Spatial Analysis of Street Tree Condition and Proximity to Gas Leaks and Leak-Prone Infrastructure

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Abstract

Despite the environmental pollution associated with fracking and aging infrastructure, natural gas usage and reliance is projected to increase in the United States (U.S.) in coming years. Continuing reliance on this fuel source will not be a sustainable option moving forward, due in large part to the methane (CH_4) pollution from leaking aged natural gas infrastructure. Therefore, improving the scientific knowledge of the environmental and public health consequences associated with natural gas energy is crucial. This study focuses on the interaction of leaking natural gas distribution pipelines and street trees in Massachusetts (MA). In cities, natural gas distribution pipelines are becoming a significant source of fugitive CH_4 pollution, especially in MA where more than 11% of the distribution network is made of leak-prone materials, such as cast iron. As natural gas leaks from a pipeline beneath the streets, CH_4 can travel through soils in tree pits and escape into the atmosphere. While there are studies that explore the detrimental effects of CH_4 in a soil environment, there has been little research studying the spatial distribution of sick and/or dying street trees and their proximity to gas leaks.

This study aims to determine whether there is a significant relationship between sick and/or dying trees and their proximity to a gas leak. Publicly available data from street tree inventories done in Chelsea, MA was utilized along with publicly available data of the location of gas leaks, as reported by the gas utilities to the MA Department of Public Utilities. Additional data was collected using Google Street View (GSV) and the novel data collection tool “Underground Utility V1.2” to record street markings painted by the utilities labeling pipeline characteristics, such as pipe material and diameter. Utility companies use spray-painted markings to denote the location of underground pipes in a construction zone. Spatial statistical tests will be conducted to determine if there is a significant relationship between the condition of street trees and their nearness to a gas leak, as well as the relationship between dead trees and pipe material, where known. These analyses will be completed to support the hypothesis that dying trees and street tree dead zones are closer to gas leaks and leak-prone pipes than street trees in better condition. Upon completing the spatial analysis, findings will be validated with field measurements of soil CH_4 concentrations in tree pits.

From this analysis, a risk assessment model will be generated to determine which trees, given their proximity to a gas leak, leak-prone pipe, and empty planting sites are vulnerable to death because of leaking gas pipelines. Results from this study will be useful for municipalities to prioritize gas leak repair projects for the benefit of the urban tree canopy.

1. Introduction

Natural gas energy has long been depicted as a *natural* and *environmentally-friendly* fuel type, designed in part to be a bridge fuel from fossil fuels onto renewables.[1] Unfortunately, natural gas has become a dominant fuel for homes and businesses across the United States (U.S.).[2] However, research into natural gas energy has been working to debunk the myth that natural gas is an environmentally-friendly fuel type and highlighting the complex environmental damages associated with natural gas.[3] An emerging and compelling area of research is studying aging natural gas distribution infrastructure buried beneath streets in cities and towns across the U.S. As this buried infrastructure ages, the likelihood of leakage occurs. These pipes leak un-combusted natural gas, which is largely comprised of methane (CH_4), a potent greenhouse gas that is highly explosive.[4] Cities and towns have become increasingly concerned with the threat these gas leaks present, not only to the health and safety of their residents but also their significant contributions to greenhouse gas emissions in the form of fugitive CH_4. These leaking pipes have become a public health and safety concern, in addition to contributing to the city's greenhouse gas emissions.[5] Therefore, improving upon and building the scientific knowledge of the environmental and public health consequences associated with natural gas energy is crucial to inform cities and towns on energy transition policy.

As stated above, one of the main components of natural gas is CH_4, which has a higher warming potential per molecule than CO_2.[6] As of 2018, in the U.S., natural gas accounted for 34% of electric power generation,[7] and with increased demand projected on natural gas as an energy source, aging infrastructure will be put under increasing stress to meet the demand.[8] The aging natural gas distribution infrastructure is of growing concern to municipalities, as old pipes spring leaks that spew CH_4 into the surrounding environment.[9] Natural gas leaks, from extraction through distribution, are the second largest contributor of CH_4 in the country.[10] This study focuses in Massachusetts (MA) because of the intensity of the natural gas leaks problem there. In MA, more than 11% of the distribution network is made of leak-prone materials, such as cast iron, wrought iron, and unprotected steel.[11]

Threats associated with natural gas leaks include explosive hazards, climate change impacts, and decreased efficiency in gas distribution, which leads to higher utility costs.[12][13][14] In addition, gas leaks have deleterious effects on soil and tree health.[15][16] As natural gas leaks from a pipeline beneath the streets, CH_4 can travel through soils in tree pits and escape into the atmosphere.[17] There are studies that explore the detrimental effects of CH_4 in a soil

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[1] Howarth, 2014
[2] Howarth et al. 2011
[3] Alvarez et al. 2012
[4] Moore et al. 2014
[5] Moore et al. 2014
[6] Brandt et al. 2014
[7] EPA, 2020
[8] Hendrick et al. 2016
[9] Brandt et al. 2014
[10] EPA, 2018
[11] PHMSA, 2018
[12] Jackson et al. 2014
[13] EPA, 2020
[14] Phillips et al. 2013
[15] Adamse et al. 2972
[16] Davis, 2977
[17] Hoeks, 1972

environment, harming and/or altering both the microbial community and the roots of trees or other vegetation living in the soil.[18][19] [20] As CH_4 infiltrates a street tree pit along the side of the road, CH_4 can displace oxygen, lowering oxygen availability for tree roots and other vegetation.[21] In addition to oxygen displacement, studies have shown that elevated levels of soil CH_4 can create conditions for methanotrophs (methane-oxidizing bacteria) that further consume oxygen in the soil for energy leaving even less oxygen available for trees and other vegetation.[22]

Understanding the threat of gas leaks to street trees has important public health implications because of the variety of ecosystem services that street trees supply, especially in a dense urban area.[23] Benefits of street trees include but are not limited to, cooling effects via shading and transpiration that together lead to energy savings, CO_2 reduction, decreased air pollution, management of storm water runoff, and increased aesthetic and recreational values.[24] A recent study by Schollaert et al., focused in Chelsea, MA, provided a first-look case study on the relationship between tree health and soil CH_4 measurements. The authors found that street trees with “elevated soil CH_4 concentrations [were] associated with significant increased odds of tree death”.[25] This study aims to build on this research and conduct an analysis of the spatial relationship of sick and/or dying street trees and their proximity to gas leaks and leak-prone natural gas infrastructure in Chelsea, MA.

By performing an analysis on the spatial relationship between sick and/or dying trees and the location of unrepaired gas leaks in Chelsea, MA this study will determine whether there is a significant relationship between sick and/or dying trees and their proximity to a gas leak and/or leak prone infrastructure. Using data from multiple sources, including publicly-available gas leaks data, municipal street tree inventories, and data collected using Google Street View (GSV), spatial statistical tests were conducted to determine the relationship between gas leaks, leak-prone infrastructure, and sick and/or dying street trees. Our hypothesis was that street trees in close proximity to natural gas leaks in Chelsea, MA were more likely to be dead or showing signs of death than street trees farther away from natural gas leaks.

2. Methods

2.1 Study Area

This study was conducted in the City of Chelsea, MA. Chelsea was chosen for multiple reasons for this analysis. Chelsea is a densely populated environmental justice community just north of Boston and is unfortunately, one of the poorest communities in MA.[26] Chelsea met many criteria for the purposes of this project, due in large part to the publicly-available street tree database published in 2016 from a street tree inventory completed by arborists hired by the city, publicly-available through OpenTreeMap.[27]

[18] Adamse et al. 1972
[19] Kaye et al. 2004
[20] Smith et al. 2004
[21] Adamse et al. 1972
[22] Adamse et al. 1972
[23] Soares et al. 2011
[24] Soares et al. 2011
[25] Schollaert et al. 2020
[26] Healthy Chelsea, 2019
[27] OpenTreeMap, 2019

2.2 Street Tree Data

This project was based on spatial analysis and statistics implemented in a geographic information system (GIS), ArcGIS, produced by ESRI. The publicly-available street tree database was utilized from Chelsea, MA.[28] The street tree inventory included variables for each tree catalogued, including species, diameter at breast height (DBH), and tree condition (e.g. canopy cover, evidence of pruning, greenness in the crown). Factors included in the street tree inventory were dictated by the International Society of Arboriculture and trees were rated as Excellent, Very Good, Good, Fair, Poor, Critical, or Dead depending on the rating across factors.[29] The street tree data was projected on a GIS map.

2.3 Gas Leaks Data

The street addresses of recorded gas leaks are made publicly available annually and are reported to the Massachusetts Department of Public Utilities by the gas utilities.[30] Reported gas leaks had an address and a gas leak grade associated with each. Gas leaks are graded on a scale from 1 to 3, grade 1 being highly dangerous to humans and requiring immediate repair, while grade 2 and 3 are considered non-hazardous and are monitored every 6 to 12 months.[31] However, research has shown that leak grade does not correlate with the CH_4 flux from a leak.[32] Gas leaks were projected onto a GIS map.

2.4 Google Street View & "Underground Utility V1.2"

Using GSV, the entire road network in the City of Chelsea was navigated and locations of gas utility spray-paint markings were recorded. These markings can include information such as buried pipeline material and diameter. This data was recorded and geocoded using a tool developed by our research group called "Underground Utility V1.2" (Figure 1).[33] Street tags identifying leak-prone infrastructure, such as cast iron or wrought iron, and non-leak-prone materials, such as plastic, were added into this dataset for spatial analysis.

[28] OpenTreeMap, 2019
[29] Smiley et al. 2011
[30] DPU, 2019
[31] Mass. Gen. Laws Ch. 164 § 144
[32] Hendrick et al. 2016
[33] Ma, 2018

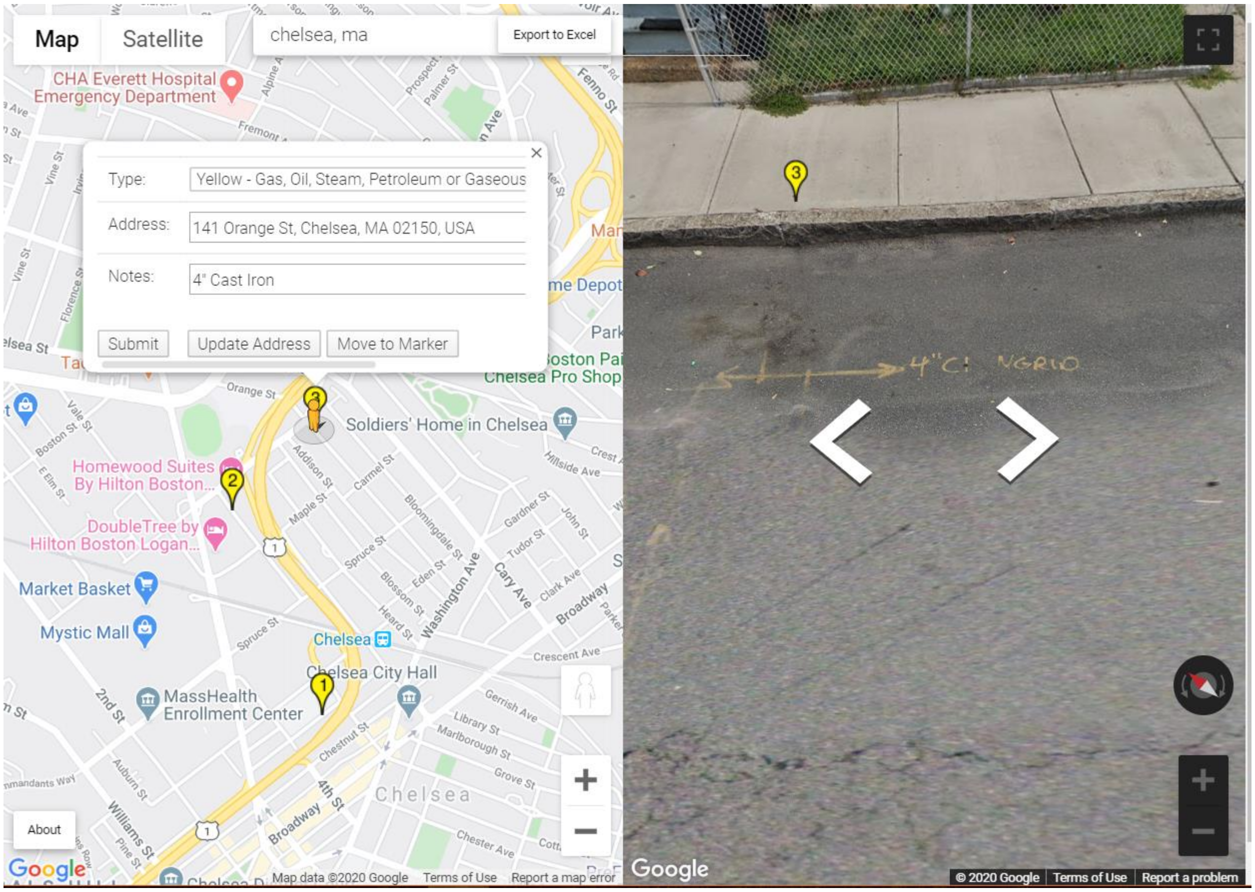

Figure 1. Screenshot of user experience in "Underground Utility V1.2". On the right a user identifies a spray-painted utility marking on a street in Chelsea, MA left behind by utility workers. This tag identifies a 4 inch cast iron (CI) pipe underneath the street. User can then drop a pin, which marks the location in an active Google Maps window. Geocoded markers can then be downloaded from the Google Map and used for analysis.

By using the "Underground Utility V1.2", an additional layer of data became available for analysis. This novel technique of geocoding gas pipeline information from GSV provided an additional data layer to validate street tree damage and mortality related to gas leaks and proximity to leak-prone infrastructure.

2.5 Spatial Statistical Analysis

Using spatial autocorrelation and descriptive statistics, patterns were investigated and relationships between street tree mortality, gas leak location, and proximity to leak-prone pipeline infrastructure were quantified. In ArcGIS, spatial joins were used to quantify leaks and poor-condition trees within census block groups across Chelsea. Spatial statistical tests were conducted using the Getis-Ord G_i^* hot spot analysis and the Anselin's Local Moran's I.[34][35]

When permitted beyond COVID-19 research and travel restrictions, this analysis will be further validated with *in situ* soil methane concentration measurements to identify urban trees with elevated CH_4 concentrations. Additionally, street tree pits within a 30m buffer of a reported gas leak will be measured for soil CH_4 concentration to better quantify the distribution of gas into soil from the point source.

[34] Getis & Ord, 1996

[35] Anselin, 1995

3. Results

**Results from this analysis are preliminary and should not be considered conclusive before additional data validation can occur when COVID-19 travel and research restrictions are lifted.

Utilizing the publicly-available street tree inventory, the location of all street trees, with an associated condition, were converted to shapefiles and projected in ArcGIS (Figure 2).[36]

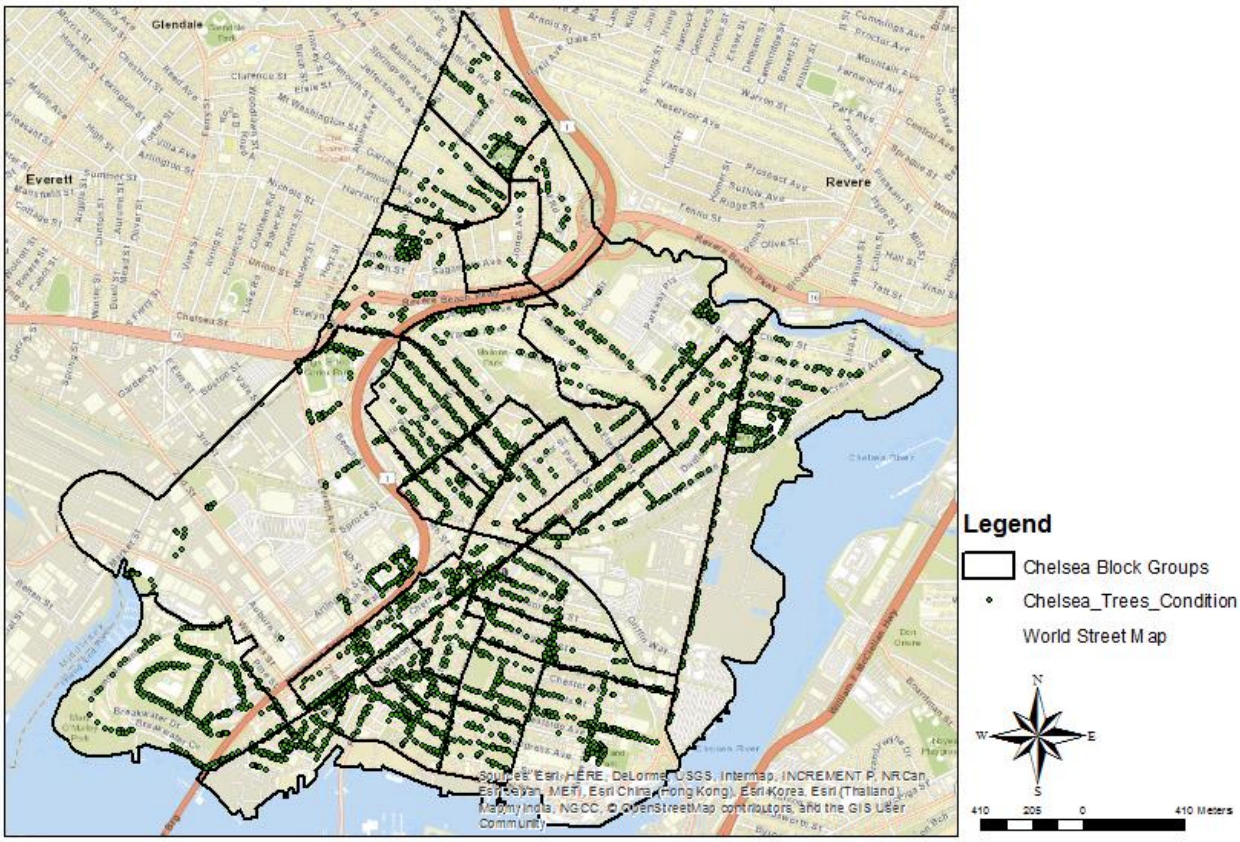

Figure 2. Map of Chelsea, MA with inventoried street trees from the 2016 street tree inventory, available on OpenTreeMap. Trees with a condition rating were included in this map, representing a sample size of 3,317 trees. Condition was defined as “excellent”, “very good”, “good”, “fair”, “poor”, “critical”, or “dead” according to the tree rating system outlined in Smiley et al. 2011.

Street trees were uniformly distributed throughout the city, with the exceptions of areas zoned industrial. Publicly-available information, published by the gas utility, on the location of reported gas leaks throughout Chelsea, MA were geocoded and added as a shapefile for analysis (Figure 3).

[36] OpenTreeMap, 2019

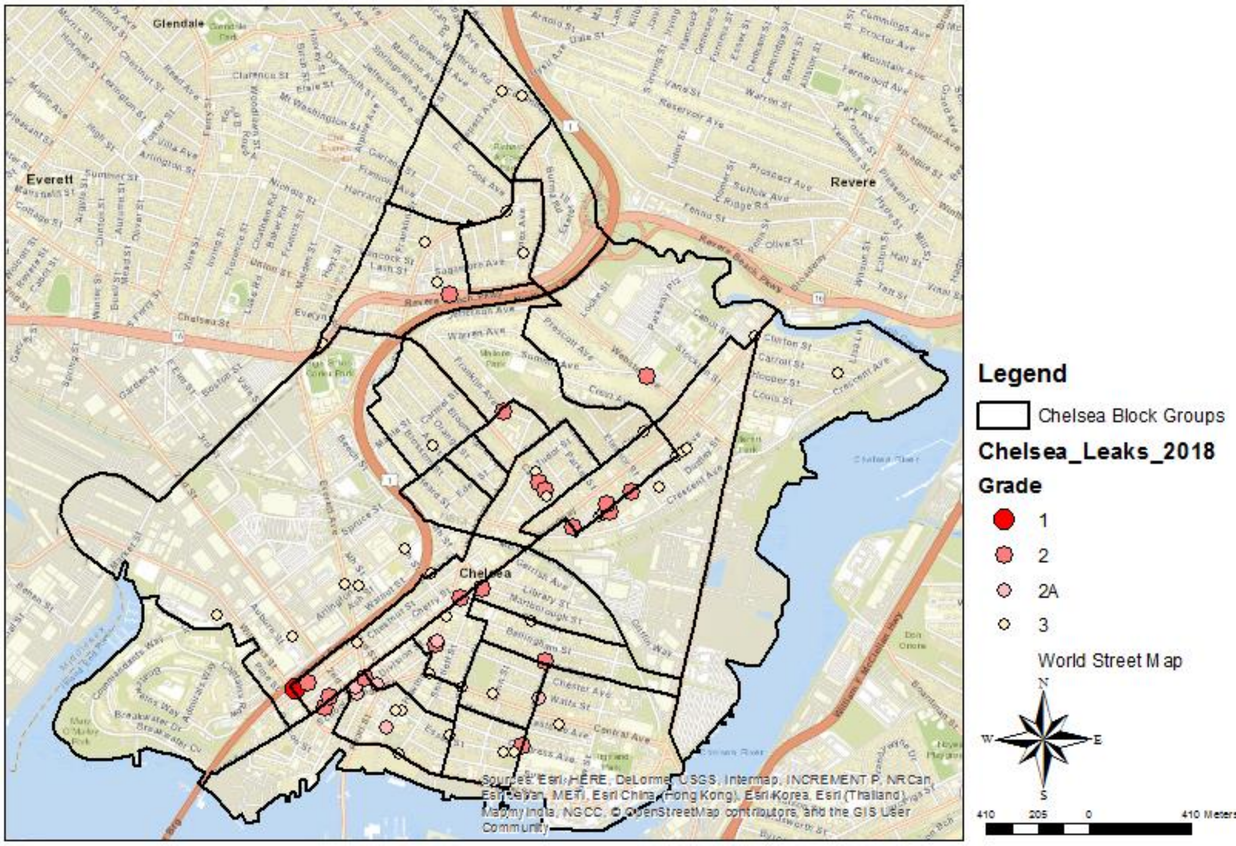

Figure 3. Map of gas leaks across Chelsea, MA. 64 unrepaired graded leaks were reported by the gas utility company in 2018 and made publicly-available. Gas leaks are graded 1) high risk of hazard, repair immediately, 2/2A) less explosive, check every 6 months, and 3) not hazardous, monitor yearly.

Gas leaks information included the grade of the gas leak, ranging from 1-3. A grade 1 leak is considered hazardous and should be fixed immediately. As the grade increases, the danger associated with the leak decreases, down to grade 3 leaks which are simply monitored annually.[37] Research has shown that while the danger of a leak is associated with the grade, there is no correlation of CH_4 flux among the leaks.[38]

After projecting the pipeline markings from GSV into ArcGIS, the locations of three pipeline material markings were overlaid onto the occurrences of leaks per census block group in Chelsea, MA (Figure 4). Cast iron pipes were defined as leak prone pipe material and plastic and steel were defined as non-leak-prone materials.

[37] Mass. Gen. Laws Ch. 164 § 144

[38] Hendrick et al. 2016

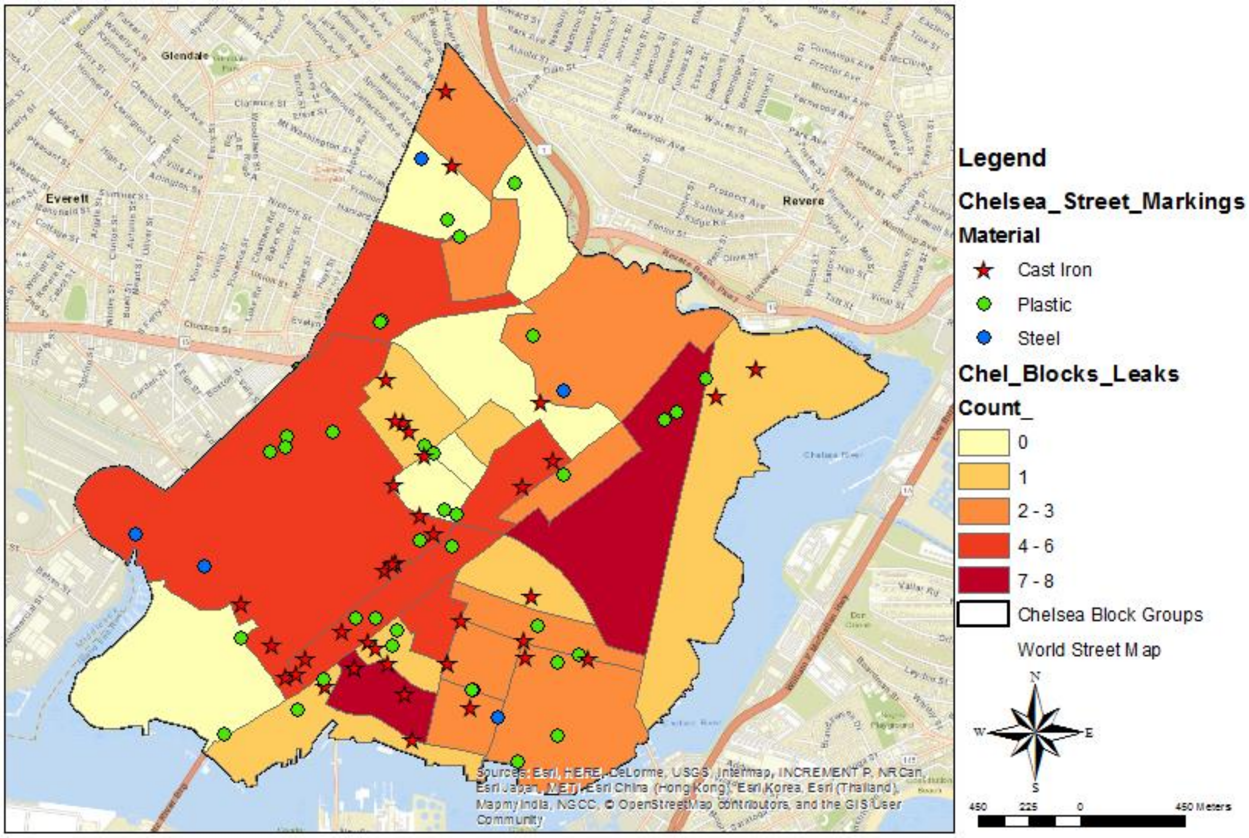

Figure 4. Census block groups are used to count occurrences of gas leaks across all grades. Markers indicate location of utility-painted spray paint markings across various streets in Chelsea, MA. GSV images used from 2019 to catalogue these markings. Leak-prone material (cast-iron) are generally concentrated in areas of high leak count, without 50% of cast iron markings located in block groups with 4 or more reported leaks, and 66% located in block groups with at least 2 reported leaks. Non-leak prone materials included plastic and steel. These markers commonly occurred in areas with lower leak counts. This is not a conclusive list of street markers nor pipe material for the entire city, as this was only one snapshot in time.

Areas of high leak occurrence (4 or more leaks) contained 50% of the leak-prone cast iron markings in the city, and medium to high leak occurrence (2+ leaks) accounted for nearly two-thirds of the leak prone markings. These markings are not an accurate description of the entirety of the infrastructure network throughout Chelsea but instead are a snapshot of available data on the date of capture from GSV.

Getis Ord G_i* hot spot analysis was run to determine the spatial pattern of inventoried street trees dependent on the condition of the tree (Figure 5). Trees inventoried but with no condition reported were not included in this analysis.

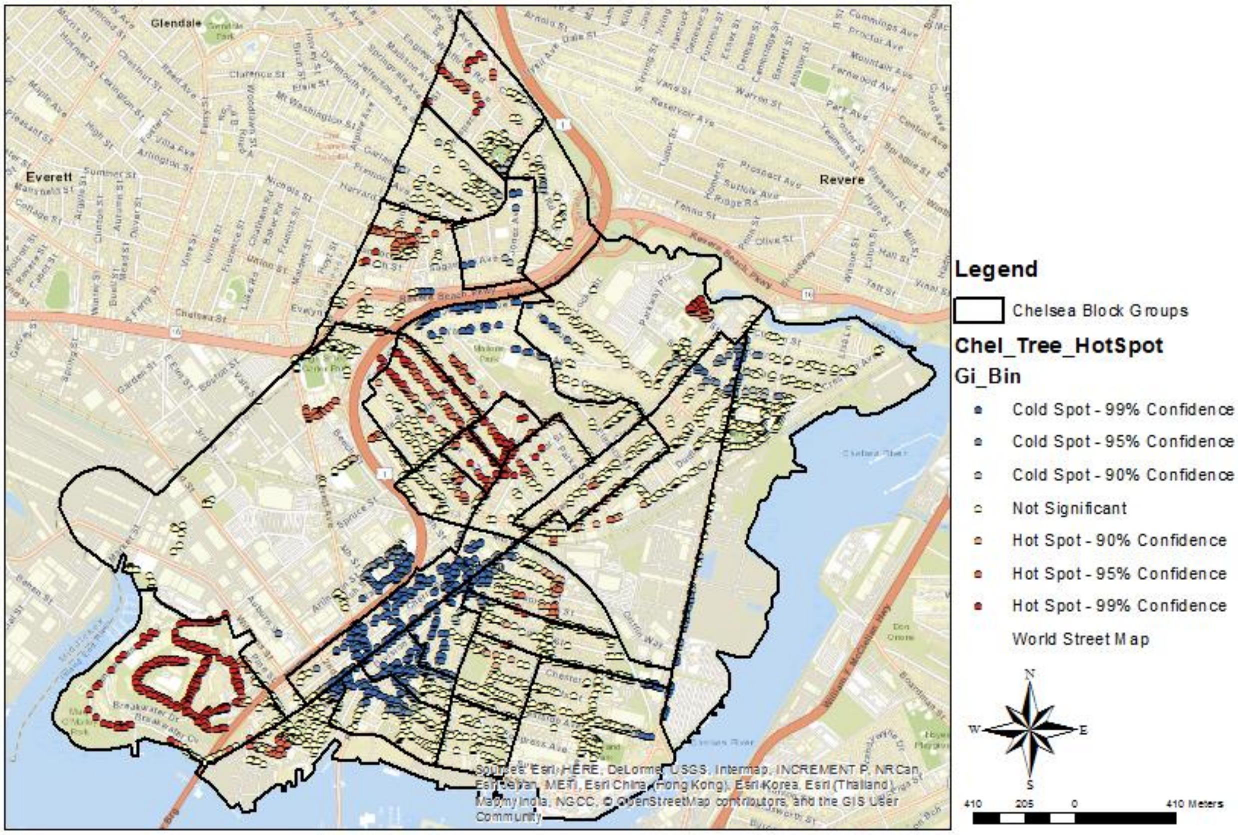

Figure 5. Results from Getis Ord G_i* hot spot analysis run on street tree condition show areas of statistically-significant hot and cold spots throughout the urban tree canopy in Chelsea, MA. Hot spots represent areas of trees that are in good condition and surrounded by other trees with high condition ratings, such as “good” or “excellent” according to the Smiley et al. 2011 tree condition classification. Cold spots represent areas of trees in poor conditions and surrounded by other trees with poor condition ratings, such as “poor”, “critical”, or “dead”. These results had a z-score of -1.82 and a p-value of 0.10.

The Getis Ord G_i* hot spot analysis showed statistically-significant spatial patterns in the condition rating across street trees in Chelsea, MA with a p-value of 0.10. Areas of healthy trees and areas of trees in poor health or dead are easily identifiable. To better quantify the distribution of street trees by condition, further analysis was completed using the Anselin Local Moran’s I cluster mapping tool (Figure 6.).

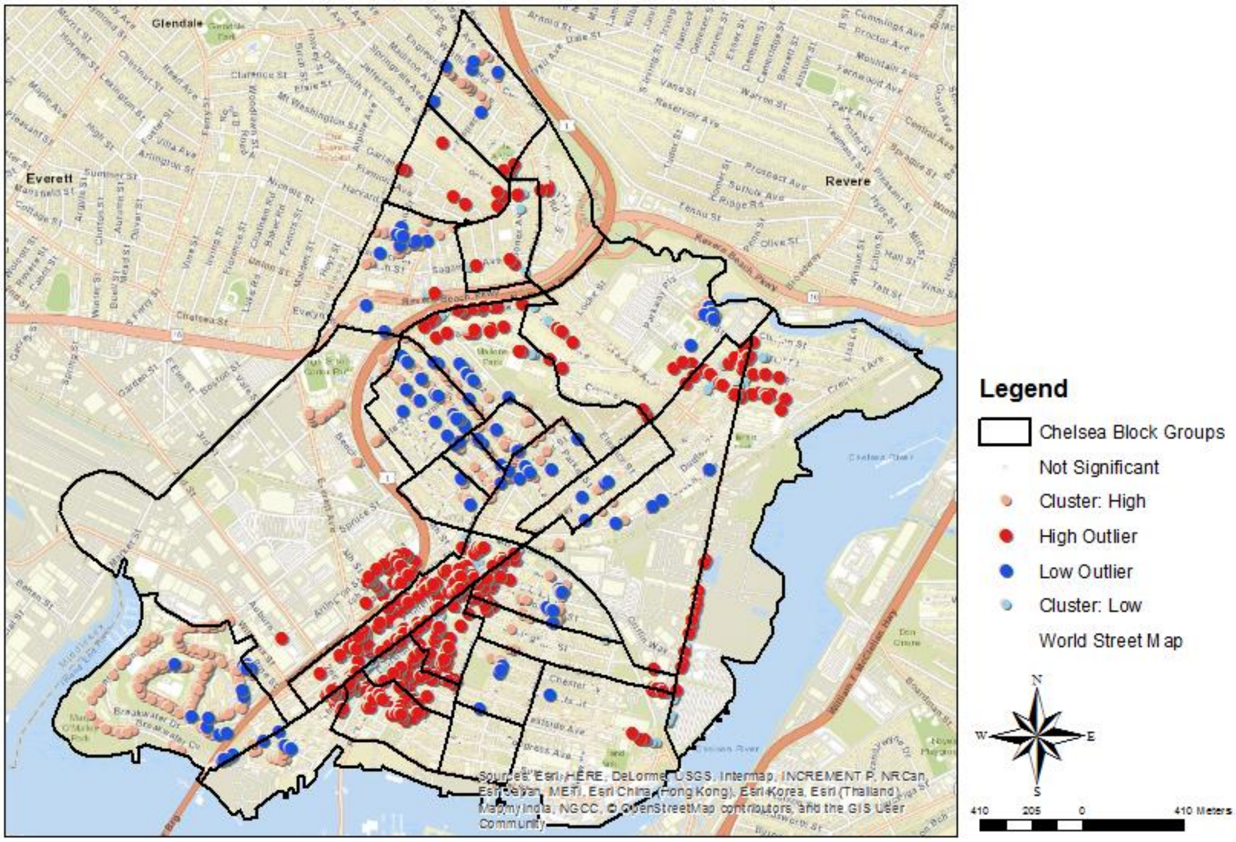

Figure 6. Results from Anselin Local Moran's I provide more insight into the distribution of street trees by condition across Chelsea, MA. Clusters of both high and low values show similar spatial patterns to the Getis Ord G_i* hot spot analysis but also highlight high and low outliers. Statistically-significant high/low clusters and outliers are displayed with a z-score of 21.97 and a p-value of >0.01.

Although data collection was not completed and important validation data collection has been delayed, using ArcGIS and spatial mapping highlighted important patterns that could be identified for prioritizing gas leaks repair in order to maintain the urban tree canopy (Figure 7).

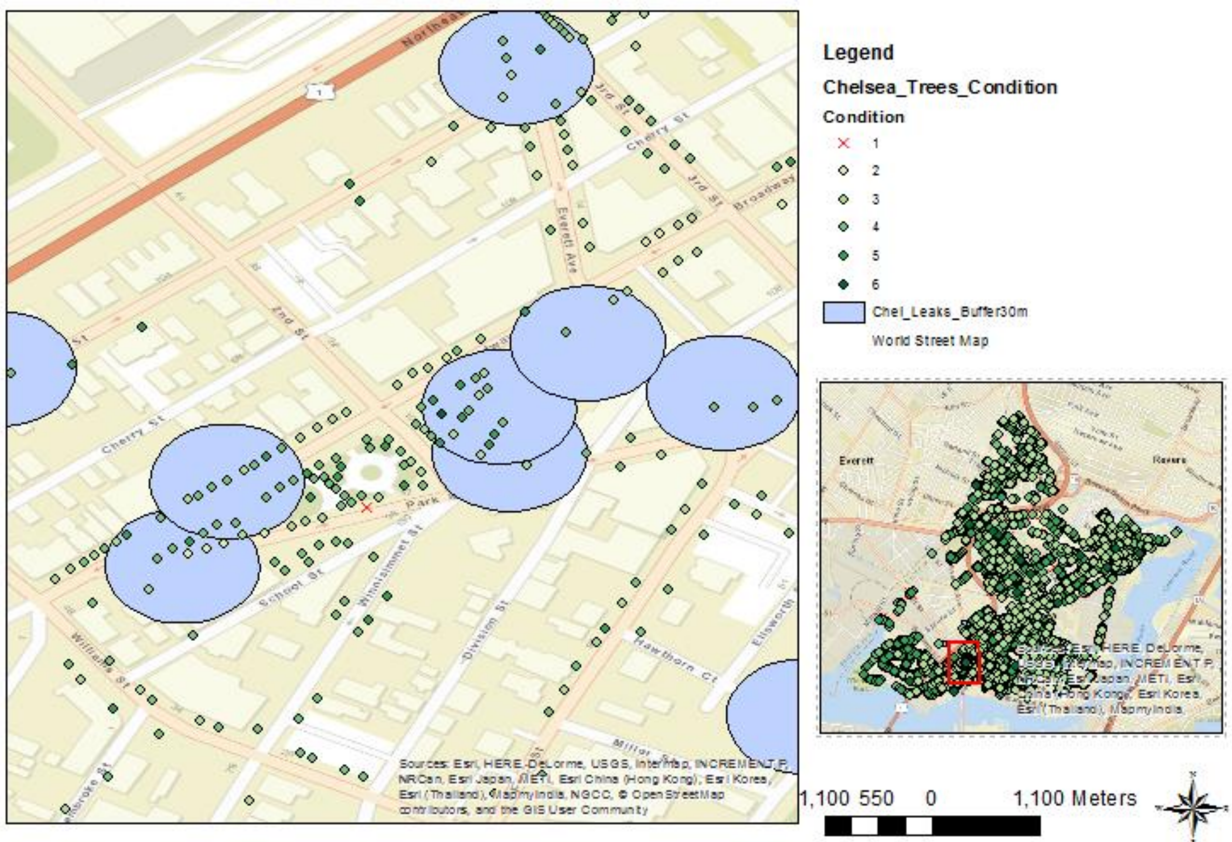

Figure 7. Inset map shows 30m buffer around reported gas leak locations and street trees in close proximity to reported leaks.

Using a 30m buffer around a gas leak can represent the possible spread of gas from the reported address in the utility report. The visualization of the 30m buffer allows for vulnerable street trees to be identified. Additional information can be drawn from the spatial representation of these various data sets including proximity of reported leaks and street trees to leak-prone pipe material (Figure 8).

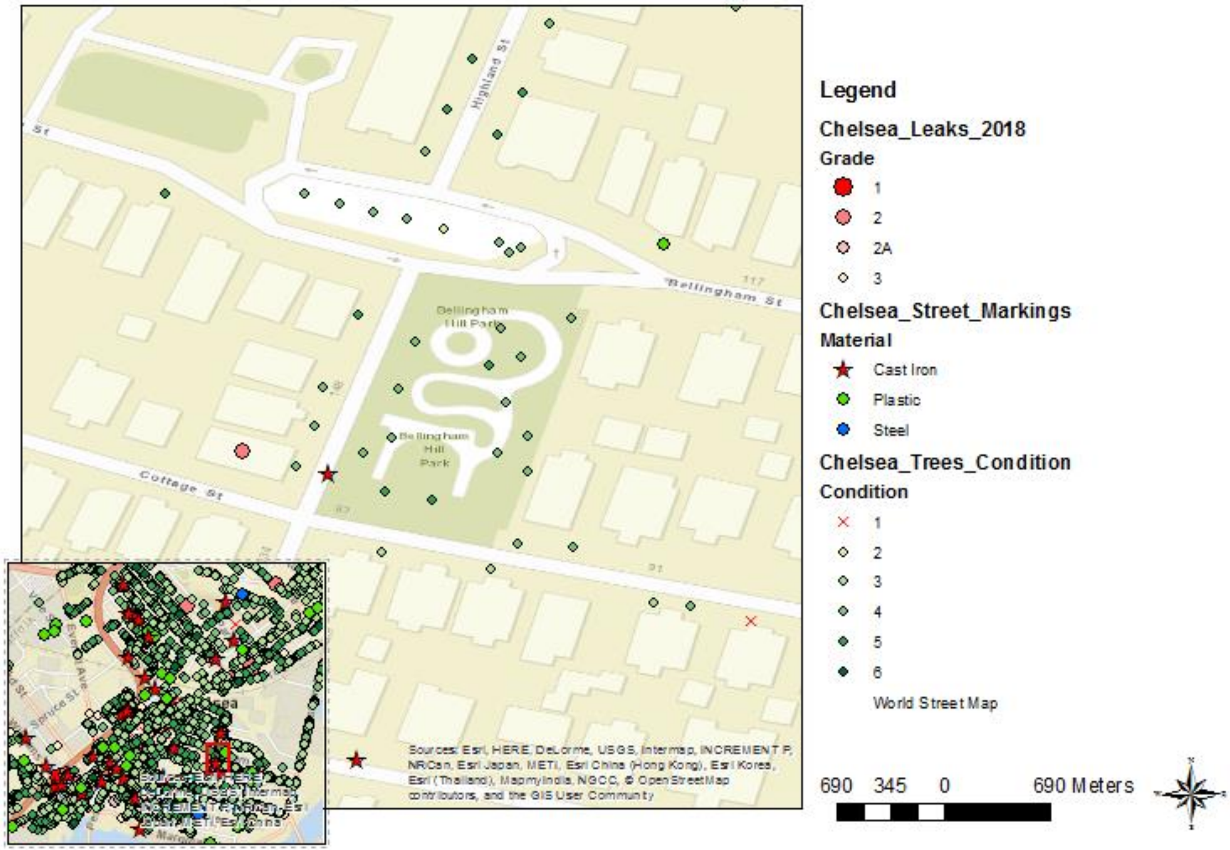

Figure 8. Inset map shows a local park in Chelsea, MA with street and park trees surrounding a reported gas leak. These trees are also vulnerable to the leak prone infrastructure seen nearby the reported leak address.

Utilizing the location of leak-prone pipe material highlights the vulnerability of street trees to CH_4 pollution, whether or not a reported leak is present. Leak-prone material, until replaced or taken off-line poses a threat of leaking and polluting nearby street tree soils with CH_4.

4. Discussion

Results from this analysis aimed at providing municipalities insight into how to manage their aging gas leaks infrastructure in an effort to prioritize the public health benefits of a robust urban canopy. As demonstrated in the spatial analysis of the street tree inventory, there were spatial patterns that emerged showing clusters of trees in both highly rated and poorly rated condition. Having a spatial representation of what areas have a concentration of street trees in poor condition will help inform municipal leaders on where to focus their efforts to improve the health of the tree canopy. Maintaining a robust urban canopy has many ecosystem benefits that are of increasing importance to urban areas deemed environmental justice communities, like Chelsea, MA.[39]

Identifying areas and neighborhoods within a municipality with an especially high occurrence of leaks will provide municipalities' information on where gas leaks pose the largest threats to public health and safety and the urban canopy. Understanding and quantifying these leak hot

[39] Schwarz et al. 2015

spots give municipalities information on how to prioritize gas leak repair projects and consider transitioning off of natural gas to further prevent vulnerable leak hot spots from emerging. Additionally, through identifying and displaying locations where leak-prone infrastructure is present in communities, municipalities can better quantify street trees that may soon be damaged by a gas leak. Although these marking locations are only representative of one point in time and not a conclusive list for the entirety of gas infrastructure in the City of Chelsea, using utility pipeline markings to identify potentially vulnerable trees can provide useful information for municipalities. Perhaps municipalities can avoid planting new street trees near leak-prone infrastructure and monitor the condition of existing trees near leak-prone infrastructure.

Using a spatial mapping approach to combine useful and publicly-available datasets can highlight important spatial patterns to influence a municipality's management of their street trees. Although this analysis is incomplete in data collection and validation, the novel data collection approach using GSV holds promise for informing municipality street tree planting and urban canopy management. Ideally, municipalities will begin transitioning off of natural gas but in the interim, identifying and understanding patterns relating gas leaks and street tree conditions will be beneficial. Maintaining a robust urban canopy and fixing and/or replacing gas distribution infrastructure will help municipalities lower their greenhouse gas emissions and provide important ecosystem services benefitting human health.[40]

5. Conclusion

This study aimed to quantify and determine the spatial relationship between the condition of street trees and their proximity to a known gas leak and leak-prone infrastructure. Although data collection and validation was incomplete at the time of submission, this project highlighted important patterns relating gas leaks, leak-prone infrastructure, and the condition of street trees. It is the hope of the investigators this project has practical applications that encourage city planners and tree wardens to consider the concentration of CH_4 in tree pits before planting a new street tree. Planting a new street tree can cost a municipality upwards of $1000 in costs and labor, so ensuring that trees survive to maturity is important not only for the public health benefits of street trees and their ability to clean urban air but also for the town's economy.[41] Results from this project will serve to advance the knowledge of how gas leaks damage trees and degrade air quality, as well as develop a more robust strategy for municipalities to do smart planning decisions about their energy future. Ideally, this research will prove helpful in implementing a transition off of natural gas energy as cities and towns discuss energy transitions and plan integrated climate change strategies.

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[40] Soares et al. 2011

[41] Citizen Forester, 2018

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