



Historical Urban Tree Canopy Cover Change in Two Post-Industrial Cities

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Abstract

Present-day spatial patterns of urban tree canopy (UTC) are created by complex interactions between various human and biophysical drivers; thus, urban forests represent legacies of past processes. Understanding these legacies can inform municipal tree planting and canopy cover goals while also addressing urban sustainability and inequity. We examined historical UTC cover patterns and the processes that formed them in the cities of Chelsea and Holyoke, Massachusetts using a mixed methods approach. Combining assessments of delineated UTC from aerial photos with historical archival data, we show how biophysical factors and cycles of governance and urban development and decay have influenced the spatiotemporal dynamics of UTC. The spatially explicit UTC layers generated from this research track historical geographic tree distribution and dynamic change over a 62-year period (1952–2014). An inverse relationship was found between UTC and economic prosperity: while canopy gains occurred in depressed economic periods, canopy losses occurred in strong economic periods. A sustainable increase of UTC is needed to offset ongoing losses and overcome historical legacies that have suppressed UTC across decades. These findings will inform future research on residential canopy formation and stability, but most importantly, they reveal how historical drivers can be used to inform multi-decadal UTC assessments and the creation of targeted, feasible UTC goals at neighborhood and city scales. Such analyses can help urban natural resource managers to better understand how to protect and expand their cities' UTC over time for the benefit of all who live in and among the shade of urban forests.

Keywords Urban forest · Legacy effect · Urban greening · Aerial photography · Urban environmental history · Land cover change

Introduction

Urban tree canopy (UTC) is the portion of urban land covered by trees, and is comprised of trees along streets, in parks, and on public or private properties. UTC is shaped by the complex relationships between various human and biophysical drivers, which produce, over time, landscapes

that represent legacies of past physical and social processes (Roman et al. 2018). These legacies explain species composition and distribution of trees planted across different time periods as well as social inequities (Roman et al. 2018, Watkins and Gerrish, 2018). In the United States (US), racial segregation and redlining (a race-based US policy that promoted segregation tactics in real estate, see Rothstein, 2017) from the early 20th century is associated with large environmental inequalities within cities, such as exposure to extreme heat due to high levels of impervious surface and low levels of UTC, compared to non-redlined neighborhoods (Hoffman et al. 2020, Locke et al. 2021, Nowak et al. 2022). In post-industrial cities, mid- and late-20th century depopulation and urban renewal also had lasting impacts on UTC in terms of building demolition, tree growth on abandoned lands, and interconnected suburbanization phenomena (Roman et al. 2021, Haase et al. 2014). The present-day spatial patterns of UTC within a given city

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result from the intricate ways these legacies have played out on the landscape.

Recent studies have statistically associated UTC distribution with sociodemographic variables: Schwarz et al. (2015) found a positive correlation between UTC cover and median household income across several US cities, while Zhou et al. (2021) found that across 38 US cities, people who are lower income, have low educational attainment, and are a minority live in hotter neighborhoods with less UTC. In response, local governments, nonprofit organizations and tree advocacy groups have committed to substantial tree planting and canopy cover goals to address urban sustainability and inequity (Nguyen et al. 2017, Eisenman et al. (2021)), but the legacies that produced current UTC do not typically inform how these programs establish and meet their goals. Much of the motivation for tree planting relates to the ability of trees to provide ecosystem services, which has taken more prominence in the scholarly literature (Roy et al. 2012) and urban environmental management (Young, 2013). This has led municipalities to gather information on the UTC within their boundaries (O’Neil-Dunne et al. 2013, Parmehr et al. 2016), and set goals for future UTC levels (Nguyen et al. 2017, Locke et al. 2016). But these analyses miss the patterns and processes of how current urban forests formed, and what might affect them in the future. Understanding past drivers is critical to inform future urban environmental management approaches. Furthermore, trees are slow-growing organisms requiring decades to reach maturity, with a temporal lag between planting actions and substantial tree cover gains (Roman et al. 2018). Therefore, long-term, multi-decadal assessments and analysis of UTC and their associated historical drivers is needed to inform reasonable UTC goals (Roman et al. 2021), and to better understand how to protect trees and greenspaces over time.

The mapping of UTC over several decades has been used to study canopy gains and losses attributed to urban development (Berland 2012, Bonney and He 2019) and to assess forest fragmentation in suburbanizing landscapes (Zhou et al. 2011). Multi-decadal canopy cover assessment can be accomplished using various types of remotely sensed data, such as aerial photographs and airborne/satellite imagery (Walton et al. 2008). Over the past decade, the most common approaches for estimating canopy cover use fine resolution (<2 m) imagery and include the dot method to visually interpret percent canopy cover based on randomly laid points across a landscape (Berland, 2012, Roman et al. 2017) or a fused combination of LiDAR and either aerial or satellite imagery to delineate canopy cover (O’Neill-Dunne, 2013, Parmehr et al. 2016). The dot method does not create spatially explicit layers; therefore, using it to identify patterns in UTC change is difficult (Locke et al. 2017, Roman et al. 2021). Unfortunately, fine resolution satellite imagery pre-1990s and LiDAR pre-2000s is nonexistent. However, aerial

photographs have long been used in landscape ecology (Morgan et al. 2010, Brook and Bowman 2006), and to delineate urban forested patches and tree density in a spatially explicit manner (Zhou et al. 2011, Gillespie et al. 2012).

Currently, mixed-method, interdisciplinary research has had little representation in the field of urban forestry but there are calls for this to change (Roman et al. 2018, Vogt, 2018). Qualitative historical analysis can help interpret past UTC change processes and spatial patterns (Roman et al. 2017, Roman et al. 2021, Nix et al. 2022), leading to a better understanding of human and biophysical impacts on UTC. Incorporating local urban history into UTC assessments can provide a more holistic understanding of the causes and consequences of UTC change, revealing how legacy effects impact the present-day UTC (Roman et al. 2021), while better informing future planning and policy.

In this study, we investigate historical UTC cover patterns and processes in Chelsea and Holyoke, Massachusetts (US; Fig. 1) from 1952 to 2014. During this time period, both cities experienced post-industrial downturns, radical shifts in population racial makeup, urban renewal programs, and economic transformation. Similar change processes occurred throughout many post-industrial towns and cities in the midwestern and northeastern US, southeastern Canada, and western Europe (Wachter and Zeuli, 2013, Neumann, 2016). The UTC cover changes that played out in Chelsea and Holyoke may therefore be indicative of broader changes that have taken place in other old industrial centers. UTC metrics were assessed and then contextualized using local history from each city, generating insights into the drivers of change that will be critical for informing urban tree planting and management.

Methods

Study Area

Massachusetts is in the New England region of the US and was forested prior to European colonization. During the 18th–19th centuries, forests were cleared around much of New England as land was converted to agriculture. Chelsea is situated in eastern Massachusetts, 4 km northeast of Boston, in a humid subtropical climate, while Holyoke is located in western Massachusetts in a humid, continental climate. This study covers the entirety of Chelsea (5.7 km²), which has the second-highest population density in the state. Holyoke is geographically much larger (59.0 km²), but a forested state park constitutes nearly half the city area. Our analysis focuses on the heavily urbanized city core (10.2 km²), which we selected based on 1952 imagery outlining neighborhoods surrounding the city center.



Fig. 1 Holyoke and Chelsea, Massachusetts city boundaries displaying the study area, water bodies, 2014 urban tree canopy cover and major roads

Chelsea historical context

Originally a resort for Boston's elite (Gillespie, 1898), by the mid-19th century Chelsea had developed into an industrial center with extensive ship construction and manufacturing (Lake, 2011), including the establishment in 1836 of the Chelsea Naval Hospital. The city quickly became a hub for new immigrants, especially Russian Jews (Lake, 2011). Chelsea suffered a catastrophic fire in 1908 that burned down more than one-quarter of the city. This area was rebuilt with a focus on manufacturing, which created new jobs and led Jewish migrants to settle in Chelsea. The mid-20th century saw residential tax increases, increasingly dilapidated aging housing, and the construction of the Mystic River (Tobin) Bridge and US Route 1 highway, displacing residents and leading many families to leave to surrounding suburbs (Lake, 2011).

Chelsea's population peaked in 1930 at 45,816 (US Census, 1930), which declined due to the suburbanization process just described, with more outmigration following another massive fire in 1973 that destroyed approximately one-fifth of the city. The population bottomed out at 25,431 in 1980 (US Census, 1980). New immigrants from Puerto Rico and Central America began to settle in Chelsea in the late-20th century due to the location in the Boston metropolitan area and low cost of housing, despite racial tensions with local government authorities (Lake, 2011). Following years of reduced tax revenue, misgovernance and corruption, Chelsea was managed by

Table 1 2020 sociodemographic characteristics of Chelsea, Holyoke, and the Commonwealth of Massachusetts (US Census, 2021; US Census, 2019)

Selected demographic variables	Chelsea	Holyoke	Massachusetts
Total population	40,787	38,238	7,029,917
Race			
White	48.4%	87.5%	80.6%
Black	6.4%	4.5%	9.0%
Other	45.2%	8.0%	10.4%
Hispanic or Latino	67.0%	53.9%	12.4%
Educational attainment (age 25+)			
4+ Years college	18.5%	21.5%	43.7%
Household median income	\$56,802	\$40,769	\$81,215
Persons below poverty level	18.1%	29.3%	9.4%

the Commonwealth of Massachusetts from 1991 to 1995, after which local governance was restored. (The Boston Globe, 1991a, The Boston Globe, 1994). See Table 1 for 2020 US Census data for Chelsea.

Holyoke historical context

In contrast to Chelsea, Holyoke was a company town that sprung up quickly as a planned industrial community next to the Connecticut River. Specifically, a group of Boston financiers founded the Hadley Falls Company, which

funded the construction of the Hadley Falls Dam and canal system starting in 1847 (The Hadley Falls Company, 1853). The city plan, created by the company, called for dwellings 3–4 stories high, located adjacent to the industrial area, because the company believed Holyoke would eventually grow to a population of 200,000 and wanted to preserve land around the canals for mills and factories (Curran, 1960). This land use pattern shaped the present city core, while surrounding neighborhoods developed later with mostly single-family homes. By 1920, the population of Holyoke had grown to over 60,000, with dozens of mills and machine shops. The closure of some of these businesses resulted in outmigration from Holyoke, slowing down only in the 1940s due to World War II spending. Holyoke was once a major global center of papermaking, but more than half of the paper plants closed by the 1990s (Jacobson-Hardy and Weir, 1992). Due to mechanization of agriculture in Puerto Rico and the resulting mass unemployment, between 1945–1965 there was a large migration of Puerto Ricans to Holyoke, and other eastern US cities (Borges-Méndez, 2007). The magnitude of Puerto Rican settlement in Holyoke has given the city the highest percentage of Puerto Ricans of the total population of any municipality in the US, outside of Puerto Rico (Hardy-Fanta and Gerson (2002)). See Table 1 for 2020 US Census data for Holyoke.

Aerial Photo Preparation

To assess the spatial patterns and extent of UTC in Chelsea and Holyoke over time, we delineated tree canopy from digitally scanned and georeferenced aerial photos, following Nix et al. (2022). Whereas Nix et al. (2022) focused on urban parks, we expanded upon that study by applying similar methods to an entire city and an urbanized city core. Following this precedence and those of other studies on multi-decadal urban tree and forest cover (Zhou et al. 2011, Merry et al. 2014) we manually delineated tree cover polygons to create spatially illustrative datasets. We used leaf-on imagery across 62 years: 1952, 1971, 2003, and 2014 (Table 2).

Aerial photos from 1952 were stored as 9 × 9-inch (22.86 × 22.86 cm) prints at the Clark University Map

Library while the 1971 aerial photos were stored as negatives at the US Department of Agriculture Aerial Photography Field Office located in Salt Lake City, Utah. Both sets of images had 1:20,000 resolution, and individual images had an approximate extent of 20 km². We scanned the image sets into either Tagged Image File Format (TIFF) or GeoTIFF and prepared for georeferencing. We cropped the images that covered the study area (Chelsea—two images per year; Holyoke—4 images per year) to remove registration marks and edge distortion. We used United States Geological Survey (USGS) imagery from 2014 with 30 cm resolution (MassGIS, 2019) for the georeferencing process. We selected this USGS imagery because it has higher resolution than the NAIP imagery (1 m) used in this project and because it shares the same projection as the NAIP imagery: NAD83/UTM Zone 18N (for western Massachusetts) or 19N (for eastern Massachusetts).

We selected ground control points (GCP) to connect the 2014 USGS imagery to the 1952 and 1971 aerial photos, favoring hard-edged GCPs (i.e., building/roof corners, street and sidewalk intersections, monuments) as they are locations that normally do not change position over time and usually lead to lower Root Mean Square Error (RMSE) (Hughes et al. 2006). On average, 14.3 GCPs were used per image—removing or replacing some that had abnormally high RMSE values (>15 m). By keeping first order RMSE within an acceptable level (Berland, 2012, Baily and Inkpen (2013)), we applied second or third order polynomial transformations to the images based on levels of alignment and distortion, which led to an average RMSE of 2.97 m. Post georeferencing, we mosaicked the images together to create a final composite of each study area.

Manual Delineation of UTC Cover

We created a set of rules (Table 3) to accurately and consistently digitize polygons of canopy cover, adapting rules used by Zhou et al. (2011) and Nix et al. (2022). We used a minimum polygon size of 7 m² as the threshold for a minimum mapping unit, similar to Gillespie et al. (2012). This mapping unit was the smallest unit at which a juvenile tree could be consistently recognized by an interpreter based on its shape and corresponding shadow. Displacement can

Table 2 Imagery data table

Year	Resolution	Type	Source
1952	1:20,000	Black and white film	USDA Agriculture Stabilization and Marketing Service ^a
1971	1:20,000	Black and white film	USDA Farm Service Agency ^b
2003	1 m	Color film	USDA National Agriculture Imagery Program
2014	1 m	4 Band digital	USDA National Agriculture Imagery Program

^aClark University Map Library

^bUSDA Aerial Photography Field Office

cause small amounts of error between each year of UTC cover polygons (primarily in georeferenced datasets). When placed over one another, the polygons will look offset from each other, but such errors can be reduced by utilizing the stated minimum mapping unit. As suggested by Zhou et al. (2011), we employed a minimum area of change across these metrics (7 m², the same as the minimum mapping unit), to reduce the effects of misregistration and small amounts of edge change that may not be considered as real change. Some shrub cover was also included in the delineation of tree cover as there is no way to entirely differentiate the two in a two-dimensional image (Nowak and Greenfield, 2020, Roman et al. 2017).

All imagery used in this study was leaf-on, therefore some edges of tree canopy were obscured by shadow. Table 3 describes the rules that were used for reducing delineation error due to shadow effects and for identifying canopy

Table 3 Rules for delineation of tree canopy polygons

1. Tree canopy polygon area must be greater than or equal to 7 m². Polygons smaller than this can be removed post delineation.
2. Remove treeless gaps within a canopy cover polygon if groundcover is identifiable and the gaps are not dominated by shadow. e.g., open space in a forested patch.
3. Use shadow to aid in discernment of tree canopy versus shrub (i.e., a juvenile tree would produce a visible, angled shadow denoting its height, while low-to-ground shrubs would not have this trait).
4. Use visual obstruction of objects (i.e., sidewalks, rooflines, roads) by tree cover to aid in identification.
5. Edges of delineated tree canopy that extend beyond the study area boundary should be clipped to said boundary post delineation.
6. A variable viewing scale of 1:400 to 1:1000 was used across all imagery during delineation.

cover versus other types of cover (i.e., shrub cover, grass cover, impervious surface). The other dates of imagery used in this study assisted in the interpretation and delineation of UTC. We used one interpreter for the study to promote consistency, with validation areas being delineated by a second interpreter (Berland, 2012, Roman et al. 2017, Nowak and Greenfield, 2018, Roman et al. 2021).

Canopy Cover and Error Assessment

We assessed UTC metrics according to the computational definitions in Table 4. Then we made gain/loss/persistence maps for each time interval of the study period: 1952–1971, 1971–2003, 2003–2014 (Pontius et al. 2004). Notably, *persistence* in UTC can be computed relative to a given study area (e.g., the entire city) or relative to the initial canopy from the earliest time period. For instance, considering the pairs of images just mentioned (1952–1971, 1971–2003, 2003–2014), we calculated persistence both as a portion of the entire study area, and as a portion of the canopy area from the first image (1952, 1971, and 2003, respectively).

However, while persistence is often discussed in relation to only 2 years of imagery (Pontius et al. 2004, Locke et al. 2017), the notion of where canopy persists can be extended beyond this to span more than 2 years of imagery, and the intersection of persistence across multiple time periods. When more than two images are compared, we considered *stable canopy* as that which was tree cover across multiple images, adapting Roman et al. (2021). More specifically, as with persistence, stable canopy can be calculated in relation to a given study area or relative to initial canopy from the earliest time period.

Table 4 Definitions for urban tree canopy (UTC) metrics used in this paper

UTC metric	Computational definition
UTC	The area of delineated tree canopy for a given year, divided by the area of the study area.
UTC net change	For 2 years of UTC, the percentage point increase or decrease in tree canopy. O’Neil-Dunne (2017) refers to this as “absolute change” in UTC.
Persistence relative to initial canopy area	For 2 years of UTC, the overlapping tree canopy area between those 2 years is divided by the tree canopy area of the earliest year of the pair. In other words, the portion of initial canopy from the first date that remained canopy in the second date.
Persistence relative to study area	For 2 years of UTC, the overlapping tree canopy area between those 2 years is divided by the study area. In other words, the portion of the entire study area that was canopy in both years.
Stable canopy relative to initial canopy area	For more than 2 years of UTC, the intersected area of tree canopy from all available years is divided by the tree canopy area of the earliest year. In other words, the portion of initial canopy from the first date that remained canopy in all subsequent years of available UTC. Roman et al. (2021) referred to this as simply <i>stable canopy</i> .
Stable canopy relative to total study area	For more than 2 years of UTC, the intersected area of tree canopy from all available years is divided by the study area. In other words, the portion of the entire study area that was canopy throughout all available years of UTC.
Maximum saturation	The aggregated area of tree cover across the entire study period (i.e., spaces that had tree in any year) is divided by the area of the study area.

Table 5 Interpreter agreement between validation areas for Chelsea and Holyoke

	Interpreter agreement			
	1952	1971	2003	2014
Chelsea	96.92%	97.77%	96.46%	96.48%
Holyoke	93.66%	95.09%	93.34%	95.66%

We also propose a new UTC metric, *maximum saturation*, which is defined as the aggregated area of tree cover across the entire study period (i.e., spaces that had tree cover in any year), divided by the area of the study area. This metric is useful for understanding what the potential maximum of UTC could be across the study area, based on past and current land cover. The metrics we used in this study are reported on the scale of the total study area for each city (i.e., the entirety of Chelsea and the urbanized core for Holyoke), and then at the neighborhood scale.

Discrepancies between image interpreters can introduce error into the UTC product (Richardson and Moskal, 2014). To reduce this error, one interpreter carried out manual delineation across the entire study area while another interpreter delineated ~10% of the area to validate the replicability of the dataset. We calculated the percent agreement between interpreters (Table 5) and both cities had over 93% agreement between interpreters, similar to other studies of this nature (Roman et al. 2021, Roman et al. 2017, Zhou et al. 2011). Both interpreters' tree cover estimates were close, with the average difference across all years in Chelsea being 0.54 percentage points and 1.80 percentage points in Holyoke. We calculated detectable change thresholds for each city following Roman et al. (2021). For the entirety of the 62-year study period, UTC changes larger than 1.07 percentage points in Chelsea and 4.76 in Holyoke will represent detectable change.

Historical Research

This study follows other research that uses qualitative historical narrative to explain quantitative UTC change (Roman et al. 2017, Roman et al. 2021, Ogden et al. 2019). In order to link UTC change with local history, we consulted local archivists at the Chelsea Public Library Historical Archives, Holyoke Public Library History Room and Wistariahurst Museum about published histories and articles regarding Chelsea and Holyoke and concerning potential drivers of UTC change during the study period. They suggested various sources, such as published histories and articles (e.g., Curran, 1960, Harper, 1973, Lake, 2011), and public budgetary and planning documents (e.g., Presley Associates Inc., 1999, City of Chelsea, 2006, City of Holyoke, 2017), which led to backward and forward

chaining to identify pertinent articles. This information provided a contextual backdrop for the underlying issues affecting each city, such as large infrastructure developments, significant racial change, and municipal budget cuts. We examined these topical leads further through newspaper articles using the database of newspapers.com (Ancestry, 2021). We investigated the processes behind large UTC changes detected in the imagery using the resources mentioned above; site investigations across the imagery verified the types of change taking place (i.e., vacant site in one time period has apartments in the next). Collectively, all this information was used to uncover major local events and processes that impacted UTC spatiotemporal patterns.

Results

Chelsea: Canopy Cover

Between 1952 and 2014, UTC cover more than doubled in Chelsea (+6.41 percentage points), far higher than the detectable change threshold (1.07), indicating that UTC change was meaningful. The largest UTC increase took place between 1952 and 1971 (Table 6). Both persistence metrics increased over the study period (Figs. 2–4) with the largest amounts of persistence from 2003 to 2014 (Table 7; Fig. 4). This is because the 2003–2014 time interval is shorter than the others, which inflates the percentage. However, the growth of persistence UTC also suggests that areas consistently covered by tree cover are growing. The low portion of Chelsea that has been consistently covered by UTC (0.87%) in all images (i.e., stable canopy metrics, Table 8) reflects the already low canopy cover found in Chelsea (Table 6), but also the high level of UTC turnover taking place—that is, the readily visible gain and loss in each time interval (Figs. 2–4). The spatiotemporal dynamism of UTC in Chelsea is also reflected by the stable canopy relative to initial canopy area, which is 14.08%. In other words, only 14.08% of the UTC present in 1952 remained tree covered in all subsequent images. The maximum saturation of UTC for Chelsea was 24.71%, with a breakdown by neighborhood in Table 9.

Figure 5 shows the neighborhoods of Chelsea and the UTC levels in each year of the study. Every neighborhood except for Everett Avenue, Mill Hill, and Addison Orange had net gains of ~5% points of UTC. Everett Avenue, Mill Hill and City Center had the lowest maximum saturation but also appear to have had the highest levels of impervious surface in the city and the least greenspace. The residential neighborhoods of Shurtleff Bellingham, Soldier's Home, and Prattville all increased in canopy cover, while Addison Orange declined.

Table 6 Urban tree canopy (UTC) cover metrics for Chelsea and Holyoke for each year in the study as well as the overall net change of urban tree canopy from 1952 to 2014

Year	Chelsea		Holyoke	
	UTC (m ²)	UTC (%)	UTC (m ²)	UTC (%)
1952	355,439.5	6.20	1,924,237.1	18.79
1971	553,315.6	9.65	1,900,202.8	18.56
2003	623,431.4	10.87	2,328,049.2	22.73
2014	723,109.4	12.61	2,157,104.4	21.06
1952–2014 Net change	+367,669.9	+6.41	+232,867.3	+2.27

Table 7 Persistence relative to initial canopy area and persistence relative to study area urban tree canopy metrics for Chelsea and Holyoke for each time interval in the study

Year	Persistence relative to initial canopy area (%)		Persistence relative to study area (%)	
	Chelsea	Holyoke	Chelsea	Holyoke
1952–1971	37.07	48.47	2.29	9.11
1971–2003	37.02	57.61	3.57	10.69
2003–2014	59.68	67.98	6.49	15.46

Table 8 Stable canopy relative to initial canopy area, stable canopy relative to study area, and maximum saturation urban tree canopy (UTC) metrics for Chelsea and Holyoke from 1952 to 2014

UTC metric	Chelsea	Holyoke
Stable canopy relative to initial canopy area (%)	14.08	27.30
Stable canopy relative to study area (%)	0.87	5.13
Maximum saturation (%)	24.71	40.92

Chelsea: UTC Historical Change and Context

1952–1971

Construction of the double decker Tobin Bridge (1948–1950) and the Route 1 highway (1956–1958) in Chelsea split the city in two. Many residential properties were demolished (Lake, 2011) and canopied thoroughfares were cleared so Boston could have better connections to neighboring towns. Streets were also widened, leaving little to no space for street trees. In other parts of Chelsea, residential areas lost canopy to densification as apartment buildings were built and some vacant and other properties were built up for multi-family housing. The Everett Avenue neighborhood had industrial properties built on aggregated smaller properties that previously had tree canopy on their property. The Prattville neighborhood had new housing built on vacant lots which led to some tree loss, but most of the change there is from UTC turnover.

Properties with steep inclines around the Soldiers Home neighborhood were never built on and have filled in with vegetation over time. Similar growth occurred in the Admiral's Hill neighborhood around the US Naval Hospital. Edges along railroad corridors saw increased canopy cover as well as vacant and under-developed properties. Patches of canopy cover growth were seen in residential areas across the city and were especially strong in Prattville, where the properties are slightly bigger with more greenspace.

1971–2003

In 1973, a large fire destroyed most of the Everett Avenue neighborhood, including the canopy. The burned area was redeveloped into an industrial park and large retail mall (Lake, 2011) and the site appears to have more impervious surface than the previous land use, while trees were planted along the periphery and streets. The US Naval Hospital, in the Admiral's Hill neighborhood, was closed in 1974 and donated to the Commonwealth of Massachusetts and the City of Chelsea (The Boston Globe, 1974b). The waterfront area around the Naval Hospital became a state park, locking in the greenspace for public use and UTC growth. The remaining area of the Naval Hospital was developed into apartments and condos, reusing some existing Naval Hospital buildings and constructing several new ones (The Boston Globe, 1983), which resulted in canopy loss. Canopy growth expanded most in the state park and in steeper incline areas where development was more difficult. New housing and commercial developments were built in the Soldier's Home, Mill Hill, and Shurtleff Bellingham neighborhoods and were responsible for UTC loss, which was visible from the aerial photos. Most of the new housing that was built were apartments and townhomes with only one small section where single-family homes were built in Mill Hill. Further densification seems to have taken place as properties were developed/redeveloped.

Many of the larger visual UTC gains came from vacant, undeveloped, and edge areas across the city, for example, properties bordering Route 1 (Fig. 3). A commercial area in the Soldier's Home neighborhood has highly visible UTC growth but across the city most UTC growth was constrained to smaller properties. Public parks saw an increase in UTC, as well as some streets in the Shurtleff Bellingham neighborhood, which were recipients of a 1994 Massachusetts Department of Conservation (DCR) street tree planting grant (Massachusetts DCR, 2008). In 2001, the city started its own tree planting campaign (The Boston Globe, 2001), but details on the number of trees planted are unavailable. The city received another DCR tree planting grant in 2002 (Massachusetts DCR, 2008).

Other highly visible changes were the high amounts of turnover taking place in the residential neighborhoods. Street tree canopy loss seems to be taking place at a higher level in Prattville, when compared to other residential neighborhoods

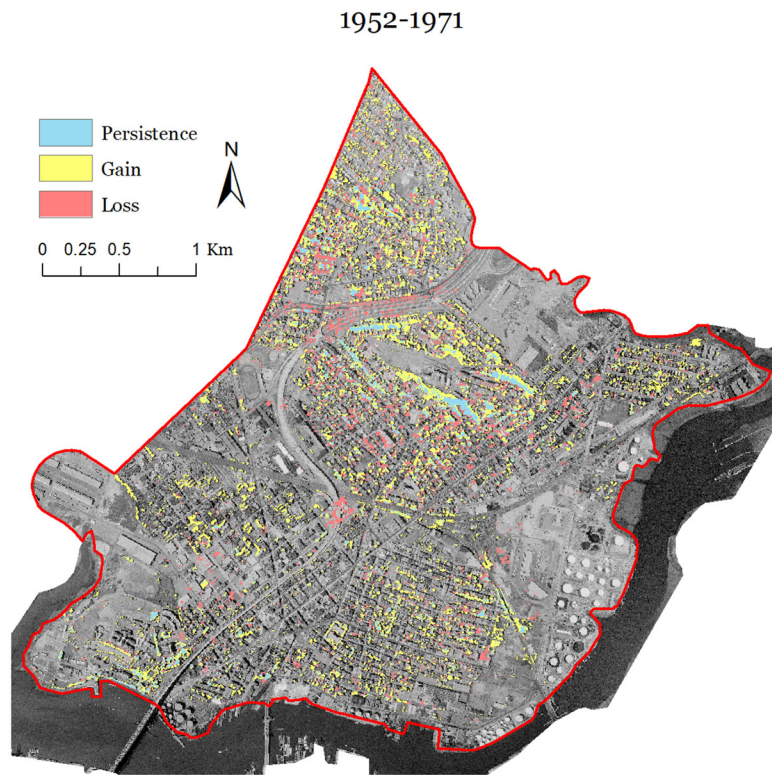


Fig. 2 Urban tree canopy gain, loss and persistence in Chelsea from 1952 to 1971 with 1971 imagery as the background

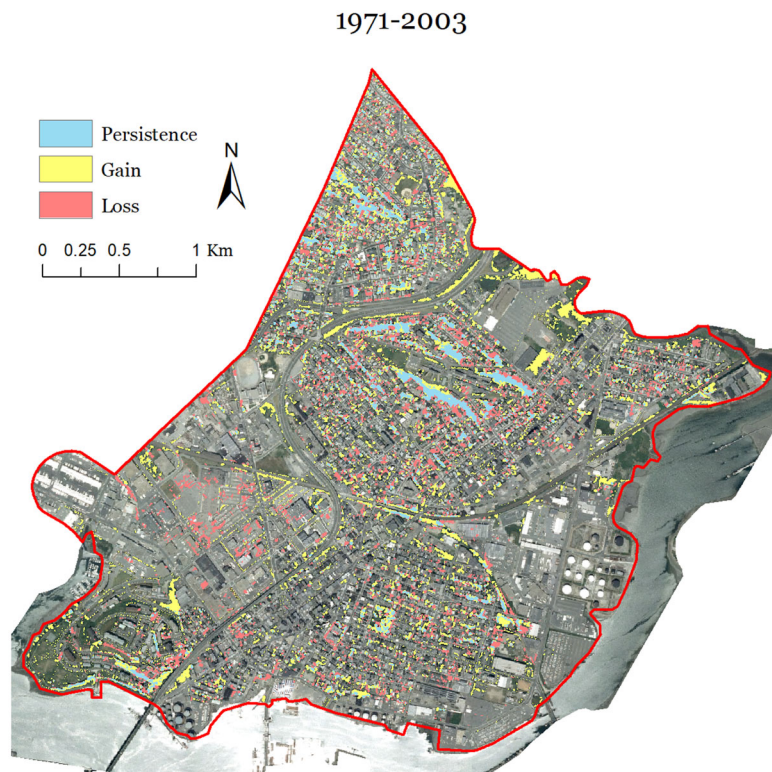


Fig. 3 Urban tree canopy gain, loss and persistence in Chelsea from 1971 to 2003 with 2003 imagery as the background

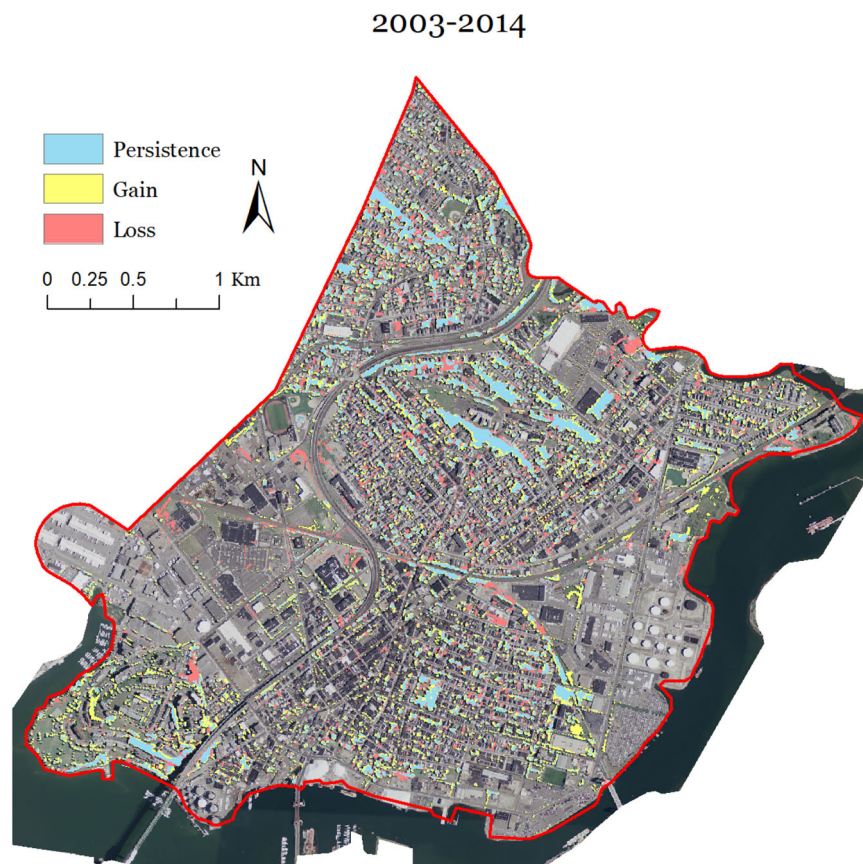


Fig. 4 Urban tree canopy gain, loss and persistence in Chelsea from 2003 to 2014 with 2014 imagery as the background

of Chelsea. UTC may also have been impacted during this period due to a budget crisis and storm damage. As noted earlier, the city of Chelsea went into receivership in 1991, with budgets cut back to essential services only (The Boston Globe, 1992), but there was no specific mention about tree care. Also in 1991, Hurricane Bob hit several New England states causing widespread damage to infrastructure and trees (The Boston Globe, 1991b). Other large storms of note also passed through in 1993 and 1997.

2003–2014

Post-2000, Chelsea experienced economic renewal. When Chelsea left receivership in 1995, it had solid fiscal footing and was able to invigorate several areas of the city with new development, which was then associated with UTC loss. New apartment and assisted living developments in the Shurtleff Bellingham, Mill Hill, Addison Orange, and Admiral's Hill neighborhoods visibly reduced UTC. Commercial areas were developed/redeveloped in the Prattville, Soldier's Home, and Everett Avenue neighborhoods, with the latter being one of the most important, as it replaced a failing mall with a new transit-oriented development. Parts of the mall were demolished (The Boston Globe, 2007), and the property was relandscaped with

new trees planted. Other commercial sites in Chelsea cleared emergent or weedy tree growth from their property. Some vacant properties were also cleared, for instance, a brownfield site situated in the Mill Hill neighborhood. Trees had been cut and a windmill installed, but further development halted as funding evaporated in 2009 (The Boston Globe, 2013).

Other undeveloped and vacant properties in Chelsea saw UTC growth, but across fewer sites in this period. In the Admiral's Hill neighborhood UTC growth continued to expand in steeper incline areas, and increase along streets, open spaces, and in the state park. There was also an increase of UTC along several streets in the Everett Avenue and Shurtleff Bellingham neighborhoods.

During this period, UTC turnover is evident, but overall there was UTC gain across the city. Several factors played a role in this outcome such as tree planting grants, zoning regulation, and management. Capital Improvement Plans (City of Chelsea, 2006, 2010, 2014)—5-year urban planning implementation reports—consistently mentioned street tree planting, but without any specific details. A 2008 budget report detailed specific tree planting by the city's Public Works department the previous year (63 trees) as well as a DCR grant of \$15,000 for planting 60 more trees (City of Chelsea, 2008). Chelsea also received tree planting



Fig. 5 Chelsea neighborhoods with 1952 imagery as the background

Table 9 Chelsea neighborhood breakdown of urban tree canopy (UTC), stable canopy relative to initial canopy area and maximum saturation

Neighborhood	1952 UTC (%)	1971 UTC (%)	2003 UTC (%)	2014 UTC (%)	Stable canopy relative to initial canopy area (%)	Maximum saturation (%)
Admiral's Hill-Waterfront*	3.9	7.4	10.4	14.6	20.8	22.9
Everett Avenue*	2.1	4.9	4.5	5.1	2.2	13.1
Mill Hill*	3.0	4.5	5.7	7.5	5.8	14.7
City Center*	3.5	5.2	7.6	10.1	6.7	18.6
Shurtleff Bellingham*	5.2	10.1	11.8	15.2	12.8	27.3
Addison Orange*	14.1	14.5	12.9	12.8	8.1	35.0
Soldier's Home*	10.1	16.4	19.6	21.9	29.6	36.6
Prattville*	12.9	18.9	20.0	19.9	12.4	42.1

Asterisk represents neighborhoods that exceeded the detectable change threshold

grants for the years 2004 and 2005 (Massachusetts DCR, 2008). Zoning regulations in Chelsea were changed in 2005 mandating requirements for new developments that outlined specific setbacks, amounts of greenspace, and the spacing of trees in planting strips (City of Chelsea, 2005). Also, in 2005 a municipal Tree Board was formed to help advise the city and to manage their annual Arbor Day planting event. That same year Chelsea joined the Tree City USA program and has continued with that program ever since. In 2012, the city received a DCR grant for an urban forest assessment, which reported the 2012 UTC with change metrics from 2004, sociodemographic analysis of UTC patterns,

and very broad, undetailed tree planting plans focused only on public spaces (City of Chelsea, 2016).

Holyoke: Canopy Cover

Between 1952 and 2014, UTC in the Holyoke study area increased by 2.27 percentage points (Table 6), which is lower than the detectable change threshold (4.76), meaning that the total level of UTC largely remained the same across Holyoke during the study period. However, our change maps show UTC turnover occurring throughout the study area. For example, the persistence map of 1952–1971 (Fig. 6) shows many small areas

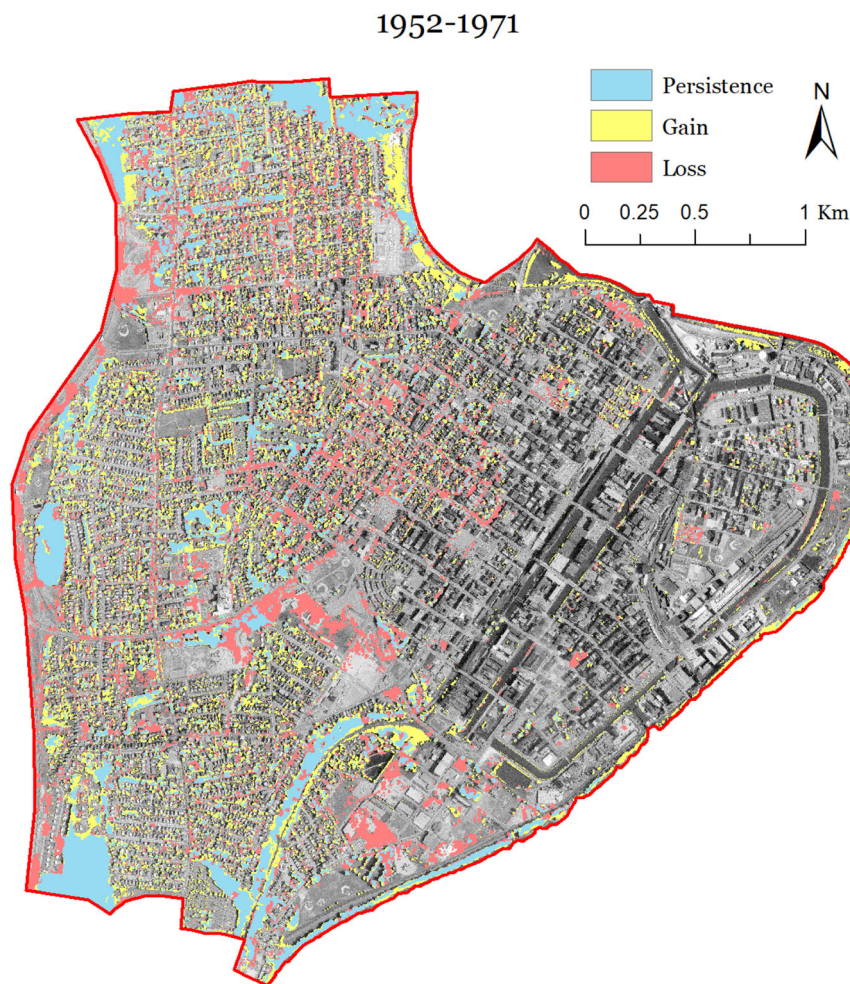


Fig. 6 Urban tree canopy gain, loss and persistence in Holyoke from 1952 to 1971 with 1971 imagery as the background

of loss and gain. UTC cover did have a more than a 4% point gain in 2003 and is visually affirmed in the persistence map of 1971–2003 (Fig. 7) with the overwhelming yellow areas signifying the areas of gain, while there was an UTC loss from 2003 to 2014 (Fig. 8). Additionally, Fig. 8 shows large areas of persistence, and as with Chelsea, this is due to the time period of 2003–2014 being much shorter than the others in this study. However, the overall change in persistence signifies that areas consistently covered by tree cover are growing. The low levels of stable canopy in Holyoke (i.e., the portion of land covered by tree in all images, Table 8) are higher than in Chelsea, reflecting the generally higher UTC found in Holyoke, but, like Chelsea, denotes that a high amount of UTC turnover has taken place. The high amount canopy turnover in Holyoke is further supported by the stable canopy relative to initial canopy area (Table 8) which is 27.30%. Therefore, just above one-quarter of the original area covered by canopy in 1952 remains covered in all subsequent images. The maximum saturation of UTC for Holyoke was 40.92%.

Figure 9 shows the neighborhoods of Holyoke and Table 10 shows UTC levels for each neighborhood and year of the

study. Three neighborhoods—The Flats, South Holyoke, and Downtown—had the highest net growth, with an approximately 5 percentage point increase or more in UTC. These three neighborhoods appear to have some of the highest levels of impervious cover in the city and the least amount of greenspace, as they are mostly comprised of commercial and industrial areas. Along these lines, the maximum saturation is lower in the aforementioned three neighborhoods in comparison to the more residential neighborhoods of Highland, Oakdale and Elmwood. These three neighborhoods, made up of predominantly single-family homes, have the most consistent UTC percentage across the study period.

Holyoke: UTC Historical Change and Context

1952–1971

UTC losses due to construction played a large role in Holyoke's changing landscape in this period. Construction of Interstate 91 (1965) cut through the last remaining

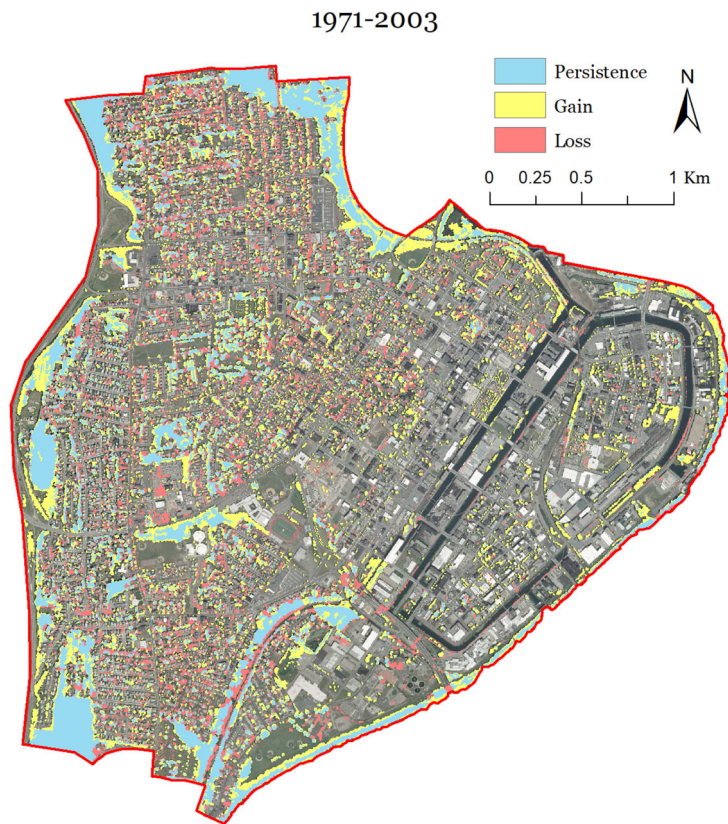


Fig. 7 Urban tree canopy gain, loss and persistence in Holyoke from 1971 to 2003 with 2003 imagery as the background

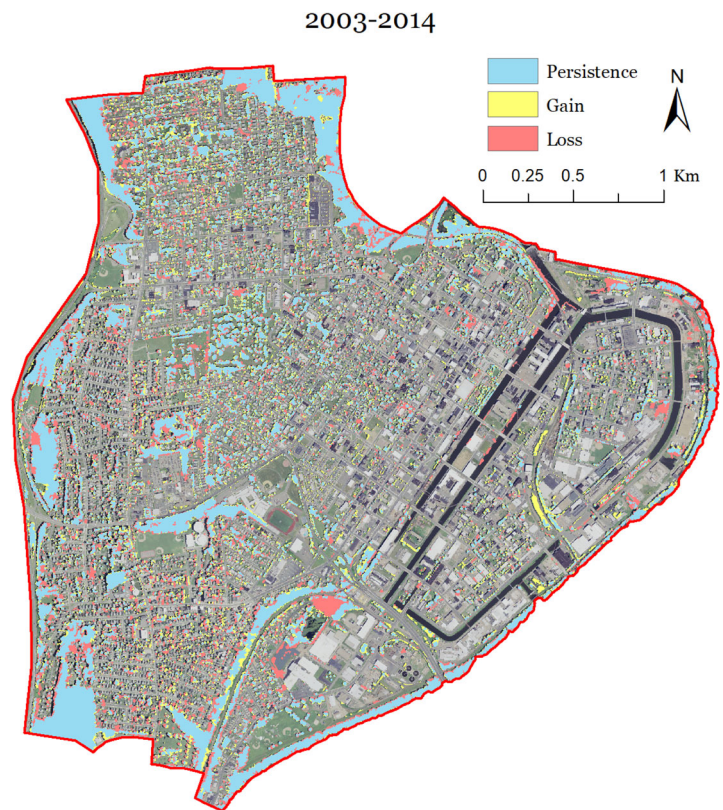


Fig. 8 Urban tree canopy gain, loss and persistence in Holyoke from 2003 to 2014 with 2014 imagery as the background



Fig. 9 Holyoke neighborhoods with 1952 imagery as the background

Table 10 Holyoke neighborhood breakdown of urban tree canopy (UTC), stable canopy relative to initial canopy area and maximum saturation

Neighborhood	1952 UTC (%)	1971 UTC (%)	2003 UTC (%)	2014 UTC (%)	Stable canopy relative to initial canopy area (%)	Maximum Saturation (%)
The Flats*	2.9	6.0	13.2	12.3	24.1	20.6
South Holyoke*	2.9	4.4	9.4	11.5	21.9	17.4
Downtown*	8.7	8.2	14.7	13.6	6.8	27.3
Churchill	7.1	5.2	7.6	9.6	8.3	18.9
Highlands	30.6	30.8	33.0	32.4	29.4	59.5
Oakdale	25.0	24.7	28.2	25.4	24.2	51.7
Elmwood	25.8	25.4	28.6	25.0	32.6	50.9
Springdale	22.5	18.9	23.9	18.8	24.1	43.1

Asterisk represents neighborhoods that exceeded the detectable change threshold

orchards and agricultural areas, as well as some forested patches along the western boundary of the study area. This construction reshaped major roadways in the city as arterial roads connecting to the highway were widened and mature street trees and plantable strips were removed. Street widening also seems to be the cause of street tree loss in the neighborhoods of Downtown, Oakdale and Churchill. Some streets completely lost all roadway planting spaces, while others were reduced in size. There

was a large loss of mature street trees during this time period. The Springdale and Churchill neighborhoods had the most remaining undeveloped properties in 1952 but were subsequently built by 1971. The construction of a high school (1964) and middle school (1973) in the Elmwood neighborhood removed canopy on forested land that was previously part of a public park (Sanborn Map Company, 1956, Harper, 1973). Several other public parks lost tree canopy for an array of reasons: one factor could

have been *Ophiostoma* sp., or Dutch Elm Disease (DED), which afflicted Massachusetts during this period, with half a million trees lost across the state from 1941 to 1974 (The Boston Globe, 1974a). The full impact of DED in Holyoke is not known, but records from the Municipal Register of the City of Holyoke (an annual budget report) show expenses related to DED from 1949 to 1963, with 1963 being the last budget year in the archival collection (City of Holyoke, 1920–1963). These budget records also shed light on the nature of tree planting taking place in Holyoke. Prior to DED, tree planting was variable from year to year and may have completely stopped during World War II, due to funding cuts (City of Holyoke, 1920–1963). The budget records show tree planting starting again in 1954 and continuing every year through 1963 (when the record ends), seemingly to replace trees lost to DED (City of Holyoke, 1920–1963). Another factor that may be responsible for UTC loss is weather: three hurricanes hit western Massachusetts between 1954 and 1955, which downed trees and caused flooding (The North Adams Transcript, 1954, The Berkshire Eagle, 1954). Two of the hurricanes struck in 1954 and the Holyoke budget records show a special expense in that year for storm damage (City of Holyoke, 1920–1963). These factors may also explain the high amount of tree canopy turnover taking place in residential areas, mainly in the neighborhoods of Highland, Oakdale and Elmwood.

Canopy gain in this period was mainly on residential property with other notable gains on undeveloped and vacant properties in industrial areas and along railroad lines. We also observed UTC gains along the Connecticut River edge but have not identified a driver of this gain from the archival records. In the 1952 imagery, the shoreline of the river was mostly clear of brush and trees, presuming that it had been mowed, but in the 1971 imagery forest emergence is seen.

1971–2003

Visible UTC losses during this period came from the expansion of the Holyoke Medical Center and water treatment plant (Valley Health & Life, 2018, MassLive (2014)). Road construction for Interstate 391 (completed 1982) on the border of the Springdale and South Holyoke neighborhoods led to canopy loss as streets were widened and lanes added to develop the ramps needed for the interstate. Wistariahurst, a public historical center and garden, was a heavily canopied greenspace in the Churchill neighborhood in 1952. By 2003 the majority of UTC had been lost, with the property-surrounding street trees almost all removed without replacement, while the grounds maintenance of Wistariahurst primarily consisted of “vegetation removal and keeping the lawn areas mown”

(Presley Associates Inc., 1999). Public parks also saw canopy loss during this period. Another notable loss of UTC can be seen along the canals in thin strips. Hundreds of flowering trees had originally been planted along the canals between the late 1940s and early 1970s (Harper, 1973). By 2003, many of these trees appeared to have died or been removed.

This period saw the largest increase of UTC overall. The imagery details canopy growth along the river edge, as well as emergent forest on undeveloped properties and abandoned vacant industrial properties (Jacobson-Hardy and Weir, 1992). However, many of the vacant lots in the Churchill neighborhood [products of urban renewal projects that demolished many buildings in the older parts of the city (City of Holyoke, 2017)], and rebuilt housing in the Downtown and The Flats neighborhoods, were not areas of tree canopy growth. The rebuilt housing replaced former three-to-four story, apartment-style, stacked tenement housing with duplexes or multi-family townhomes (City of Holyoke, 2017). This new housing had larger yards and expanded plantable space for trees, but UTC growth in these areas is much smaller than the emergent forest seen on vacant industrial properties. Public spaces such as parks and schools in the Downtown and Churchill neighborhoods saw an increase of tree canopy, especially as trees matured and increased their canopy size. Other city parks saw expansion of their canopy as greenspace areas filled in, although it is unclear whether this park canopy growth was due to planting, unintentional forest emergence, or both. Properties abutting Interstate 91 saw an increase of canopy directly next to the interstate. Some of the canopy gain during this period may have been due to tree plantings that took place in 1995, 2001, and 2003, made possible by grant awards by the DCR (Massachusetts DCR, 2008).

2003–2014

Major areas of UTC loss for this period are mostly tied to development of new or previously underused properties. For example, commercial development led to visible UTC loss in the Springdale neighborhood while industrial properties in The Flats reclaimed overgrown land. Downtown lost UTC around the canals as new investments for an innovation area led to a publicly accessible canal walkway and the building of the Massachusetts Green High Performance Computing Center (The Boston Globe, 2012, 2016a). As in previous time periods, public spaces faced UTC loss as parks were remodeled and expanded. For example, part of a forested city park was cut down for a new dog park (MassLive (2012)). The city library was renovated, and several large trees were removed to accommodate construction (The Boston Globe, 2016b, MassLive (2011)).

The major areas of UTC growth were visibly constrained to unintentional forest emergence along a rail line and vacant properties in South Holyoke. Much smaller gains scattered throughout the study area may be the result of crown expansion of surviving trees, and resident and/or city tree planting. In 2004, the city received a grant from the DCR for tree planting in its Downtown neighborhood (Massachusetts DCR, 2008).

Discussion

Our analyses illustrate the spatiotemporal variation of UTC across two cities. The UTC level in Holyoke was mostly steady across the study period, but saw large changes to its geographic distribution, similar to the findings from Merry et al. (2014) for Detroit and Atlanta between 1951 and 2010. In contrast, Chelsea saw a large increase in UTC during the study period, and this city also witnessed large changes in UTC distribution. Overall, both cities had low levels of stable canopy, with some differences across neighborhoods, and high amounts of turnover taking place in residential areas. Urban development, disease, storms and other factors can partly explain the low stability and high turnover, but more needs to be understood about UTC in residential neighborhoods, as they typically have higher levels of UTC, stable canopy, and greenspace for planting. Residential neighborhoods contain large portions of tree canopy in many cities (Nguyen et al. 2017), so future research should investigate the drivers of tree cover gains and losses on residential properties.

Urban form constrains or enables the trajectory of each city and neighborhood to gain UTC, particularly in terms of the amount of non-impervious plantable space (Roman et al. 2018, Ossola et al. 2019). Holyoke's industrial neighborhoods exemplify this phenomenon, as such neighborhoods have the lowest UTC, with residential neighborhoods having the highest. While other studies have found spatial relationships among land use, urban form, and UTC change (Ossola et al. 2019, Pham et al. 2017), more research is needed regarding long-term UTC dynamics in industrial and post-industrial urban landscapes, particularly planned industrial areas like Holyoke. Notably, land use and urban form are far from permanent (Kane et al. 2014), and land use changes can impact the availability of UTC. Urban renewal had little direct effect on increasing UTC in Chelsea and Holyoke. Chelsea's urban renewal funding led to the creation of an industrial park (Lake, 2011) while Holyoke's produced vacant lots, but they were seemingly maintained to suppress vegetation growth. Evidence from other post-industrial cities like Baltimore and Philadelphia demonstrate that urban renewal can result in increased UTC in a variety of ways: urban renewal funding sponsored the

planting of street trees, and buildings that were demolished and abandoned through urban renewal policies became sites of unintentional forest emergence (Merse et al. 2009, Roman et al. 2021). Other post-industrial and suburbanization processes such as highway construction and shifting economies had substantial impacts on UTC change in our study cities. Currently, both Holyoke and Chelsea are struggling to overcome the legacies of highway building. Both cities lost greenspace and UTC to highway construction, but also, surrounding streets were widened, resulting in the shrinking or removal of street tree planting strips. Similar impacts have been recorded in other US cities due to highway construction and street widening (McPherson and Luttinger, 1998, Merse et al. 2009), but more research is needed to fully understand the historical impacts of the US highway system on UTC. Holyoke also saw forest emergence around abandoned factories, schools, and an industrial park. In Chelsea, areas rebuilt from the 1973 fire appear to have more impervious cover than previous land uses, and more recently, urban density has increased with the construction of high-density residential buildings. Roman et al. (2021) found similar connections as redevelopment construction led to lower UTC as some neighborhoods densified and/or gentrified in Philadelphia. Increasing urban density has been seen as a positive development since it can counteract the negative effects of urban sprawl (Haaland, Bosch, C.K. (2015)). Yet, it can also reduce the amount of available greenspace in a city (Brunner and Cozens 2013). Preserving trees and greenspace is critical with new developments, requiring zoning and ordinance regulations that include conserving vegetation and/or planting it as part of building and landscape design (Jim, 2004, Chojnacky et al. 2020).

UTC gains from unintentional forest emergence during years of declining municipal budgets came mostly from edge spaces and steep slope areas that are difficult to develop, similar to findings of Berland et al. (2015) where hilly terrain in Cincinnati was a primary factor for high UTC. Holyoke's shoreline became forested after these areas were seemingly abandoned. Steep slopes limited development in the hills of Chelsea, leaving some areas to be maintained greenspaces and others small forest patches. In both Chelsea and Holyoke, spaces bordering the interstate or highway were canopied consistently over time. We characterize such UTC increases as unintentional forest emergence, similar to observations by Roman et al. (2021) and Nix et al. (2022) for vacant properties and unmaintained parks in post-industrial Philadelphia.

UTC losses due to biophysical factors play a large role in UTC change. Hurricanes caused large swaths of damage across Holyoke and Chelsea. DED impacts varied, with Holyoke budgetary documents providing evidence of substantial tree loss—like other cities in New England and the

midwestern US (Roman et al. 2018)—while in Chelsea it only played a small role, if at all. An elderly archivist who lived in Chelsea all his life does not remember *U. americana* trees being discussed in the city, nor has he come upon any archival information talking about DED (B. Collins, personal communication, March 16, 2021). Therefore, past species choices and resulting loss from an invasive pathogen can explain some differences in UTC loss between Holyoke and Chelsea.

Other UTC change, both unintentional and intentional, are more broadly linked to economics. Both cities suggest an inverse relationship between wealth and UTC, contrary to other literature tying wealth to higher UTC (Roman et al. 2017, Locke et al. 2017). Specifically, we observed unintentional forest emergence during poor economic and budgetary periods, and the loss of it during economically strong periods. Some of the largest gains in UTC came from majority industrial and commercial neighborhoods where neglected and vacant properties became sites of unintentional forest patches. This effect has been seen in other post-industrial cities (Haase et al. 2014, Berland et al. 2020) and is especially prevalent for cities in forest biomes (Roman et al. 2018, Roman et al. 2021). Years later, the neglected and vacant properties have started to be reclaimed from the forest patches, with declining UTC from tree removal, and future UTC growth in these neighborhoods is constrained due to lack of greenspace. Forest emergence in edge spaces may represent a significant portion of UTC to the local neighborhood, however, such areas may not be protected greenspace and may be lost depending on the economic prospects of Holyoke and Chelsea. For land managers and urban environmental advocates, preserving unintentional forests can achieve similar ecological goals to traditional tree planting, but with less municipal investment and a greater chance of long-term success (Del Tredici, 2010), yet they will require some maintenance, otherwise overgrown forested areas may be perceived as socially undesirable weedy spaces (Brownlow, 2006, Roman et al. 2021).

More recently, a smaller amount of new canopy was formed through new economic and governance structures such as grant funding, nonprofit initiatives, new regulations and new governing bodies. Grant funding and nonprofit programs have provided small bursts of new UTC in both Chelsea and Holyoke, especially during the 2003–2014 period, but more sustainable governance structures are needed to provide a constant influx of UTC that can compensate for UTC losses each year. Chelsea has enhanced urban tree governance through zoning regulations, the addition of a tree board to the local government, and by participating in national tree programs, all which have recently helped increase UTC in the city. However, without dedicated governing and funding structures (i.e., tree-focused municipal departments, city budget allocations

for tree planting) sustainable canopy growth and retention cannot be achieved. Simply funding tree planting is not enough to increase the UTC, as newly planted trees require high levels of tree stewardship to ensure long-term survival and growth to fulfill UTC goals (Roman et al. 2015). Trees also require plantable greenspace, which is minimal in some dense neighborhoods in Chelsea and Holyoke, similar to other post-industrial cities in the northeastern US (Nguyen et al. 2017). The maximum saturation metric used in this paper uncovers the total extent of UTC across each city, which can help shape long-term UTC goals because it represents an approximate UTC maximum. By breaking it down further to the neighborhood level, feasible UTC goals that can be tailored to individual neighborhoods. This can impact how, where, and with whom tree planting programs focus their time and energy.

The availability of imagery for this research exposed how the scaling of time intervals effects affects visible UTC change. The first two time periods of this study cover 19 and 32 years of change respectively, while the last time period covers 11 years. These different time intervals display varying levels of UTC change and persistence. Measuring UTC over longer periods shows broad levels of change and low levels of persistence while shorter periods show specific UTC changes and high levels of persistence. These differences in temporal scale can be used to aid specific research goals, like understanding the spatial and historical factors of UTC, or small amounts of change that occur after a small number of years in response to new tree regulations or planting programs. As UTC mapping progresses in more cities, temporal scaling and other metrics can be used to analyze specific or broad levels of UTC change.

This study broadly concurred with drivers of UTC change identified in other post-industrial cities located within forested biomes, like Philadelphia, Cincinnati and Baltimore. Therefore, the UTC cover changes that played out in Chelsea and Holyoke may be indicative of broader changes that have taken place in post-industrial cities located within forested biomes. Our results cannot necessarily be generalized to cities with different socioeconomic histories or ecological conditions and further research is needed to compare long-term UTC spatiotemporal patterns across cities with divergent socioeconomic and ecological contexts.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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