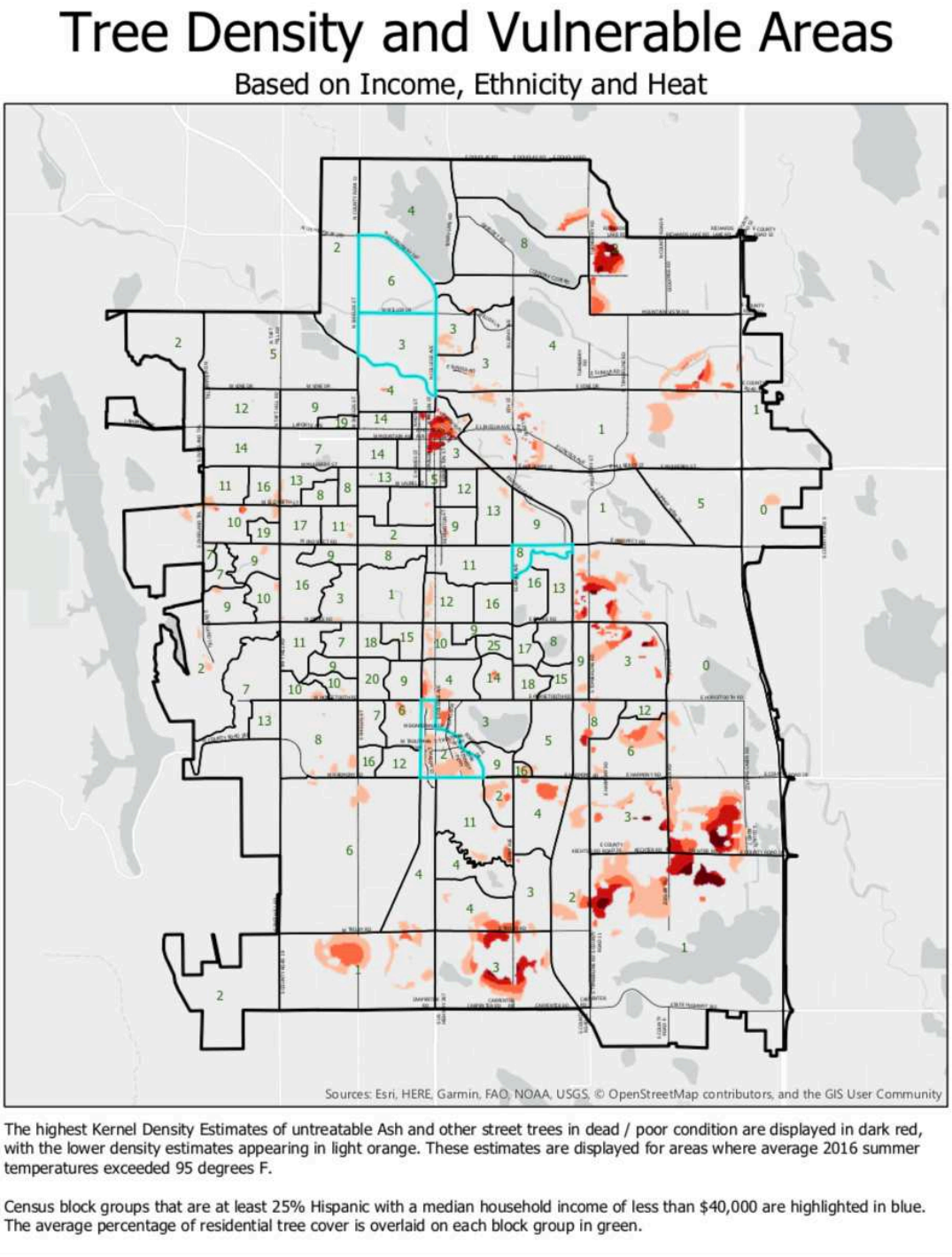

Figure 2.2: Tree Density and Vulnerable Areas map of the City of Fort Collins. This map illustrates areas across the city with high tree mortality (severity shown from orange to red), along with percent residential canopy cover per census block (written in green in each census block). Census blocks whose populations are at least 25% Hispanic with a median household income of less than $40k are highlighted in blue. I used this map, made by the city of Fort Collins, to identify the four blue census blocks I used for this study.

Each census block was further divided into three or four study areas. Study areas of interest were determined by zoning type as provided by the City of Fort Collins (Online Map Applications: City of Fort Collins) and Larimer County Assessor's Office (Property Search Assessor). Areas zoned as natural areas and open space restrict tree planting to preserve native ground cover, because of this, the city's forestry team does not have authority over tree planting and care in such areas, so they were left out of the study. The two northern most census blocks, CB#80690013041 and CB#80690013042, contain areas outside of Fort Collins' city limits. Areas outside city limits are not classified into zones by the city, so I determined the extent of study areas outside city limits by grouping areas based on land use (neighborhood/residential, or agricultural and industrial use) as determined by parcel information provided by the Larimer County Assessor's Office.

Once the four census blocks were divided into smaller study areas based on land use, I used the i-Tree Canopy tool from i-Tree, a free, web-based software that estimates canopy and land cover, as well as their associated benefits (I-Tree Canopy, 2023). I-Tree Canopy delineates each study area via a shapefile or drawn boundary and then randomly samples satellite imagery from within the area. A yellow cross appears in the center of each satellite image, creating a point whose land cover must be classified by the user. Points were classified into one of the following seven categories: Grass/Herbaceous, Impervious Buildings, Impervious Other, Impervious Road, Soil/Bare Ground, Tree/Shrub, or Water. This point classification process was repeated 1000 times (n=1000) per study area (13 study areas), generating a randomly selected point dataset for each analysis. Visual observations and observational notes of each study area were made using Google Satellite Imagery. Land cover data generated by the I-Tree Canopy tool was collected and analyzed; I then illustrated the data through the creation of graphic figures.

These graphs depict the seven land cover types and their count for each study area in a single census block (see figures 2.3.1a - 2.3.5b).

Statistical regressions were not run on the collected data because there were not enough samples of each zoning type to render an accurate representation of the larger population. For instance, there were thirteen total study areas (subsections of census blocks); of those study areas, only three were trailer home/manufactured home parks. While we can compare the data from these Manufactured Home Park study areas (see figures 2.3.5a and 2.3.5b), there is not enough data to support a statistical claim that all Manufactured Home Parks in the city would have similar land cover distributions.

2.3 Results

The following results are presented in sections broken up by census blocks, with each section detailing the results found from study areas within that census block. Four census blocks featuring a low-income (<$40k per year) and high Hispanic identifying (>25% identify as Hispanic) population were analyzed. These census blocks were further broken down into 13 total study areas based on city of Fort Collins zoning or land use by parcel as recorded by the Larimer County Assessors' Office.

2.3.1: Census Block #80690009021

The first census block, #80690009021, can be found in central Fort Collins bordered by the major city streets E Prospect Road, S Lemay Avenue, the Spring Creek Trail running through Edora Park, and a portion of railroad (see figure 2.3.1). This census block contains four different

study areas: the Edora Acres Neighborhood, a Neighborhood Commercial District, the Spring Creek Village Neighborhood, and the Stonehenge Neighborhood.

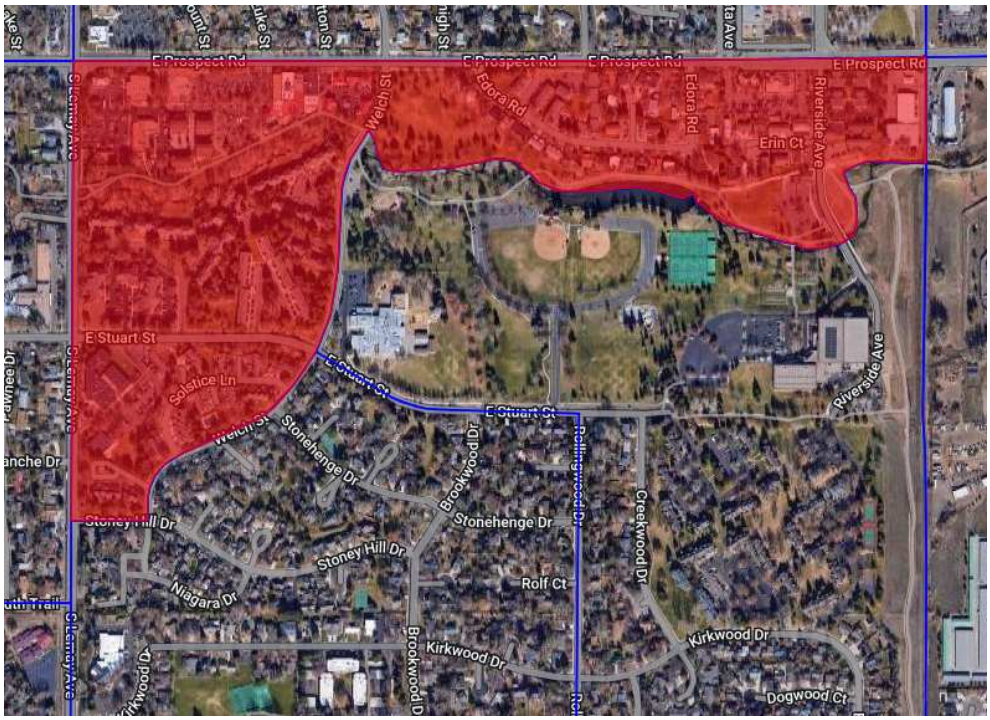

Figure 2.3.1: Illustrates Census Block #80690009021, which can be seen shaded in red (satellite imagery by Maxar Technologies 2023). The census block's perimeter includes the following: E. Prospect Road, S. Lemay Ave, Stoney Hill Drive, Welch Street, and the Spring Creek Trail.

Edora Acres Neighborhood

The Edora Acres Neighborhood Study Area makes up the northeastern portion of census block #80690009021 and is bordered by E Prospect Road and the Spring Creek Trail that runs through Edora Park (see figure 2.3.1a). This study area is zoned as a Medium Density Mixed Use Neighborhood district which means the area is intended to, "be a setting for concentrated housing within easy walking distance of a transit and commercial district (Fort Collins Municipal Code Division 4.6)." The area is also known as the Edora Acres Annexation because the neighborhood was annexed into Fort Collins in 1969. This study area features 30.1% Tree/Shrub

cover and the following land cover distributions as determined by i-Tree Canopy analysis: 11.5% Grass/Herbaceous, 21% Impervious Buildings, 1.7% Impervious Other, 31.5% Impervious Road, 4.2% Soil/Bare Ground, and 0.0% Water.

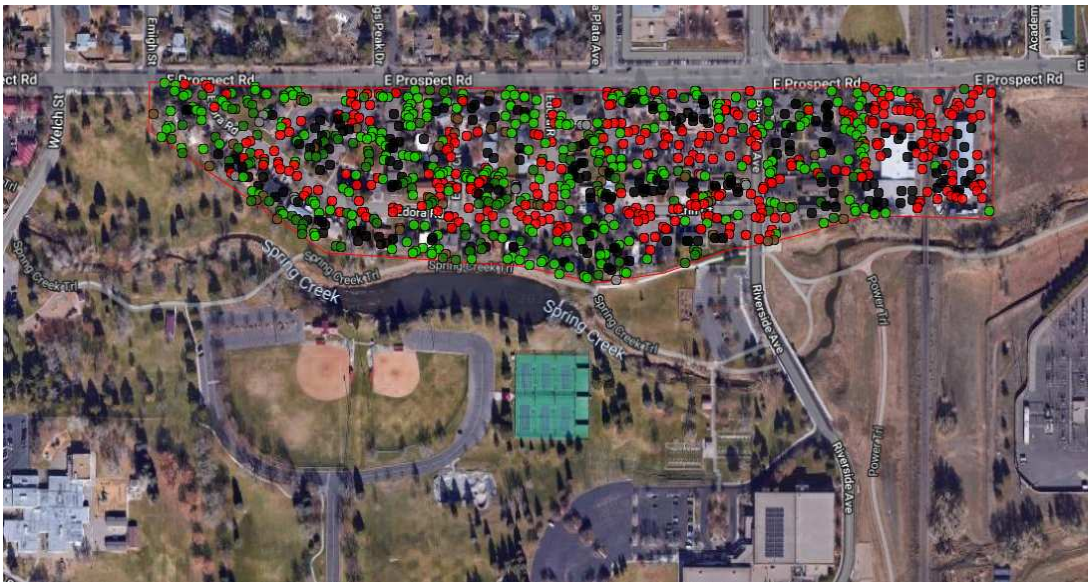

Figure 2.3.1a: Satellite Imagery of the Edora Acres Neighborhood Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Neighborhood Commercial District

The Neighborhood Commercial District Study Area makes up the northwestern portion of census block #80690009021 and is bordered by E Prospect Road, Welch Street, the Spring Creek Trail, and S Lemay Avenue (see figure 2.3.1b). This study area is zoned as a Neighborhood Commercial District which intends to, "be a mixed-use commercial core area anchored by a supermarket or grocery store and a transit stop. The main purpose of this District is to meet consumer demands for frequently needed goods and services, with an emphasis on serving the surrounding residential neighborhoods typically including a Medium Density Mixed

Use Neighborhood (Fort Collins Municipal Code Division 4.23).” This study area features 33.6% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 10.7% Grass/Herbaceous, 18.6% Impervious Buildings, 0.4% Impervious Other, 32.7% Impervious Road, 2.7% Soil/Bare Ground, and 1.3% Water.

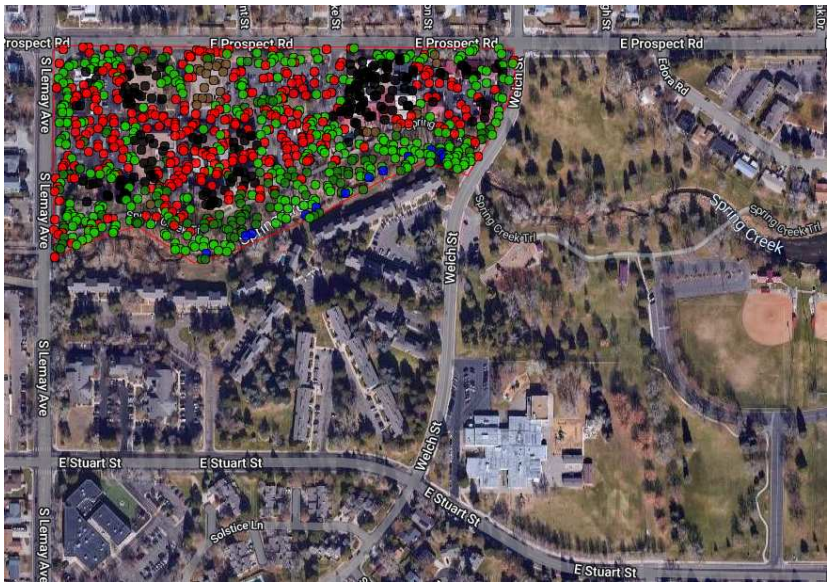

Figure 2.3.1b: Satellite Imagery of the Neighborhood Commercial District Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Spring Creek Village

The Spring Creek Village Study Area makes up the western portion of #80690009021 and is bordered by S Lemay Avenue, the Spring Creek Trail, Welch Street, and E Stuart Street (see figure 2.3.1c). Like the Edora Acres Neighborhood study area, this study area is zoned as a Medium Density Mixed Use Neighborhood District. This study area features 34.5% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 15.9%

Grass/Herbaceous, 16.7% Impervious Buildings, 0.0% Impervious Other, 28.9% Impervious Road, 3.4% Soil/Bare Ground, and 0.6% Water.

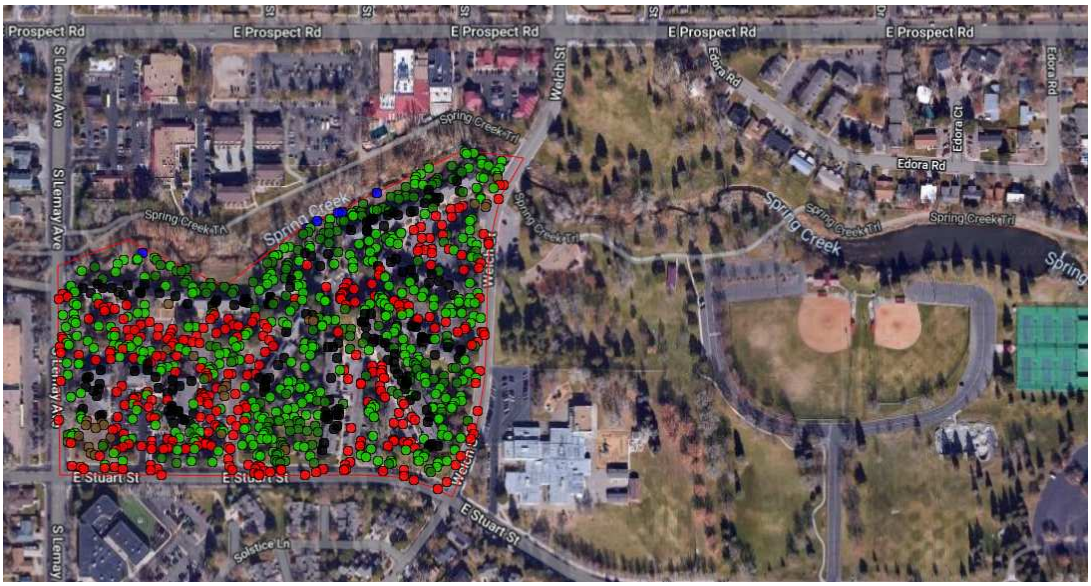

Figure 2.3.1c: Satellite Imagery of the Spring Creek Village Neighborhood Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Stonehenge Neighborhood

The Stonehenge Neighborhood Study Area makes up the southwestern portion of #80690009021 and is bordered by S Lemay Avenue, E Stuart Street, and runs parallel to (without touching) Kirkwood Drive and Creekwood Drive (see Figure 2.3.1d). This study area is part of a larger Low Density Residential District which, "is intended for predominately single-family residential areas (Fort Collins Municipal Code Division 4.4). The Stonehenge Neighborhood Study area is also known as the Spring Creek Farms 2nd Annexation, incorporated into the City of Fort Collins in 1972 (City of Fort Collins Public Records). It is

important to note that this study area stretches outside of census block #80690009021 to incorporate the entire neighborhood into one I-Tree Canopy analysis. This study area features 34.9% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 20.7% Grass/Herbaceous, 15.2% Impervious Buildings, 2.5% Impervious Other, 23.5% Impervious Road, 3.2% Soil/Bare Ground, and 0.0% Water.

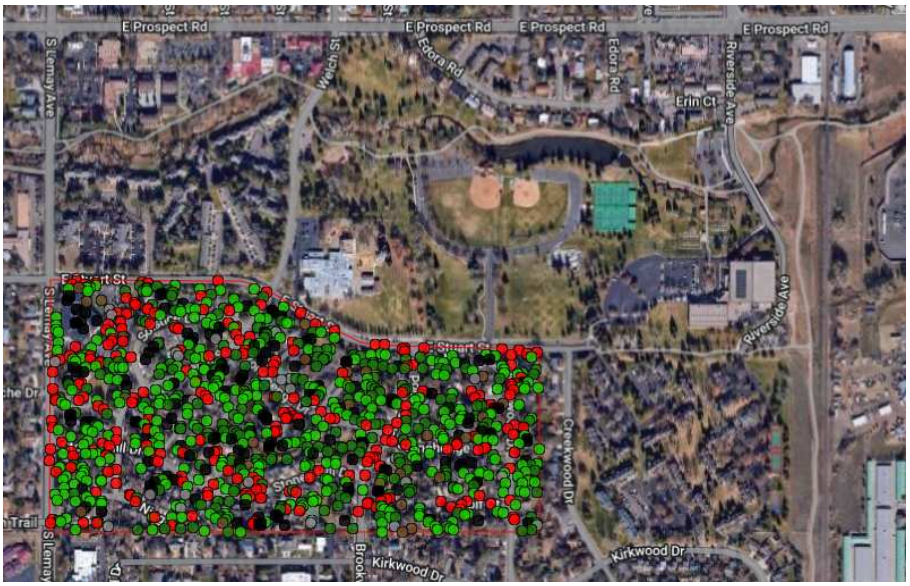

Figure 2.3.1d: Satellite Imagery of the Stonehenge Neighborhood Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue. It is important to note that census block #80690009021 only contains about one-third of the Stonehenge neighborhood (see Image 2.3.1). Census block limits were expanded to encompass the entire Stonehenge neighborhood for analysis.

Land Cover Comparison Across Study Areas for Census Block #80690009021

The land cover distributions for Census Block #80690009021 vary across the four study areas with impervious road cover and tree/shrub cover being the most common cover types (see figure 2.3.1e). I found that grass/herbaceous cover ranged from 10.7% (Neighborhood

Commercial District) to 20.7% (Stonehenge Neighborhood), impervious building cover ranged from 15.2% (Stonehenge Neighborhood) to 21.0% (Edora Acres Neighborhood), impervious other cover ranged from 0.0% (Spring Creek Village) to 2.5% (Stonehenge Neighborhood), impervious road cover ranged from 23.5% (Stonehenge Neighborhood) to 32.7% (Neighborhood Commercial District), soil and bare ground cover ranged from 2.7% (Neighborhood Commercial District) to 4.2% (Edora Acres Neighborhood), tree and shrub cover ranged from 30.1% (Edora Acres Neighborhood) to 34.9% (Stonehenge Neighborhood), and water cover ranged from 0.0% (Edora Acres Neighborhood and Stonehenge Neighborhood) to 1.3% (Neighborhood Commercial District). The four study areas average a canopy cover of 33%, which is 7% greater than the canopy cover recorded for census block #80690009021 by American Forests' Tree Equity Score (26%).

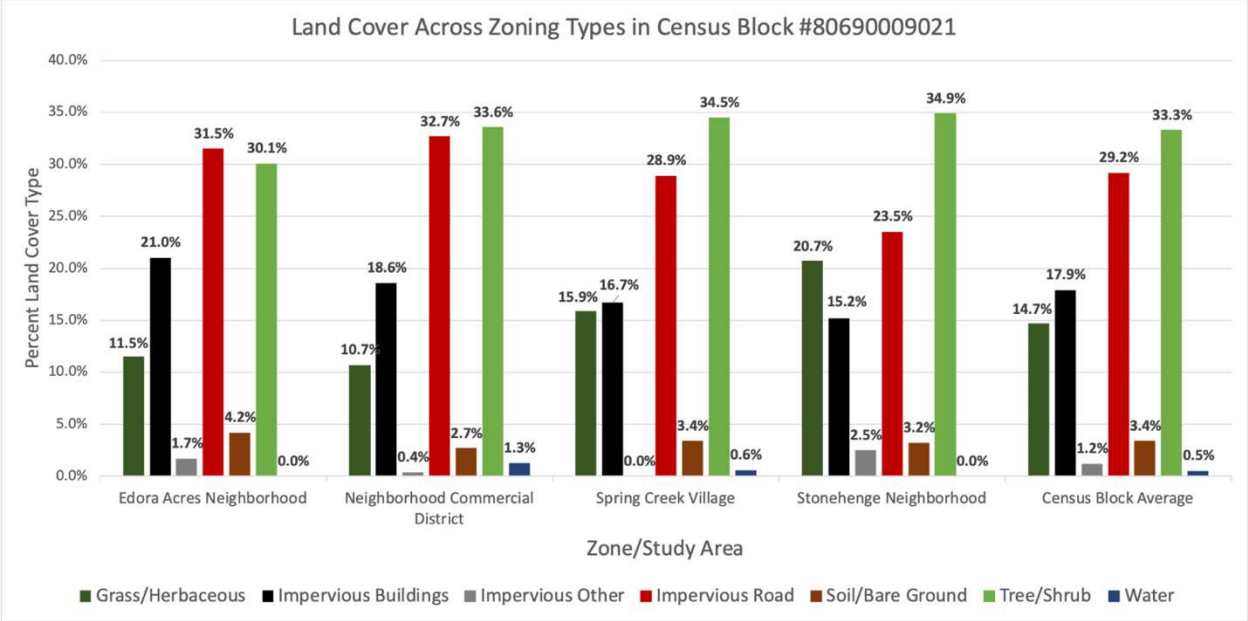

Figure 2.3.1e: The above figure illustrates land cover data for Census Block #80690009021 as collected using i-Tree Canopy. This census block features a low income (<$40k per year) and high Hispanic identifying (>25%) population. Data is organized by study area with each study area's land cover distributions captured as a percentage. The census block average (all study areas' land cover for census block #80690009021 averaged into one value) is given for reference. Census block average percentages may not add up to 100% as it is capturing averages across study areas.

2.3.2: Census Block #80690010071

The second census block, #80690010071, can be found in south-central Fort Collins bordered by the major city streets W Horsetooth Road, S College Avenue, Boardwalk Drive, E Harmony Road, and a portion of rail running between W Horsetooth and E Harmony Road (see figure 2.3.2). This census block contains three different study areas: The General Commercial District and Employment District, the Harmony Corridor District, and a Medium Density Mixed-Use Neighborhood.

Figure 2.3.2: Illustrates Census Block #80690010071, which can be seen shaded in red (satellite imagery by Maxar Technologies 2023).

General Commercial District and Employment District

This study area contains two zoning types, a portion of a large general commercial district and a portion of an employment district. The study area is bordered by the BNSF Railway, West Horsetooth Road, South College Avenue, Boardwalk Drive, East Troutman Parkway, and West Harmony Road. The general commercial district portion lies west of John F Kennedy Parkway, while the employment district portion lies east of John F Kennedy Parkway (see figure 2.3.2a). The general commercial district's purpose is, "to be a setting for development, redevelopment and infill of a wide range of community and regional retail uses, offices, and personal business services. Secondarily, it can accommodate a wide range of other uses including creative forms of housing (Fort Collins Municipal Code Division 4.21)." The Employment District's purpose is, "to provide locations for a variety of workplaces including light industrial uses, research and development activities, office and institutions (Fort Collins Municipal Code Division 4.27)." This study area features 15.1% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis 7.4% Grass/Herbaceous, 19.8% Impervious Buildings, 0.6% Impervious Other, 53.0% Impervious Road, 3.7% Soil/Bare Ground, and 0.4% Water.

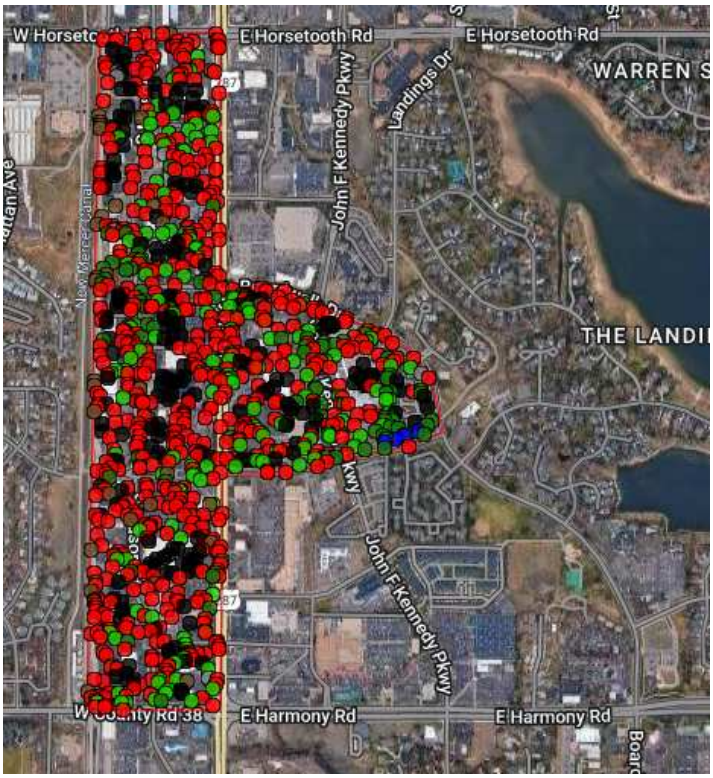

Figure 2.3.2a: Satellite Imagery of the General Commercial District and Employment District Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue. The study area is made up of two fragmented city zones, a portion of the General Commercial District (west of John F Kennedy Parkway) and a portion of the Employment District (east of John F Kennedy Parkway).

Harmony Corridor District

The Harmony Corridor District, bordered by S College Avenue, E Troutman Parkway, Boardwalk Drive, and cuts through Landings Park to connect with E Harmony Road (see figure 2.3.2b). The Harmony Corridor District is intended to, "implement the design concepts and land use vision of the Harmony Corridor Plan – that of creating an attractive and complete mixed-use area with a major employment base (Fort Collins Municipal Code Division 4.26)." This study area features 17.9% Tree/Shrub cover and the following land cover distributions as determined

by i-Tree Canopy analysis: 16.3% Grass/Herbaceous, 19.2% Impervious Buildings, 0.2% Impervious Other, 44.1% Impervious Road, 2.0% Soil/Bare Ground, and 0.3% Water.

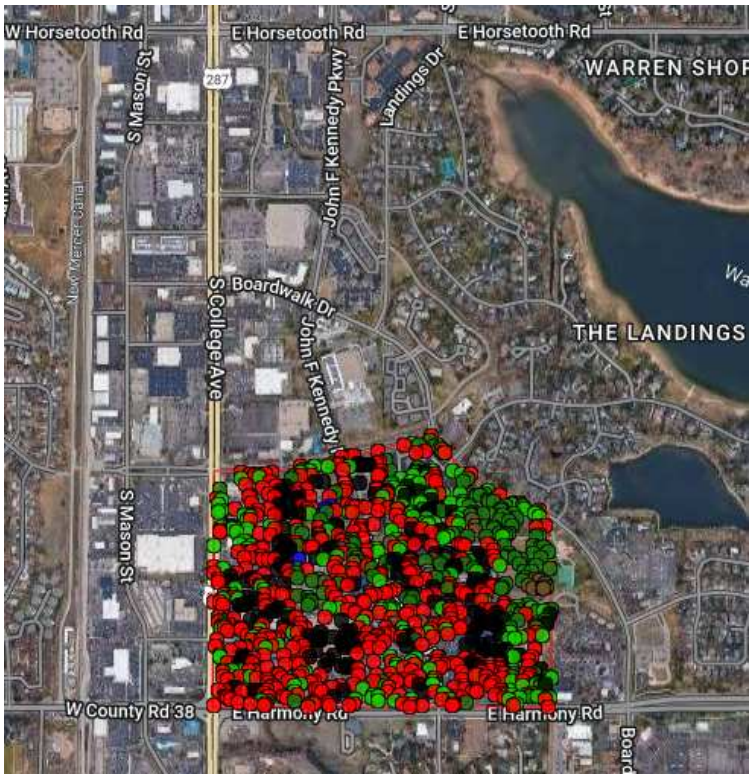

Figure 2.3.2.b: Satellite Imagery of the Harmony Corridor District Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Medium Density Mixed Use Neighborhood District

The Medium Density Mixed Use Neighborhood District is bordered by East Harmony Road, Boardwalk Drive, Whalers Way, extends to the southern shore of Harmony Reservoir, and cuts back through Landings Park to reconnect with East Harmony Road (see figure 2.3.2c). The Medium Density Mixed Use Neighborhood District is intended to, “be a setting for concentrated housing within easy walking distance of transit and a commercial district (Fort Collins Municipal

Code Division 4.6).” This study area features 17.9% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 16.3% Grass/Herbaceous, 19.2% Impervious Buildings, 0.2% Impervious Other, 44.1% Impervious Road, 2.0% Soil/Bare Ground, and 0.3% Water.

Figure 2.3.2c: Satellite Imagery of the Medium Density Mixed Use Neighborhood Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Land Cover Comparison Across Study Areas for Census Block #80690010071

The land cover distributions, as classified by i-Tree Canopy analyses, for Census Block #80690010071 vary across the four study areas with impervious road cover being the most common cover type (see figure 2.3.2d). I found that grass/herbaceous cover ranged from 7.4%

(General Commercial and Employment District) to 16.3% (Harmony Corridor District), impervious building cover ranged from 16% (Medium Density Mixed Use Neighborhood) to 19.8% (General Commercial and Employment District), impervious other cover ranged from 0.2% (Harmony Corridor District) to 4.4% (Medium Density Mixed Use Neighborhood), impervious road cover ranged from 36% (Medium Density Mixed Use Neighborhood) to 53% (General Commercial and Employment District), soil and bare ground cover ranged from 1.2% (Medium Density Mixed Use Neighborhood) to 3.7% (General Commercial an Employment District), tree and shrub cover ranged from 15.1% (General Commercial an Employment District) to 27.3% (Medium Density Mixed Use Neighborhood), and water cover ranged from 0.1% (Medium Density Mixed Use Neighborhood) to 0.4% (General Commercial and Employment District). The four study areas average a canopy cover of 20.1%, which is 7% greater than the canopy cover recorded for census block #80690010071 by American Forests' Tree Equity Score (13%).

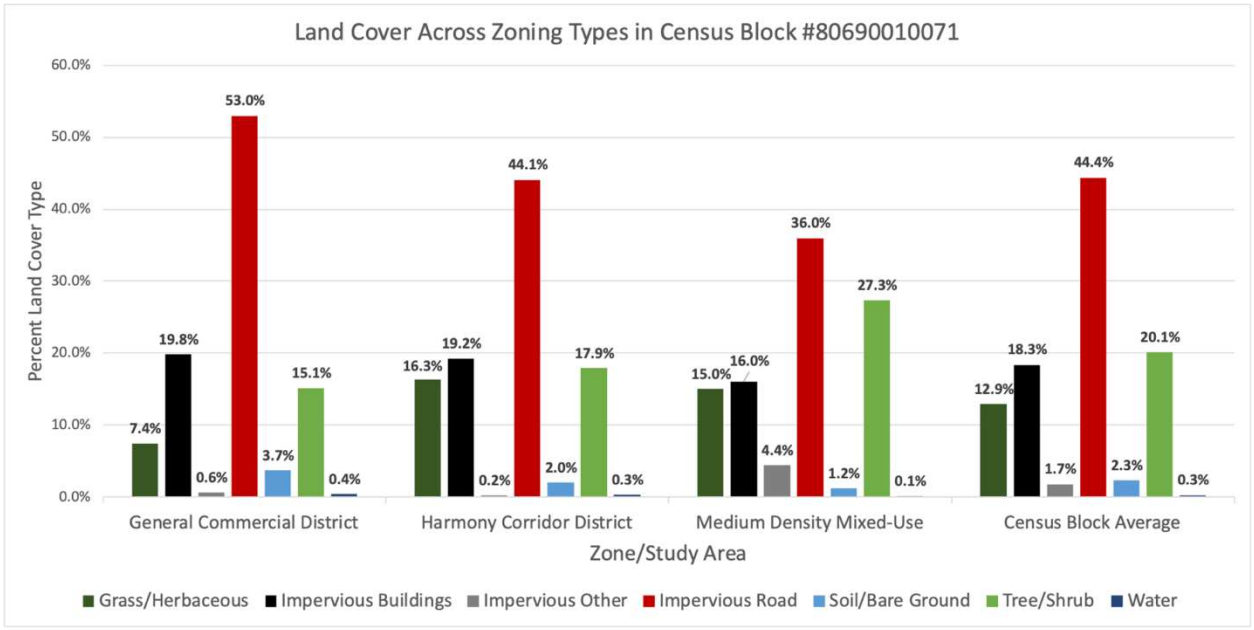

Figure 2.3.2d: The above figure illustrates land cover data for Census Block #80690010071 as collected using i-Tree Canopy. This census block features a low income (<$40k per year) and high Hispanic identifying (>25%) population. Data is organized by study area with each study area's land cover distributions captured as a percentage. The census block average (all study areas' land cover for census block #80690010071 averaged into one value) is given for reference. Census block average percentages may not add up to 100% as it is capturing averages across study areas.

2.3.3: Census Block #80690013041

The third census block, #80690013041, can be found just north of Fort Collins city limits near the southern shore of Terry Lake. The census block is bordered by the major city streets W. Willox Lane, Highway 287, and highway 17 (see figure 2.3.3). This census block contains three different study areas: an Agriculture and Industry area, an Agricultural Neighborhood, and the Poudre Valley Manufactured Home Park. Since census block #80690013041 lies just outside of Fort Collins' city limits, it is not zoned by the city. Because of this, I used data from the Larimer County Assessor's Office to group study areas based on the land use (industrial, agricultural, and residential) recorded at the parcel level.

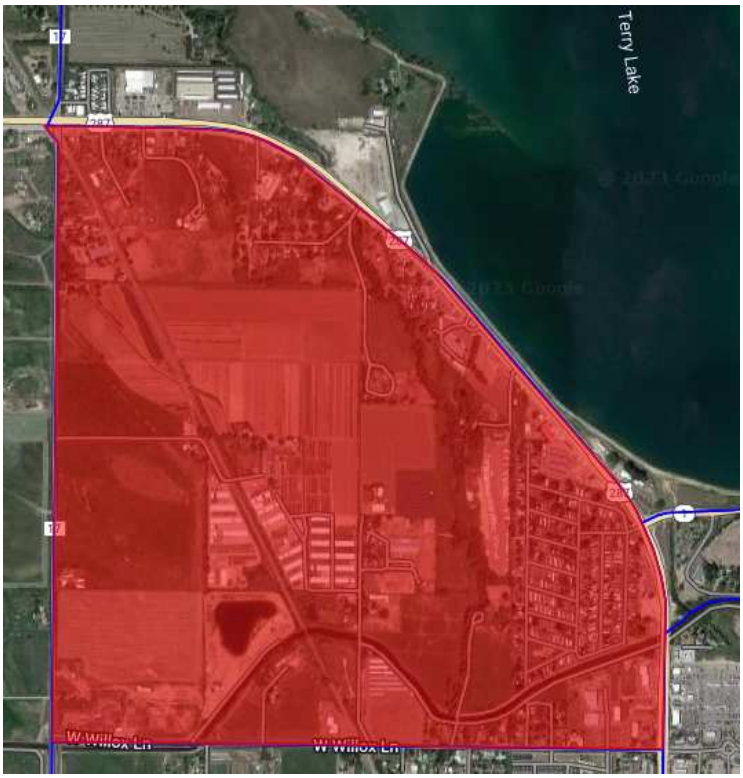

Figure 2.3.3: Illustrates Census Block #80690013041, which can be seen shaded in red (satellite imagery by Maxar Technologies 2023).

Agriculture and Industry

This study area is made up of privately owned properties (family farms, livestock, equine facilities) and businesses whose primary land use is agricultural or industrial in nature. The Agriculture and Industry study area is the largest study area in this census block and is partially bordered by West Willox Lane and North Shields Street (see figure 2.3.3a). Businesses in this area include Fort Collins Landscaping and Wholesale Nursery, Poudre Valley REA (Solar Energy Generator), Oasis Equestrian, Bivens Trucking and Excavating INC, Distinctive Welding INC, Morgan Holdings LLC, Waterwise Land and Waterscapes INC, and Charles R Willox Homestead One LLC. In addition to the businesses, there are three parcels of land owned by the City of Fort Collins, and a few privately owned properties within the area. The Agriculture and

Industry study area features 10.1% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 55.6% Grass/Herbaceous, 4.2% Impervious Buildings, 3.9% Impervious Other, 9.3% Impervious Road, 14.1% Soil/Bare Ground, and 2.8% Water. It is important to note that the nature of agricultural industries is highly seasonal, and grass/herbaceous and soil/bare ground cover of this area is likely to fluctuate with the shifts in vegetation associated with seasonal crops and harvests; meanwhile, tree/shrub, impervious building, impervious road, and impervious other ground cover distributions should remain relatively stagnant throughout the year.

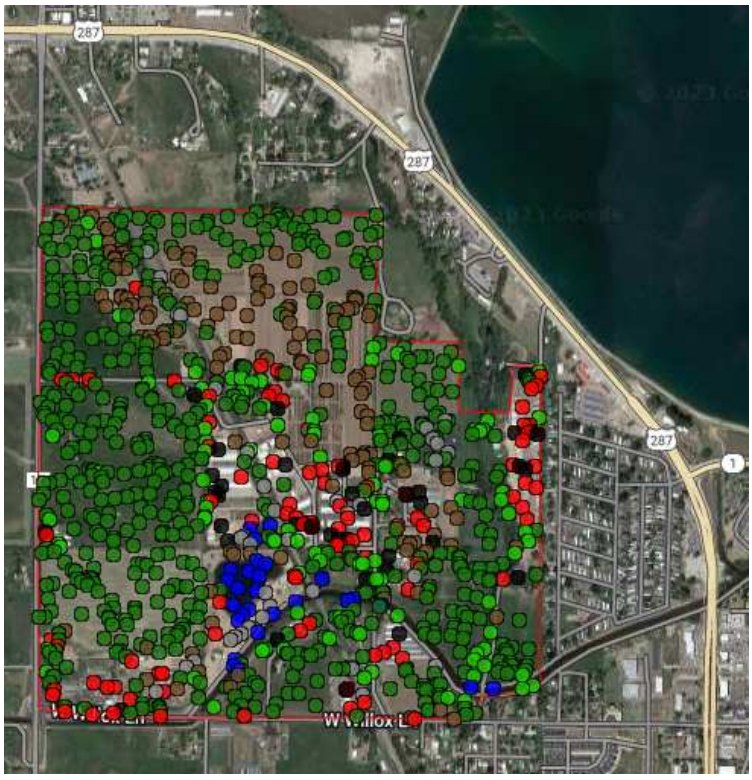

Figure 2.3.3a: Satellite Imagery of the Agriculture and Industry Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Agricultural Neighborhood

The Agricultural Neighborhood study area is made up of privately owned properties and is bordered by the Agriculture and Industry study area, Highway 287, and North Shields Street (see figure 2.3.3b). Property types range from small, manufactured home parks to plots of privately owned land. The Agricultural Neighborhood study area features 24.8 Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 41.1% Grass/Herbaceous, 6.7% Impervious Buildings, 1.1% Impervious Other, 14.8% Impervious Road, 10.5% Soil/Bare Ground, and 1.0% Water

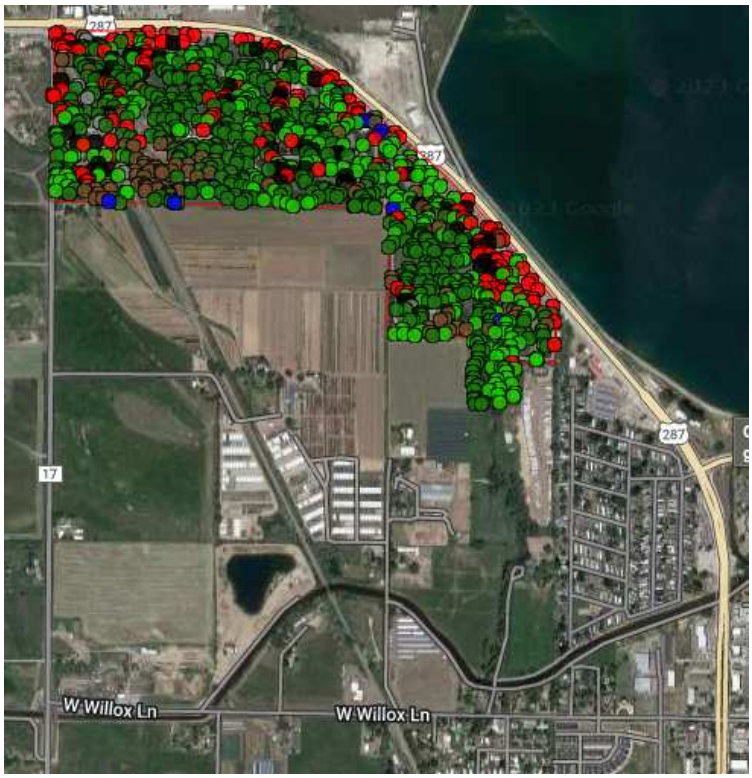

Figure 2.3.3b: Satellite Imagery of the Agricultural Neighborhood Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Poudre Valley Manufactured Home Park

The Poudre Valley Manufactured Home Park study area is bordered by Highway 287, the Agriculture and Industry study area, and the Larimer and Weld Canal (see figure 2.3.3c). The Poudre Valley Manufactured Home Park neighborhood is made up of manufactured homes and trailers and is managed by the Poudre Valley Manufactured Home Park LLC. The Poudre Valley Manufactured Home Park study area features 26.4% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 10.6% Grass/Herbaceous, 19.9% Impervious Buildings, 1.6% Impervious Other, 37.7% Impervious Road, 3.8% Soil/Bare Ground, and 0.0% Water.

Figure 2.3.3c: Satellite Imagery of the Poudre Valley Manufactured Home Park Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Land Cover Comparison Across Study Areas for Census Block #80690013041

The land cover distributions, as classified by i-Tree Canopy analyses, for Census Block #80690013041 vary across the three study areas with grass/herbaceous cover being the most common cover type in the Agriculture and Industry and Agricultural Neighborhood study areas and impervious road being the most common cover type in the Poudre Valley Manufactured Home Park (see figure 2.3.3d). I found that grass/herbaceous cover ranged from 10.6% (Poudre Valley Manufactured Home Park) to 55.6% (Agriculture and Industry), impervious building cover ranged from 4.2% (Agriculture and Industry) to 19.9% (Poudre Valley Manufactured Home Park), impervious other cover ranged from 1.1% (Agricultural Neighborhood) to 3.9% (Agriculture and Industry), impervious road cover ranged from 9.3% (Agriculture and Industry) to 37.7% (Poudre Valley Manufactured Home Park), soil and bare ground cover ranged from 3.8% (Poudre Valley Manufactured Home Park) to 14.1% (Agriculture and Industry), tree and shrub cover ranged from 10.1% (Agriculture and Industry) to 26.4% (Poudre Valley Manufactured Home Park), and water cover ranged from 0.0% (Poudre Valley Manufactured Home Park) to 2.8% (Agriculture and Industry). The four study areas average a canopy cover of 20.4%, which is 9% greater than the canopy cover recorded for census block #80690013041 by American Forests' Tree Equity Score (11%).

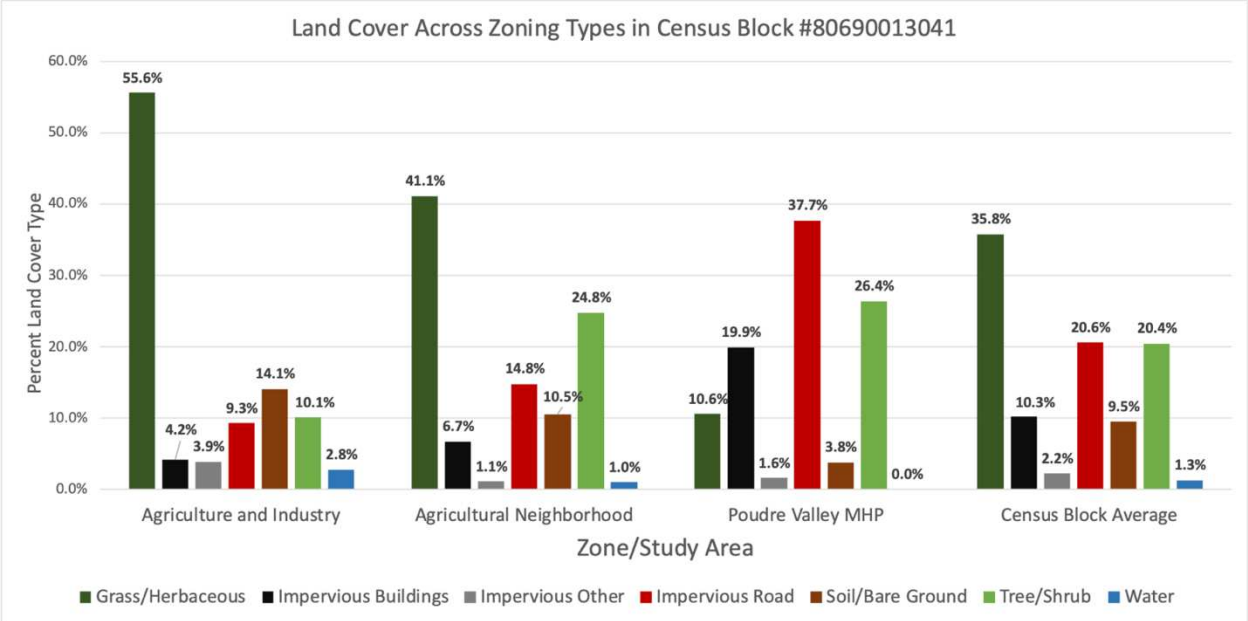

Figure 2.3.3d: The above figure illustrates land cover data for Census Block #80690013041 as collected using i-Tree Canopy. This census block features a low income (<$40k per year) and high Hispanic identifying (>25%) population. Data is organized by study area with each study area's land cover distributions captured as a percentage. The census block average (all study areas' land cover for census block #80690013041 averaged into one value) is given for reference. Census block average percentages may not add up to 100% as it is capturing averages across study areas.

2.3.4: Census Block #80690013042

Census Block #806913042 lies just south of Census Block #80690013041 along Fort Collins northern city limits. The census block is bordered by the Cache La Poudre River, North Shields Street, West Willox Lane, and North Lemay Avenue (see figure 2.3.4). The census block contains three study areas, Hickory Village Manufactured Home Park, Manufactured Home Park, and the Service Commercial District. The census block also contains the McMurray Natural Area, the Salyer Natural Area, Legacy Park, Soft Gold Park, and the Soft Gold Dog Park.

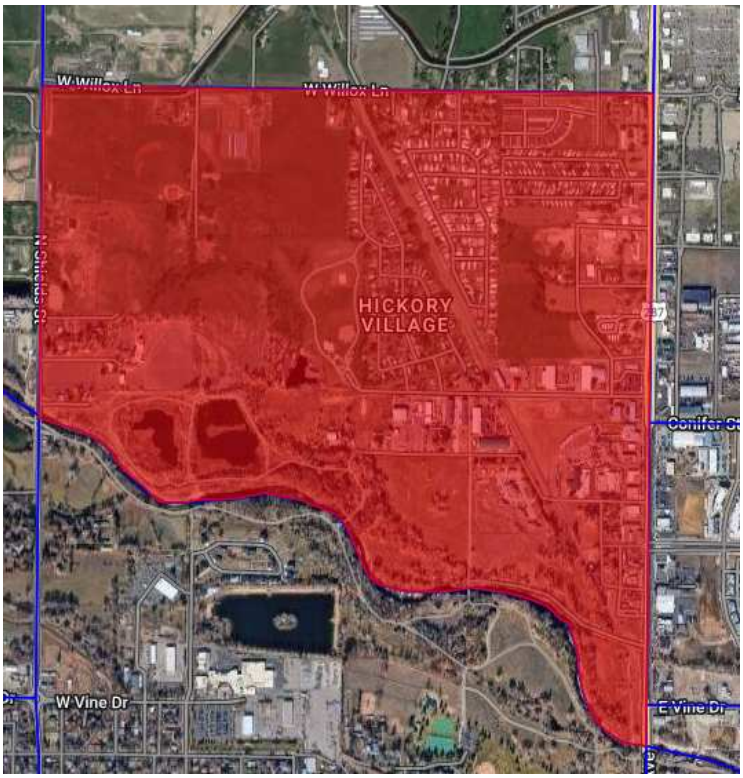

Figure 2.3.4: Illustrates Census Block #80690013042, which can be seen shaded in red (satellite imagery by Maxar Technologies 2023).

Hickory Village Manufactured Home Park

The Hickory Village Manufactured Home Park study area, which lies just south of West Willox Lane, is bordered to the west by Soft Gold Park and Soft Gold Dog Park, Hickory Street to the south, and the Union Pacific Railroad to the east (see figure 2.3.4a). The Hickory Village Manufactured Home Park is zoned as a Manufactured Housing District (M-H) which is, "designed to preserve and support existing manufactured housing communities as the predominant residential use alongside other complementary accessory and nonresidential activities which primarily serve residents of manufactured housing communities (Fort Collins Municipal Code Division 4.11)." The Hickory Village Manufactured Home Park study area features 36.2% Tree/Shrub cover and the following land cover distributions as determined by i-

Tree Canopy analysis: 15.3% Grass/Herbaceous, 22.2% Impervious Buildings, 0.4% Impervious Other, 24.8% Impervious Road, 1.1% Soil/Bare Ground, and 0.0% Water.

Figure 2.3.4a: Satellite Imagery of the Hickory Village Manufactured Home Park Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

North College Manufactured Home Park

The North College Manufactured Home Park neighborhood is split between two zoning types, a Low-Density Mixed-Use Neighborhood District (L-M-N) and a Service Commercial District (C-S) (see figure 2.3.4b). The L-M-N zoning type is, “intended to be a setting for a predominance of low-density housing combined with complementary and supporting land uses that serve a neighborhood and are developed and operated in harmony with the residential

characteristics of a neighborhood (Fort Collins Municipal Code Division 4.5).” A Service Commercial District (C-S) is intended for, “high traffic commercial corridors where a range of uses is encouraged to create a transition... to less intensive use areas of residential neighborhoods (Fort Collins Municipal Code Division 4.22).” The portion of the North College Manufactured Home Park that resides in the Service Commercial District is also included in the Service Commercial District study area. The North College Manufactured Home Park study area features 14.7% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 25.6% Grass/Herbaceous, 28.9% Impervious Buildings, 4.3% Impervious Other, 24.8% Impervious Road, 1.7% Soil/Bare Ground, and 0.3% Water.

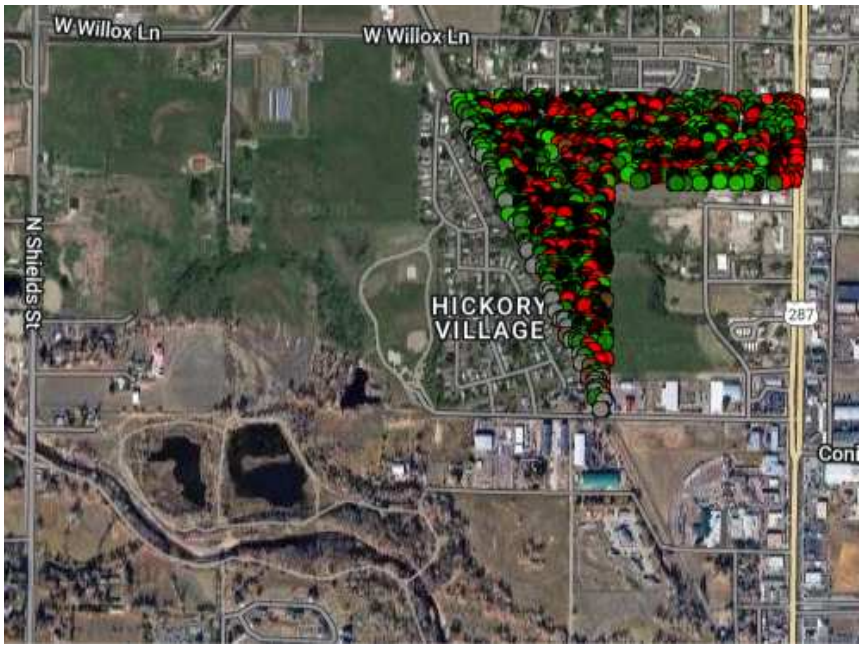

Figure 2.3.4b: Satellite Imagery of the North College Manufactured Home Park Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Service Commercial District

The Service Commercial District is the largest study area in Census Block #80690013042 and contains a portion of the North College Manufactured Home Park study area. The Service Commercial District stretches from West Willox Lane in the north to the Cache La Poudre River in the south and runs along Highway 287 in the east (see figure 2.3.4c). The Service Commercial District study area is also bordered by Legacy Park, the Salyer Natural Area, and the Hickory Village and North College Manufactured Home Park study areas. The city defines a Commercial Service District as, "a high traffic commercial corridor where a range of uses is encouraged to create a transition from commercial operations on a highway, arterial street or rail spur, to less intensive use areas or residential neighborhoods (Fort Collins Municipal Code Division 4.22)." The Service Commercial District study area features 11.9% Tree/Shrub cover and the following land cover distributions as determined by i-Tree Canopy analysis: 26.5% Grass/Herbaceous, 14.6% Impervious Buildings, 2.2% Impervious Other, 35.8% Impervious Road, 8.7% Soil/Bare Ground, and 0.3% Water.

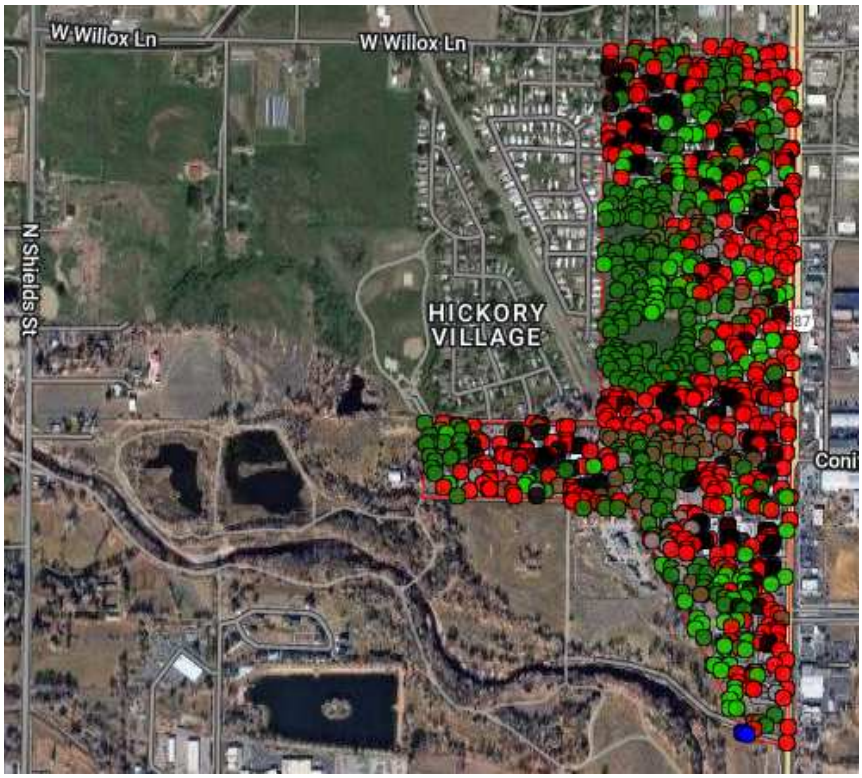

Figure 2.3.4c: Satellite Imagery of the Service Commercial District Study Area with overlaying point data from i-Tree Canopy (satellite imagery by Maxar Technologies 2023). I-Tree point data illustrates grass/herbaceous cover in dark green, impervious building cover in black, impervious other cover in grey, impervious road cover in red, soil/bare ground cover in brown, tree/shrub cover in light green, and water in navy blue.

Land Cover Comparison Across Study Areas for Census Block #80690013042

The land cover distributions, as classified by i-Tree Canopy analyses, for Census Block #80690013042 vary across the three study areas with impervious road cover being the most common cover type on average (see figure 2.3.4d). I found that grass/herbaceous cover ranged from 15.3% (Hickory Village Manufactured Home Park) to 26.5% (Service Commercial District), impervious building cover ranged from 14.6% (Service Commercial District) to 28.9% (North College Manufactured Home Park), impervious other cover ranged from 0.4% (Hickory Village Manufactured Home Park) to 4.3% (North College Manufactured Home Park),

impervious road cover ranged from 24.8% (Hickory Village Manufactured Home Park and North College Manufactured Home Park) to 35.8% (Service Commercial District), soil and bare ground cover ranged from 1.1% (Hickory Village Manufactured Home Park) to 8.7% (Service Commercial District), tree and shrub cover ranged from 11.9% (Service and Commercial District) to 36.2% (Hickory Village Manufactured Home Park), and water cover ranged from 0.0% (Hickory Village Manufactured Home Park and North College Manufactured Home Park) to 0.3% (Service Commerical District). The four study areas average a canopy cover of 20.9%, which is 5.9% greater than the canopy cover recorded for census block #80690013042 by American Forests' Tree Equity Score (15%).

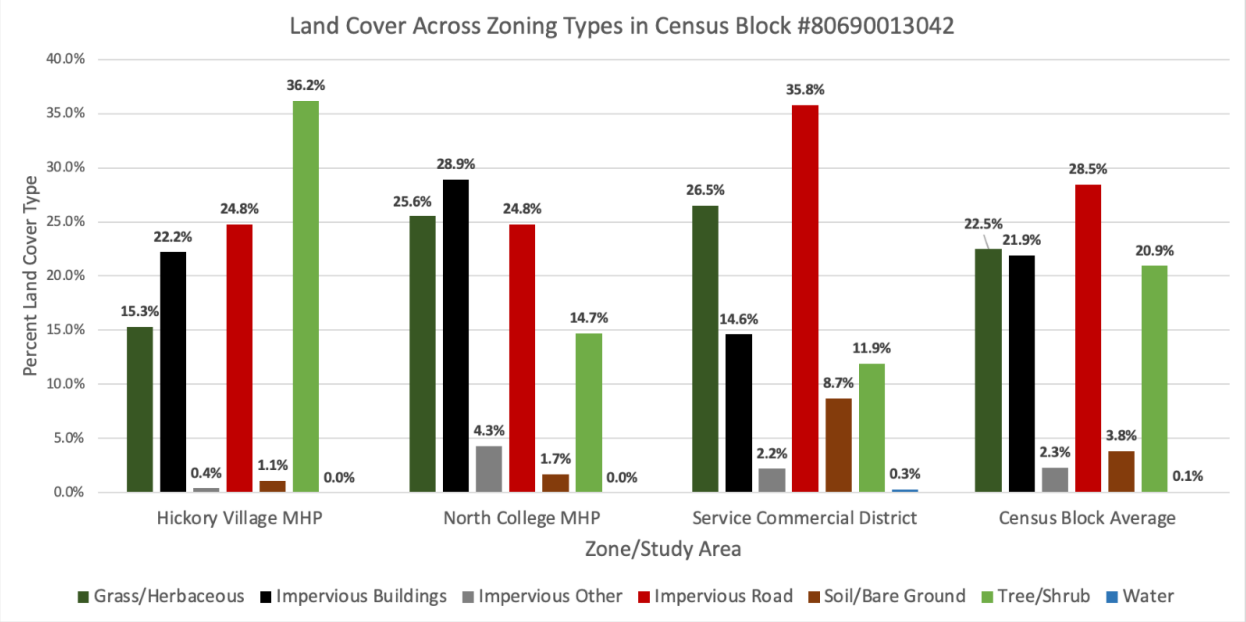

Figure 2.3.4d: The above figure illustrates land cover data for Census Block #80690013042 as collected using i-Tree Canopy. This census block features a low income (<$40k per year) and high Hispanic identifying (>25%) population. Data is organized by study area with each study area's land cover distributions captured as a percentage. The census block average (all study areas' land cover for census block #80690013042 averaged into one value) is given for reference. Census block average percentages may not add up to 100% as it is capturing averages across study areas.

2.3.5: Canopy Distributions

This section discusses land cover distribution across the study areas and is organized by three different study area zone types: 1) Neighborhoods, 2) Commercial Areas, and 3) Manufactured Home Parks. As mentioned in the methods section above, statistical regressions were not run because of a small sample size (five neighborhoods, five commercial areas, and three manufactured home parks). Because of this, discussion about land cover distribution will be limited to a comparison of land cover percentages.

Neighborhoods

This study examined the land cover of five different areas zoned primarily as neighborhoods: the Agricultural Neighborhood (CB #80690013041), the Medium Density Mixed-Use Neighborhood (CB #80690010071), the Edora Acres Neighborhood (CB #80690009021), the Stonehenge Neighborhood (CB #80690009021), and Spring Creek Village (CB #80690009021). However, the Agricultural Neighborhood will not be compared to the other neighborhoods in this study because the area was not zoned by the city. Additionally, due to its' agricultural nature, the Agricultural Neighborhood study area had extremely different land cover distributions compared to the more urban neighborhoods examined in this study.

From my analysis, I have found that these neighborhoods typically feature high canopy coverage (an average of 32%) and high impervious road cover (an average of 30%) (see figure 2.3.5a). Impervious other, soil/bare ground, and water land cover types all remained below 5% of total land cover, indicating that most of the area is developed infrastructure or landscaping. The high amount of impervious road cover can be attributed to areas with less canopy cover, or a canopy too young to sufficiently shade surrounding streets, driveways, and sidewalks. In such

areas, homeowners should be encouraged to plant shade trees in their yards to help shade driveways and sidewalks, while the city's forestry department should focus on continuing to grow street tree programs to create additional shade cover for streets.

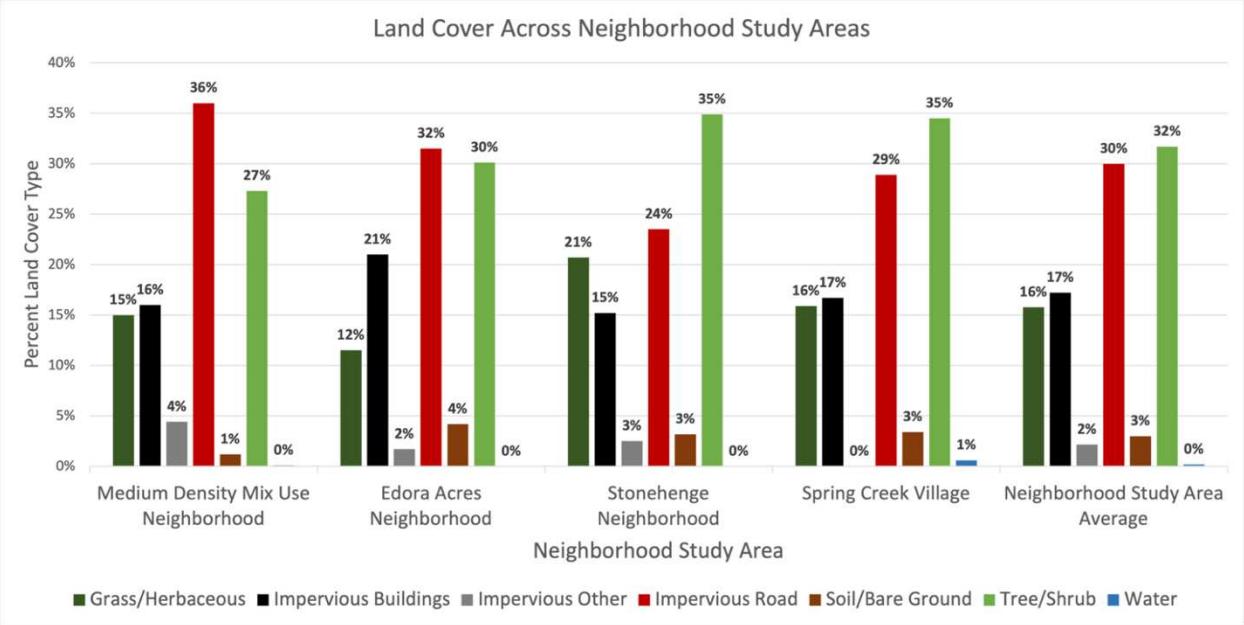

Figure 2.3.5a: The above figure illustrates land cover data across the neighborhood study areas; Agricultural Neighborhood, Medium Density Mixed-Use Neighborhood, Edora Acres Neighborhood, Stonehenge Neighborhood, Spring Creek Village, and the average cover across all neighborhood study areas as collected using i-Tree Canopy.

The Agricultural Neighborhood study area, whose northern limits abut highway 287, could benefit from additional canopy cover (currently 25%), but local interests for land use limits the number of trees residents would be willing to plant. Educational materials on the value of windbreaks in agricultural areas could be sent to private landowners in the area in hopes of encouraging tree planting in the area. Additionally, the portion of highway 287 that runs along the edge of census blocks #80690013041 and #80690013042 does not have an active street tree program. With the highway's proximity to Terry Lake, the Agricultural Neighborhood, and the Poudre Valley Manufactured Home Park (see figures from section 2.3.3), increasing canopy

cover within its' right of way would help protect the lake from harmful road runoff and insulate nearby neighborhoods from sound and light pollution associated with major roads.

Commercial Areas

This study examined the land cover distributions of five different commercially zoned study areas: Agriculture and Industry (CB#80690013041), the Service Commercial District (CB#80690013042), the General Commercial and Employment District (CB#80690010071), the Harmony Corridor District (CB#80690010071), and the Neighborhood Commercial District (CB#80690009021). As in the Neighborhoods section of this discussion, the Agriculture and Industry study area from census block #80690013041 will not be directly compared to other commercial areas because it was not officially zoned by the city.

Commercial study areas feature high rates of impervious road surfaces (an average of 41%), which is to be expected of zones with dense commercial areas that typically feature considerable amounts of impermeable surfaces such as parking lots (see figure 2.3.5b). Study areas whose prime objective is to provide access to commercial shopping and employment, like the General Commercial and Employment District and Harmony Corridor district, feature greater impervious road cover (53% and 44%, respectively) than zones that include housing alongside commercial offerings or serve as a commercial area for a neighborhood, like the Service Commercial District and Neighborhood Commercial District (36% and 33%, respectively). This is likely due to zoning requirements for fewer major roads in the neighborhood-serving districts and a higher number of residences with landscaping.

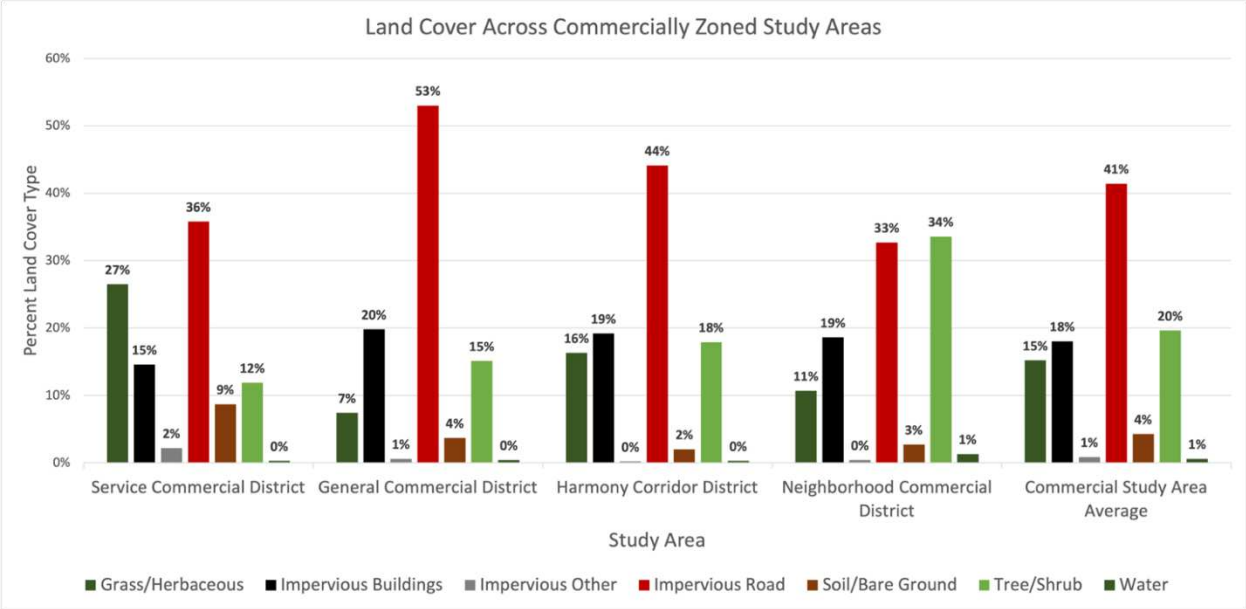

Figure 2.3.5b: The above figure illustrates land cover data for the commercially zoned study areas; Agriculture and Industry, Service Commercial District, General Commercial District and Employment District, Harmony Corridor District, Neighborhood Commercial District, and the average cover across all commercially zoned study areas as collected using i-Tree Canopy.

Canopy cover in commercially zoned study areas was typically lower than 20%, with one outlier, the Neighborhood Commercial District, which featured 34% canopy cover. Higher canopy cover in the Neighborhood Commercial District is likely due to the zoning type, which transitions from highly commercial areas to quieter neighborhoods. This transition from major roads to smaller streets coupled with higher rates of residences increases plant-able areas and the overall desire for trees on the landscape.

Manufactured Home Parks

This study examined the land cover distributions of three Manufactured Home Parks (MHPs): The Hickory Village Manufactured Home Park (CB #80690013042), the North College Manufactured Home Park (CB #80690013042), and the Poudre Valley Manufactured Home Park (CB #80690013041). Manufactured Home Parks are designed to preserve infrastructure for

manufactured homes, such as trailer homes and smaller prefabricated home kits. The Manufactured Home Parks in this study feature high rates of impervious road cover (an average of 29.1%), canopy cover (an average of 25.8%), and impervious building cover (an average of 23.7%) (see figure 2.3.5c).

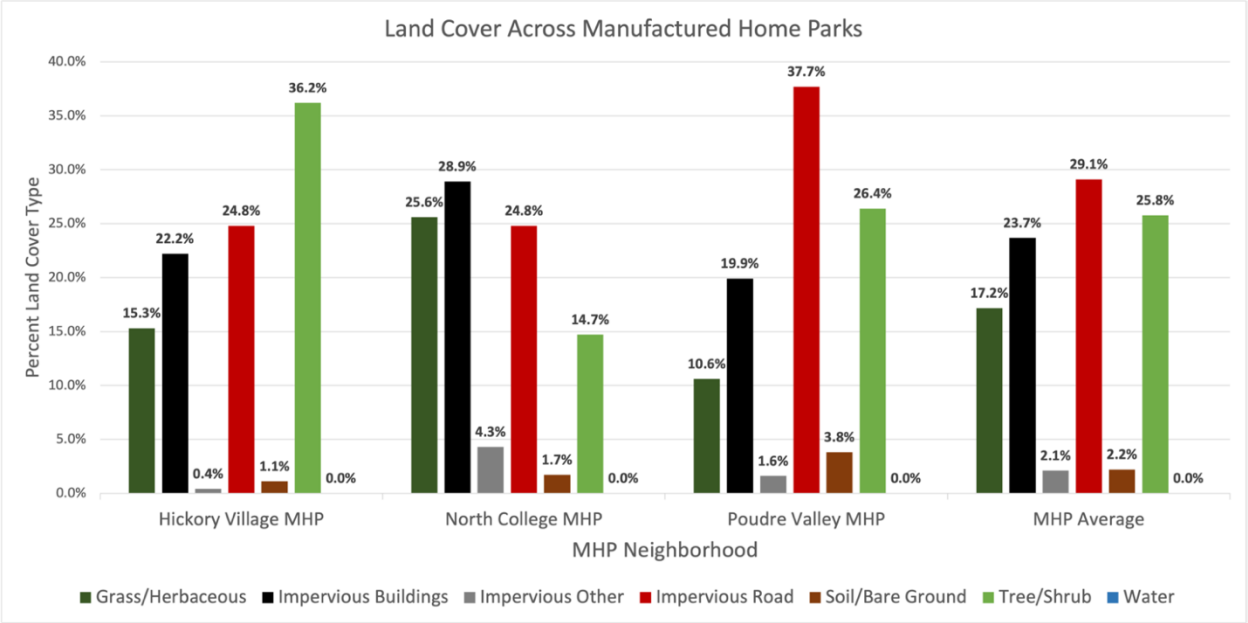

Figure 2.3.5c: The above figure illustrates land cover data for the Manufacture Home Park study areas; Hickory Village MHP, North College MHP, and Poudre Valley MHP, as well as average cover across the three MHP study areas as collected using i-Tree Canopy.

The Hickory Village and Poudre Valley MHPs feature higher rates of canopy cover (36.2% and 26.4%, respectively) than the North College Manufactured Home Park (14.7%). This is likely because the North College Manufactured Home Park overlaps with the Service Commercial District in census block #80690013042, which features low canopy cover (12%) and high impervious road cover (36%). The Poudre Valley Manufactured Home Park is bordered by Highway 287, which, as mentioned in the *Neighborhoods* section above, does not currently have a street tree program, raising the rate of unshaded impervious road cover in the area.

Manufactured Home Park canopy cover could potentially be increased by providing property owners and Manufactured Home Park managers or landlords incentives for planting trees. For instance, a water subsidy would be beneficial for property owners to offset the cost of watering new saplings, which must be done frequently in Fort Collins' semi-arid climate. A small property tax break might also be used to offset the cost of purchasing trees. These strategies reduce the overall expense of purchasing and maintaining trees within Manufactured Home Parks and could serve as an effective tool for increasing canopy cover in such areas.

2.4 Discussion

2.4.1 Canopy Limitations and Recommendations for Growth

General Limitations

General limitations such as the built environment and infrastructure, associated impervious surfaces, and privately owned properties impact canopy implementation and management across urban ecosystems (Dwyer et al. 2000, Figueiredo et al. 2016, Grimm et al 2008, Imhoff et al. 2010, Luley and Bond 2002, McPherson et al. 1997, Nowak and Crane 2000, Nowak and Dwyer 2007, Tan et al. 2016, Tsai et al. 2018) - the city of Fort Collins, Colorado is no exception. Across the city, the built environment, including buildings, sidewalks, parking lots, and roadways reduces the amount of area available for immediate tree plantings by covering the ground with impervious surfaces. The only way to adjust these limiting factors would be to reconstruct or remove them entirely, which is an unlikely outcome.

Other factors in Fort Collins' built environment like overhead infrastructure and abandoned sections of railroad or trolley tracks further limit public street tree and park tree

plantings. Overhead infrastructure, such as streetlights, trolley lines, and electrical powerlines limit vertical growing space for trees. Some of these factors, like streetlights, simply limit the acceptable range of adult tree height, while others, like powerlines, completely restrict the planting of street trees. Like the impervious surface factors discussed above, abandoned rail and trolley tracks would need to be removed entirely to become plant-able area.

There is potential to increase canopy cover in these areas, however, that potential relies on changes to the built environment that come with new construction and infrastructure revitalization. As the city builds new developments and redevelops established areas there should be a greater focus on green infrastructure, including space for canopy implementation. Additionally, the city should consider other acceptable forms of landscaping underneath overhead infrastructure; shrubbery, bushes, and perennial plants would go a long way for beautification and habitat goals. Abandoned rail and trolley tracks should also be removed from the city in favor of amplifying plant-able space.

Another major limitation to urban canopy cover is privately owned properties where city foresters have no authority to monitor canopy health or plan tree plantings. Here, city foresters can only educate property owners regarding tree species selection, placement, and care. One common solution is to host sapling giveaways and education workshops in hopes of increasing citizen awareness of the benefits of trees and a subsequent increase of trees planted on private property. However, this solution is limited by language barriers and availability of citizens to attend such events.

To increase accessibility, the city should strive to include presenters that can speak the languages commonly used in that area; in the case of Fort Collins this would mean employing a bilingual Spanish interpreter and an American Sign Language interpreter. The city should also

strive to increase the frequency of educational events and should offer each event at multiple times and days of the week. This would allow citizens who are stay at home parents, work multiple jobs, and/or not available on weekends to attend educational events and increase the overall number of engaged citizens.

Parking Lots

The commercial study areas examined in this study, particularly the General Commercial District and Harmony Corridor District, commonly feature parking lots. Parking lots are owned and maintained by the property owner who is, "responsible for maintaining any vehicular use area in good condition and free of refuse and debris and all landscaping in a healthy and growing condition, replacing it, when necessary, as determined by the City Forester (Fort Collins Municipal Code 3.22(D)(3)(e))." Shading impervious parking surfaces is imperative to controlling local UHI impacts, and a tree shading a paved surface can reduce surface temperatures by 12ºC (Armson et al. 2013). To include adequate tree cover in parking lots, Fort Collins Municipal Code Section 3.2.1(E)(5) asserts that, "6% of interior landscaping of all parking lots with less than 100 spaces, and 10% of the interior space of all parking lots with over 100 spaces shall be landscape areas… each landscaped island shall include one or more canopy shade trees and include at least 80 square feet of ground area per tree to allow for root aeration (see figure 2.4.1a)."

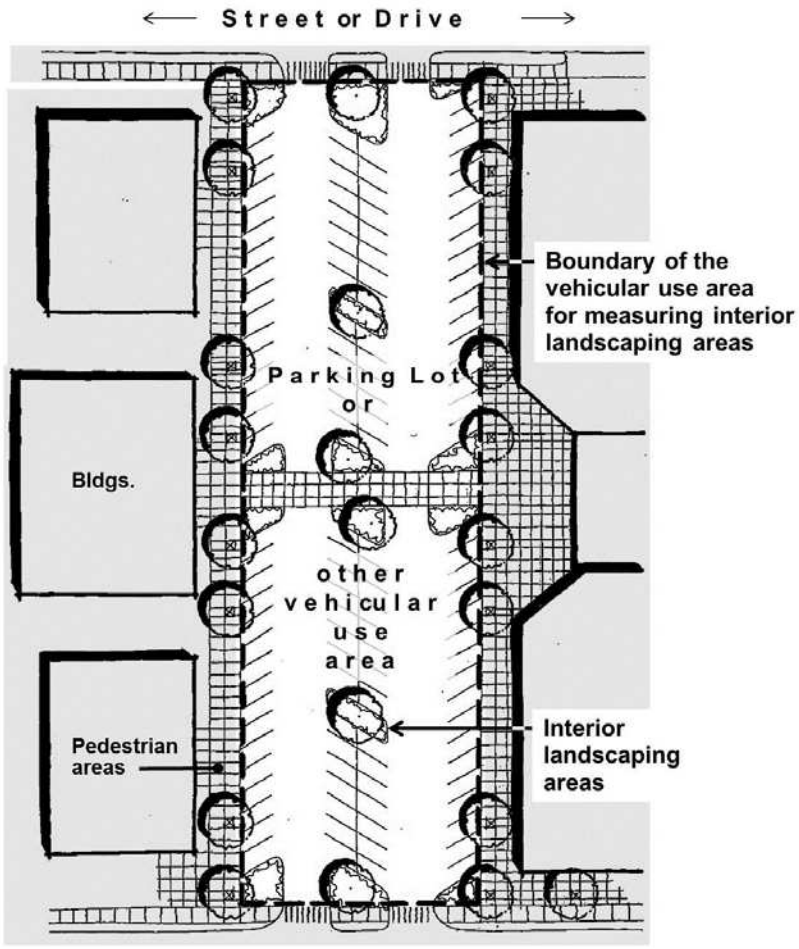

Figure 2.4.1a: "Interior Landscaping for Vehicular Use Areas" from Fort Collins City Municipal Code, section 3.2.1(E)(5). This figure illustrates the proper placement of interior landscape islands within a large parking lot.

While Fort Collins Municipal Code is clear about parking lot ownership and who is responsible for maintaining landscaping and tree cover, I have observed many parking lots across the study areas without canopy cover – even in the designated interior landscaped areas (see figure 2.4.1b). This represents a conundrum for city foresters because parking lots are technically private property, and tree plantings are done at the discretion of property owners. To help ameliorate this issue, I would recommend one or both of the following measures: First, strengthen the existing Municipal Code in Section 3.22(D)(3)(e) which, as stated above, gives

the City Forester the agency to have trees replaced within parking lots. This code should be updated to include “planting and replacing, when necessary, as determined by the City Forester” to allow city forestry to request trees be planted in a parking lot by the property owner.

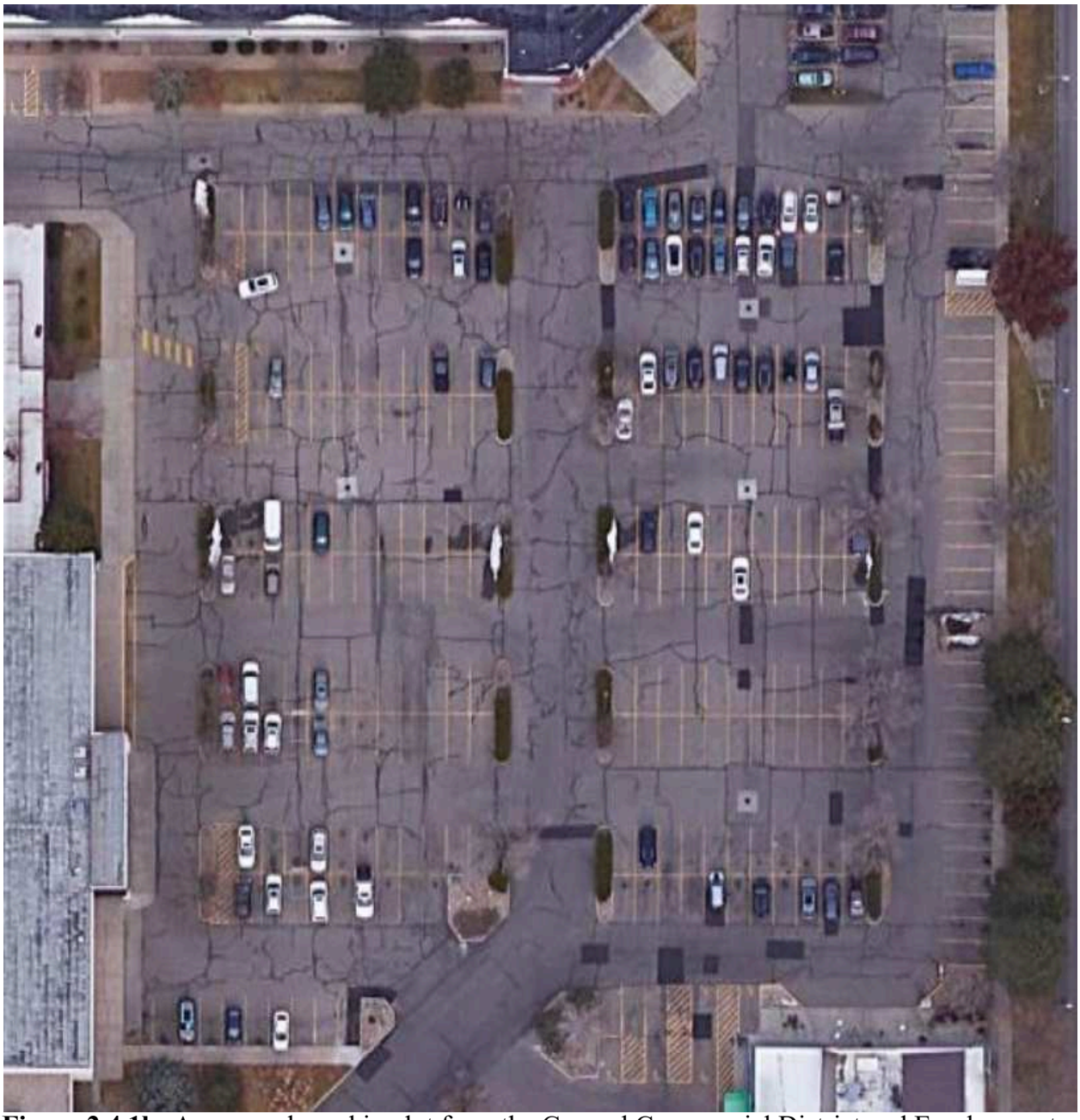

Figure 2.4.1b: An example parking lot from the General Commercial District and Employment District study area from census block #80690010071. Here, we can see that many of the landscaped islands are treeless, even though Fort Collins Municipal Code calls for tree cover (Satellite imagery by Maxar Technologies 2023).

My second measure would be to introduce either a "stick or carrot" incentive for maintaining adequate canopy cover in parking lots as outlined above by Fort Collins Municipal Code Section 3.2.1(E)(5). A "carrot," or rewarding incentive, could come in the form of a property tax break or water subsidy, which would help cover the costs of purchasing and maintaining a new tree. A "stick," or incentive by threat of punishment, could be provided by charging a fine for not complying with Municipal Code. Collected fines would be put towards forestry projects in the city, such as public street tree programs and sapling giveaways.

Railways

There are three railways that run through the city of Fort Collins, The Burlington-Northern Santa Fe line, the Great Western line, and Union Pacific line, all of which create complications for canopy continuity and connection (Train Information City of Fort Collins). According to the General Federal Railroad Right of Way Act, enacted in 1875, Railroads are granted up to a 200-foot right of way (100 feet of right of way on either side of the track) (CRS Report for Congress Federal Railroad Rights of Way). Many railroads within urban areas reduce this right of way coverage to 100 feet (50 feet either side of the track) and maintain this right of way space to ensure various safety features like keeping building zones a safe distance from tracks, maintaining vehicle and traffic distance from tracks, and limiting hazardous vegetation growth (including trees) that could impact or derail trains.

While railroad rights of way limit plant-able area across urban systems, there are many benefits to introducing trees just outside of the right of way; this includes, but is not limited to, reducing noise pollution (Maleki and Hosseini 2010), increasing sense of comfort, safety, and privacy near transportation infrastructure (Mouratidis 2019), and increasing biodiversity and

habitat connectivity (Anderson et al. 2021, Brunbjerg et al. 2018). To increase tree cover in such areas, cities should target private landowners along the tracks with educational materials detailing the benefits of canopy cover along railways. Encouraging citizens to plant trees in this area has the potential to generate a greenstrip shielding citizens from some of the negative impacts of train activity. I would recommend considering a minimum of a 150-foot buffer on either side of the rail's right of way. In the case of Fort Collins (which maintains a 50-foot buffer on either side of the tracks), this 150-foot buffer would generate an educational target area of about 1,260 acres (about twice the area of Central Park in New York City) within city limits (buffered areas outside of city limits were not included in this statistic). Fort Collins' potential 150-foot greenstrip buffer can be seen in figure 2.4.1c.

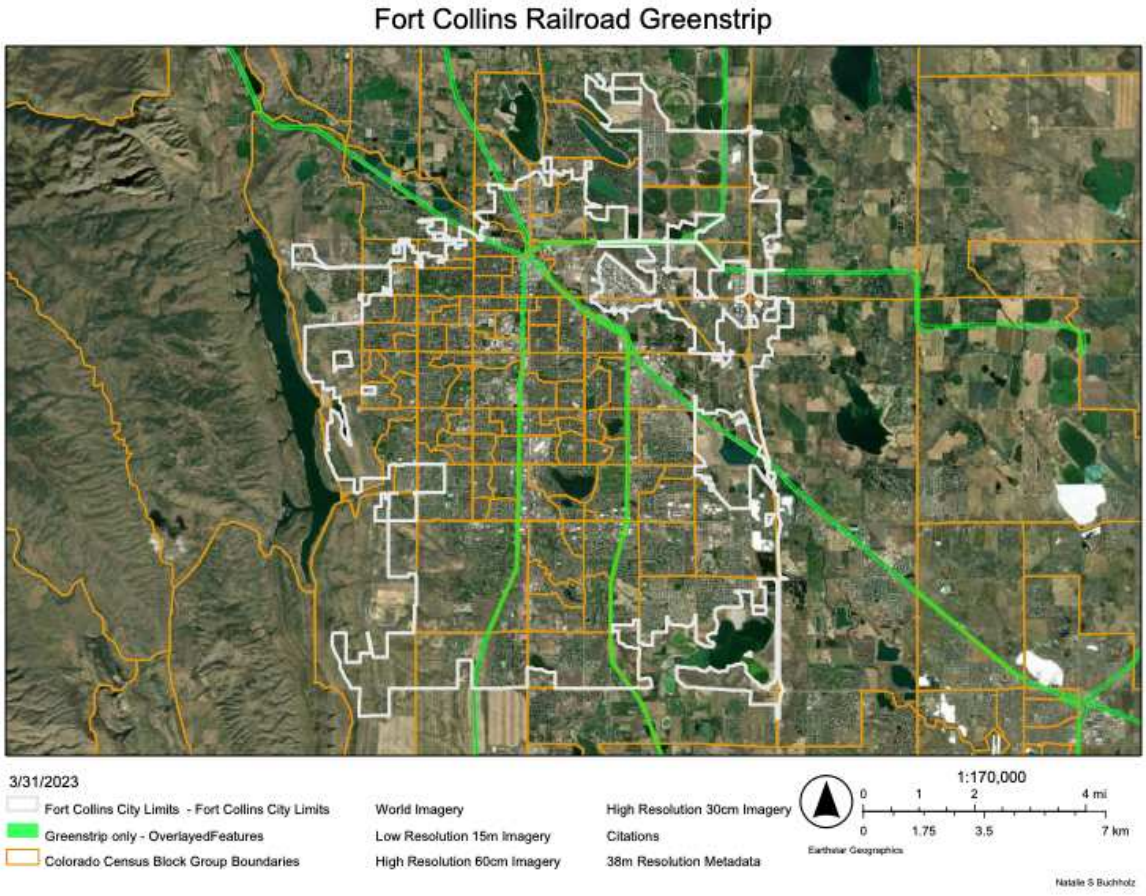

Figure 2.4.1c: A map figure displaying the entirety of a potential railroad greenstrip in Fort Collins, Colorado. This greenstrip was defined by a 150-foot buffer on either side of the rail's right of way (shown in green) and represents areas to be targeted with educational materials regarding the benefits of planting trees near railroads.

A smaller extent, which features the city's northern census blocks, can be seen in figure 2.4.1d. In this closer satellite view of the city, we can see that the greenstrip buffer features neighborhoods (including the Hickory Village Manufactured Home Park study area), farmland, and open spaces that could benefit from additional canopy coverage. Acquiring parcel and landownership data for properties within the 150-foot greenstrip buffer would be a straightforward way to collect contact information for citizens within the targeted area. The city can then generate their educational materials and send them to the proper addresses.

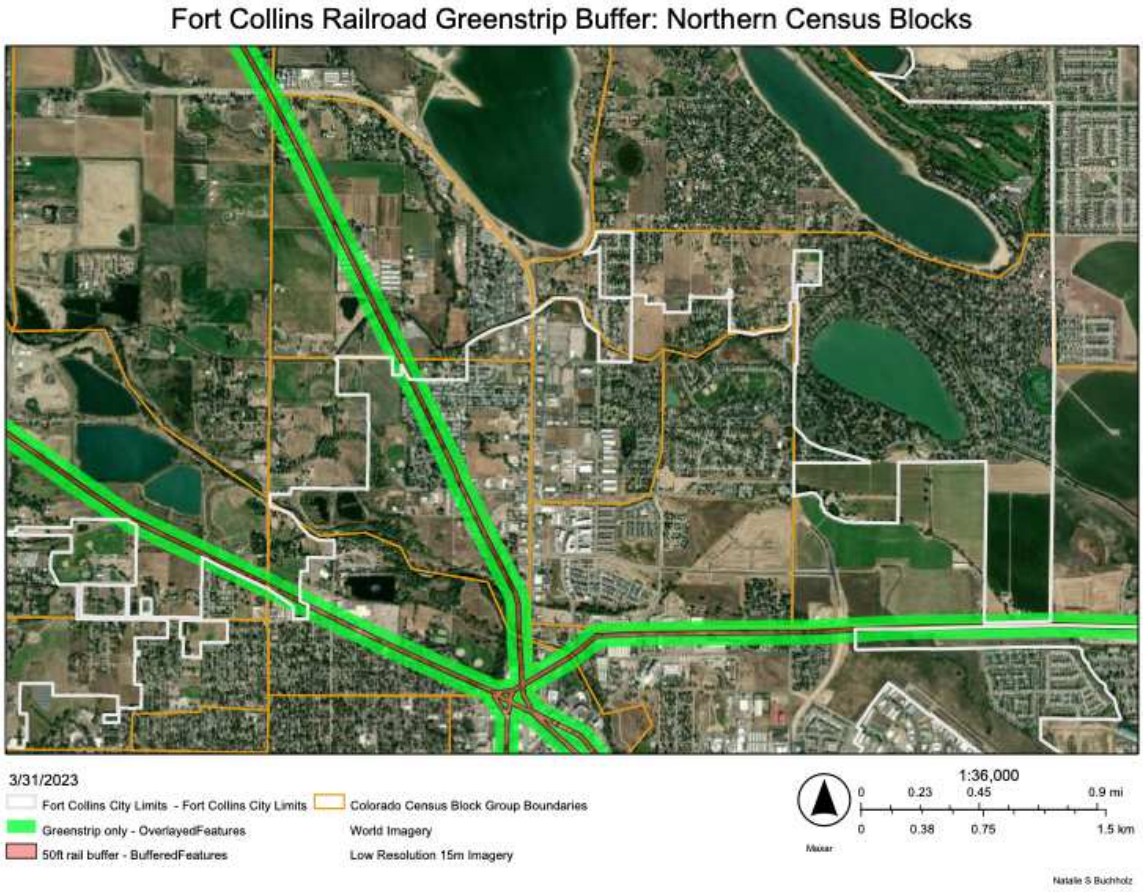

Figure 2.4.1d: A map figure displaying a portion of a potential railroad greenstrip in the northern census blocks of Fort Collins, Colorado. This greenstrip was defined by a 150-foot buffer on either side of the rail's right of way (shown in green) and represents areas to be targeted with educational materials regarding the benefits of planting trees near railroads. The greenstrip in this extent runs through two of the census blocks explored in this study: Census Block #80690013041 and Census Block #80690013042

Educational Materials

The production and circulation of educational materials is imperative to spreading knowledge about forestry related topics such as the energy benefits of trees near buildings, tree species selection and planting, Emerald Ash Borer identification and information, and benefits of trees on the landscape. The city of Fort Collins has produced many educational materials and presentations over the years, but additional resources should continue to be made available. New

educational materials should be produced to 1) encourage the planting of trees for agricultural wind breaks, 2) the planting of trees in animal agricultural pastures, and 3) educate manufactured homeowners on Manufactured Home Park specific canopy restrictions, concerns, and planting considerations. Such educational materials will help home and property owners make decisions about planting trees on their private property and will hopefully lead to an overall increase in canopy cover across the city.

As the second most spoken language in the area, it is imperative that all existing and future educational materials are translated into Spanish to increase accessibility. The census blocks examined in this study all have a population of at least 25% Hispanic identifying persons, representing a minority group that requires translated materials due to potential language barriers. Translating materials can be time consuming and costly, but this work is vitally important to publicizing canopy concerns across the municipality. To reduce costs and give back to the community, the forestry department should consider hiring master's and doctoral Spanish Language students from Colorado State University to translate materials as part of their required translation projects.

2.4.2 Study Limitations and Issues of Scale

Canopy equity and TES are typically explored at the census block level because the census block is the finest resolution at which demographic information is readily available. This causes an issue of scale that should not be overlooked. Census blocks in large, well-established cities like New York, Philadelphia, and Chicago are often smaller than blocks in mid-sized cities and municipalities, making large-city census blocks more suitable for tree equity analyses.

However, in small to mid-sized cities, census blocks can cover larger areas, making demographic information less specific to the neighborhoods they contain.

Unfortunately, this means TES cannot be calculated at a finer scale such as the neighborhoods and city zones I explored in this study. I found that when I compared my finer-scale study areas to information provided by American Forests' TES database that neighborhoods typically featured higher canopy cover than what was recorded at the census block level. For example, in census block #80690009021 American Forests' TES database reported the census block average for canopy cover was about 26%. However, at a finer scale, I found that the neighborhoods within the census block (Edora Acres, Spring Creek Village, and the Stonehenge Neighborhood) averaged a canopy cover of 33%, 7% greater than the estimate provided by American Forests.

Comparable results across the study areas, with American Forests' census block estimates of canopy cover being lower than my finer scale neighborhood estimates, implies that the census block may not be the best unit of scale for canopy equity analyses. However, until demographic information becomes available at a finer scale, it will be extremely difficult to conduct such analyses. For the time being, I recommend methods like my exploration of canopy equity across city zones to augment findings from tree equity analyses like TES. TES can provide city foresters with information on which census blocks should first be addressed, but canopy equity plans should be researched and completed at the neighborhood level to avoid overlooking local community needs. Going forward, the field of urban ecology should strive to examine canopy equity at smaller scales to capture more detailed observations and consider potential solutions at the community level.

Generally, this study was limited mostly by time which restricted my ability to analyze more study areas. Instead of analyzing city zones across all the census blocks in Fort Collins, I chose four census blocks based on income level and percent of Hispanic identifying persons to explore concerns over areas containing the largest minority populations in the city. While this allowed me to provide more specific information to the city about a population of concern, it also restricted my ability to generalize land cover distribution across the municipality. With such a small sample of study areas (n = 13), statistical regressions and analyses would not be statistically significant, representing a loss of additional information on the strength of specific canopy distribution across zoning types.

2.5 Conclusion

This study examined canopy cover across city zone types in four census blocks that featured low-income households (<$40k per year) and a high population of Hispanic identifying persons (>25%) in Fort Collins, Colorado. Through this analysis I was able to examine land cover distributions at the neighborhood scale, a finer extent than typically assessed in the field of urban ecology. This analysis revealed that the most used scale, the census block, may be too large to adequately capture canopy distribution and equity at the neighborhood level. Because of this, Tree Equity Scores calculated at the census block level should be the foundation on which additional, finer-scale research is conducted and should not be the only metric used to make canopy decisions across a municipality.

Through a combination of land cover assessments and satellite observations, I was able to make general recommendations for increasing canopy cover to the forestry department of Fort Collins. These recommendations include: starting a new street tree program along Highway 287

just north of city limits, adjusting local municipal code to strengthen the City Forester's jurisdiction over tree plantings in parking lots, incentivizing or penalizing commercial property owners to maintain a high level of canopy coverage in parking lots, increasing the number of canopy educational materials and translating this information into Spanish, generating a green strip along the railway's right of way through targeted educational programs, and increasing the number of sapling giveaways and educational events occurring in low-income neighborhoods. By introducing one or more of these measures, the forestry department of Fort Collins, Colorado can increase canopy coverage and address canopy equity concerns across the city.

CH 2 REFERENCES:

American Forests Tree Equity Score. “About Tree Equity.” American Forests Tree Equity Score American Forests, 2021. https://www.treeequityscore.org/about/ (2021)

Anderson, E. C., Avolio, M. L., Sonti, N. F. & LaDeau, S. L. More than green: Tree structure and biodiversity patterns differ across canopy change regimes in Baltimore’s urban forest. Urban Forestry & Urban Greening 65, 127365 (2021).

Armson, D., Asrafur Rahman, M. & Roland Ennos, A. A comparison of the shading effectiveness of five different street tree species in Manchester, UK. Arboriculture & Urban Forestry 39, (2013).

Brunbjerg, A. K. et al. Can patterns of urban biodiversity be predicted using simple measures of green infrastructure? Urban Forestry & Urban Greening 32, 143–153 (2018).

CRS Report For Congress, Baldwin, P. & Flynn, A. M. Federal Railroad Rights of Way (CRS Reports for Congress, 2006).

Dwyer, J. F., Nowak, D. J., Noble, M. H., and Sisinni, S. M. “Assessing our Nation’s Urban Forests: Connecting People with Ecosystems in the 21st Century.” Gen. Tech. Rep. PNW-460, US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. Hamilton, G. J. (1975). Forest Mensuration Handbook (Vol. 39, Forestry Commission Booklet) (2000).

Fort Collins, Colorado Municipal Code . Municode Library (2023). Available at: https://library.municode.com/co/fort_collins/codes/municipal_code.

Fort Collins facts || visitor 2023 Fort Collins Facts - City of Fort Collins. Available at: https://www.fcgov.com/visitor/fcfacts.php.

Fort Collins Forestry 2023 City of Fort Collins. Available at: https://www.fcgov.com/forestry/.

Grimm, N. B. et al. Global change and the ecology of Cities. Science 319, 756–760 (2008).

Heisler, G. Energy savings with trees. Arboriculture & Urban Forestry 12, 113–125 (1986).

Huang, J., H. Akbari, and H. Taha. "The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements." ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia 1990).

Imhoff, M. L., Zhang, P., Wolfe, R. E. & Bounoua, L. Remote Sensing of the urban heat island effect across biomes in the continental USA. Remote Sensing of Environment 114, 504–513 (2010).

Maleki, K. & Hosseini, S. M. Investigation of the effects of leaves, branches and canopies of trees on noise pollution reduction. Annals of Environmental Science 5, 13–21 (2011).

McPherson, E. G. et al. Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. Urban Ecosystems 1, 49–61 (1997).

Mitchell, B. C. & Chakraborty, J. Exploring the relationship between residential segregation and thermal inequity in 20 U.S. cities. Local Environment 23, 796–813 (2018).

Mouratidis, K. The impact of urban tree cover on perceived safety. Urban Forestry & Urban Greening 44, 126434 (2019).

Nowak, D. J. & Crane, D. E. The Urban Forest Effects (UFORE) model: Quantifying urban forest structure and functions. US Forest Service Research and Development (2000). Available at: https://www.fs.usda.gov/research/treesearch/18420.

Nowak, D. J. & Dwyer, J. F. Understanding the benefits and costs of urban forest ecosystems. Urban and Community Forestry in the Northeast 25–46 (2007). doi:10.1007/978-1-4020-4289-8_2

Online map applications || Geographic Information Services. Online Map Applications - City of Fort Collins Available at: https://www.fcgov.com/gis/maps.

Pickett, S. T. A. et al. Urban Ecological Systems: Scientific foundations and a decade of progress. Journal of Environmental Management 92, 331–362 (2011).

Property search (assessor). Larimer County Available at: https://www.larimer.gov/assessor/search#/property/.

Schell, C. J. et al. The ecological and evolutionary consequences of systemic racism in Urban Environments. Science 369, (2020).

Schwarz, K. et al. Trees grow on money: Urban tree canopy cover and environmental justice. PLOS ONE 10, (2015).

Selmi, W. et al. Air pollution removal by trees in public green spaces in Strasbourg City, France. Urban Forestry & Urban Greening 17, 192–201 (2016).

Simberloff, D., Parker, I. M. & Windle, P. N. Introduced species policy, management, and future research needs. Frontiers in Ecology and the Environment 3, 12–20 (2005).

Tan, Z., Lau, K. K.-L. & Ng, E. Urban Tree Design Approaches for mitigating daytime urban heat island effects in a high-density urban environment. Energy and Buildings 114, 265–274 (2016).

Train information || Planning, development, Transportation. Train Information - City of Fort Collins Available at: https://www.fcgov.com/pdt/train-information#cb-38162-6584.

Tsai, W.-L. et al. Relationships between characteristics of urban green land cover and mental health in U.S. metropolitan areas. International Journal of Environmental Research and Public Health 15, 340 (2018).

U.S. Census Bureau quickfacts: Fort Collins City, Colorado. U.S. Census Bureau quickfacts (2021). Available at: https://www.census.gov/quickfacts/fortcollinscitycolorado.

Walsh, J. R., Carpenter, S. R. & Vander Zanden, M. J. Invasive species triggers a massive loss of ecosystem services through a trophic cascade. Proceedings of the National Academy of Sciences 113, 4081–4085 (2016).

Wilson, B. Urban heat management and the legacy of Redlining. Journal of the American Planning Association 86, 443–457 (2020).