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ASSESSING THE STRUCTURE AND FUNCTION OF UTILITY FORESTS IN MASSACHUSETTS

A Thesis Presented
By
RYAN SUTTLE

Submitted to the Graduate School of the University of Massachusetts, Amherst in partial fulfilment of the requirements for the degree of
MASTER OF SCIENCE
September 2021
Department of Environmental Conservation

ASSESSING THE STRUCTURE AND FUNCTION OF UTILITY FORESTS IN MASSACHUSETTS

A thesis presented
By
RYAN SUTTLE

Approved as to style and content by:

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Brian Kane, Chair

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Environmental Conservation)

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ABSTRACT

ASSESSING THE STRUCTURE AND VALUE OF UTILITY FORESTS IN MASSACHUSETTS

SEPTEMBER 2021

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Directed by: Dr. Brian Kane

Trees in a community provide numerous benefits, including reducing ambient temperature, removing gaseous and particulate pollutants from the air, sequestering atmospheric carbon, and improving stormwater retention and filtration. However, trees also pose risks, especially in proximity to overhead utility lines. Trees near utility lines cause a large proportion of electrical power outages. As such, trees must be frequently and often severely pruned away from lines to minimize this risk. Presumably, community trees not growing near overhead utility lines are not pruned as frequently or severely. The objectives of this study are to (i) assess factors related to both individual trees and the sample populations of trees growing near and away from overhead utility lines, and (ii) determine whether those factors differed between the two groups. From May through September 2020, I sampled 200 utility easement plots and 200 non-utility plots in Eversource Energy's distribution territories, measuring 2361 trees. I measured diameter at breast height (DBH), crown height and spread, percent crown missing, percent twig dieback, and likelihood of failure. Using this field collected data, I conducted an i-Tree Eco assessment to evaluate the contribution ecosystem services delivered by trees at each sampling site.

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CHAPTER 1

INDRODUCTION

Electricity is indispensable in today’s world and enables our modern society to function smoothly. As such, customers demand uninterrupted electrical service from utility providers (Kuntz et al. 2002). However, it is seldom produced in the same areas in which it is consumed. To deliver electricity to their customers, utility companies must transport current over great distances through complex networks of overhead or underground transmission and distribution lines. These facilities must be maintained and kept in safe and working condition to provide end consumers with reliable and safe electrical service.

Trees are also indispensable to communities, and have cultural, aesthetic, and tangible value for their residents. They beautify landscapes and can hold sentimental value to people in forms of class trees, memorial trees, or simply attached to fond memories. Additionally, trees can reduce stress, shorten hospital recovery times, and serve as important cultural landmarks (Dwyer et al. 1991). It is no surprise, then, that much effort and research has been conducted on the best ways to care for and manage forests and trees. However, several of these intangible and cultural benefits are not so easily quantified, and difficult to factor into forest management plans which are commonly trying to stretch each dollar they are afforded.

More quantifiably, urban trees reduce ambient temperature (Livesly et al. 2016; Solecki et al. 2005), remove pollutants and particulates from the air (Dochinger 1980; Nowak et al. 2006), sequester carbon (Nowak and Crane 2002), improve stormwater retention and filtration (Bolund and Hunhammar 1999; Livesly et al. 2016), and even increase property values where they are planted (Escobedo et al. 2015). These ecosystem services have been extensively studied and documented, providing a useful resource for future urban forest management plans (Raum et al. 2019).

However, these two indispensable contributions to society often come into conflict. Trees cause a large proportion of unplanned outages on electric distribution systems (Simpson and Van Bossuyt 1996) by either growing or falling into the lines, thus causing short circuits or damage to the facilities which can cut power to customers. Of the two types of tree-caused outages, fall-ins cause the vast majority—either from entire trees failing or from overhanging limbs failing and falling into lines (Guggenmoos 2003, 2011)**.** This risk creates a need to prune or remove trees to ensure reliable electrical power (Olienyk 1988). Tree and power line conflicts can also lead to dangerous situations such as fires (Vogt et al. 2015), and incur high costs upon utilities due to lack of electrical service resulting from tree-caused power outages, repairing facilities after outages, as well as loss of electrical revenue (Vogt et al. 2015).

Utility arborists must manage the safety and reliability of electrical power distribution systems, cyclically pruning or removing potentially hazardous trees or known risk-species within the system (Perry 1977; Dykes 1980; Kuntz et al. 2002). Depending on the location and condition of the tree in relation to the distribution lines and the desired clearance, utility arborists must prune away large portions of a tree’s crown or remove the entire tree when adequate clearance is not achievable by pruning alone. As a result of these specialized pruning prescriptions, trees in utility easements often have unusual shapes when compared to trees which are pruned in other ways, exhibiting characteristic V or L shaped crowns to remain clear of overhead lines (Dahle et al 2006a, 2006b).

Trees, if they cannot be pruned to hold an acceptable level of compliance with distance standards from electrical facilities, must be removed by utility companies’ vegetation management programs. This results in either in clear cutting vegetation rights-of-way, or selective whole-tree removal of incompatible species, resulting in fewer trees in the utility forest. Fewer trees in the forest also results in a decrease in the total ecosystem service delivery to communities (Dupras et al. 2016).

Repeated pruning to remove branches growing near power lines sometimes creates unnatural crown shapes atypical of open grown trees (Dupras et al. 2016, Lecigne et al. 2018, Millet and Bouchard 2003). These tree shapes may lead to reductions in overall leaf area. Since ecosystem services provided by trees are generally proportional to leaf area (Giovani 1991, Nowak et al 2006), reduction in overall crown leaf area may lead to reductions in ecosystem service delivery per tree when compared to open grown individuals. Trees with smaller crowns, or crowns with large voids, will have a lower leaf area index than trees with large and complete crowns. With a lower leaf surface area value, these trees may deliver comparatively lesser values of computed ecosystem service delivery.

In addition to a lower value for cumulative leaf surface area, trees repeatedly pruned for utility line clearance often causes unnatural crown shape profiles. Repeated pruning creates more wounds from branch reduction and removal cuts, even within a natural pruning system, and may slow wound occlusion over time (Fini et al. 2013, 2015). In a recent study conducted by Fini et al., removal cuts were less than 20 percent occluded after one year had elapsed since the second pruning (three years after the initial pruning). Many utilities operate on three-year pruning intervals, and some operating on intervals as short as one year in more fire-prone areas of the country. This increase in pruning frequency, and therefore wounding frequency, increases the opportunity for decay or disease pathogens to enter the tree: both of which may increase the likelihood of failure of a particular tree.

Likelihood of failure is one of the key components of tree risk assessment. Pruning to reduce risk of both part and total failure of a tree is a common pruning objective. In the following sections, “tree failure” encompasses trunk breakage, individual branch failure, or windthrow, and occurs when the forces applied to a tree exceed the structural integrity of a tree or tree part. The most common loading forces which damage trees are wind, snow, and ice. The likelihood of failure of a tree is related to the type and magnitude of the applied load, and the ability of the tree to resist said applied load.

This study presents the findings of an observational study of trees near overhead electrical distribution lines in Eversource’s service areas in Massachusetts. It is the hope that this study of utility forest trees will be used in future vegetation management operations along Eversource utility rights-of-way. A temporally current general outline of structure and condition of utility forests will help Eversource identify potential risks which require speedy attention, or areas where vegetation management standards should be changed or expanded to improve electrical reliability or tree condition.

Independently from the Eversource deliverable report, this study aims to determine whether the high frequency and severity of pruning necessary to keep adequate clearance between trees and overhead electrical lines affects overall tree condition. Specifically, this study investigates the difference between various measured morphometric variables for trees growing in utility forest conditions and those growing elsewhere. These metrics were also inputted into the USDA Forest Service software program i-Tree Eco to calculate ecosystem delivery values per tree with the intent to investigate what relationship, if any, utility pruning may have on the ecosystem service delivery value of trees in Massachusetts. Finally, this study investigates potential differences in likelihood of failure between utility forest trees and the greater urban forest.

CHAPTER 2

LITERATURE REVIEW

Reliable and safe electrical energy distribution is imperative to meet the electrical demands of communities. Electrical distribution grids, as a critical infrastructural backbone of modern societies, are crucial in delivering energy from producers to end consumers (Espinoza et al 2016). Because of this importance, these grids must be maintained with an intense focus on resilience to power outages, including tree-caused outages (Kuntz 2002)

Urban trees reduce ambient temperature (Livesly et al. 2016; Solecki et al. 2005), remove pollutants and particulates from the air (Dochinger 1980; Nowak et al. 2006), sequester carbon (Nowak and Crane 2002), improve stormwater retention and filtration (Bolund and Hunhammar 1999; Livesly et al. 2016), and even increase property values where they are planted (Escobedo 2015). These ecosystem services have been extensively studied and quantified, providing a useful resource for future urban forest management plans (Raum et al. 2019). There are several factors which influence the amount of benefits an amenity tree is able to provide.

One factor in the ecosystem service capability of a tree is its size. Trees with a larger crown have a larger leaf area index value than trees with smaller crowns. Total leaf area and biomass strongly influence evapotranspiration, atmospheric deposition, biogenic volatile organic emissions, light interception, and other ecosystem processes (Nowak 1992). Trees intercept solar radiation and may cool their immediate surroundings significantly through blocking infrared radiation (Robinette 1972, Heisler & Herrington 1976), or by shading thermal masses which would otherwise raise ambient temperatures through the urban heat island effect (Armson et al. 2012, Hall et al. 2012). They also may be used to manipulate air movement within a city, obstructing, guiding, deflecting, or filtering prevailing winds (Robinette 1972). This can be used to further improve air temperature by guiding cooling winds towards desirable areas in summer months, or to deflect winds away from areas where it is not desired, creating a more comfortable urban environment for human residents as well as other wildlife which share the cityscape. There also exist inherent interspecies changes in tree ecosystem service delivery. For example, shading coefficients differ between tree species based on leaf area index (Nowak 1992), leading to inherent differences in possible reductions in surface temperature provided by different tree species (Abreu-Harbich et al. 2014). Species with lower leaf area index coefficients reduce solar radiation less than those with higher index coefficients, and therefore, are less effective at reducing surface temperature underneath their canopies (Napoli et al 2015). In the i-Tree Eco Model, leaf area index is used to calculate ecosystem services such as ambient cooling effects through saved money expenditures on heating and cooling, stormwater reduction, and particulate and gaseous air pollution filtration**.**

i-Tree Eco, developed by the U.S. Forest Service, has been widely used in surveys of urban tree populations worldwide to quantify and analyze these functional benefits of trees (Früchtenicht et al. 2018, Morani et al. 2014, Nowak et al. 2016, Raum et al. 2019). The integration of assessment of structure as well as function, as calculated by i-Tree eco, is an important management tool for urban forestry via free access to download from the iTree tools webpage. This software has been used in 130 different countries and is available for anyone to use. Using a sample of a larger population, recommended to consist of at least 200 sample plots, characteristics like species make up and tree condition can be inferred for the greater population at large. The software uses models to analyze field data, collected through standard set of field methods (Nowak et al 2008), and returns calculations of ecosystem service delivery amounts (eg. Kg Carbon sequestration per year per tree) and the value of said ecosystem service in dollars.

While the reported benefits of having quantified ecosystem service data are largely anecdotal, some reports claim that it improves appreciation of urban trees (Soares et al 2011), may inform management strategies (Ordóñez and Duinker 2013), may and inform tree planting plans (Morgenroth and Ostberg 2017). However, i-Tree has not been used in an evaluation of utility trees, specifically. This presents a new avenue for consideration of utility forests, which are most often approached from a risk-management standpoint alone, potentially overlooking the ecosystem service value of the managed resources.

While there are a multitude of benefits that trees may provide, trees also incur costs in the form of conflict with infrastructure. Trees may encounter above-ground conflicts when they encroach upon infrastructure which needs to be clear of vegetation. To manage an urban area's tree population, arborists prune trees to control their shape and spread for clearances from buildings or roads (Maczulajtys 1999), and to reduce their likelihood of failure by mitigating or removing structural defects (Smiley and Kane 2006, Ryder and Moore 2013). Site selection is vital in mitigation of possible space constraints of above ground tree parts, as well as overhead utility line impacts. Focusing on matching tree geometry with site limitations is an effective way of avoiding spatial conflicts of trees in cramped urban areas (Jim 1997), referred to commonly in the industry as *Right Tree, Right Place*.

Tree conflicts are not only limited to above-ground infrastructure. Below ground, root systems of trees may also cause concerns in built environments. Limited growing space causes most root damage on infrastructure (Barker 1983, Wong et al. 1988, McPherson and Peper, 1996, Randrup et al. 2001). In built environments where tree roots face spatial confinement and obstacles, roots tend to grow just below the pavement in search of available air and water. Thickening of these subsurface roots can cause pavement cracking, sidewalk upheaval, and a subsequent tripping hazard or an expensive repair. Tree roots also cause damage to underground irrigation or drainage pipes in search of water, nutrients, and oxygen (Randrup et al. 2001). Weak or leaky pipes are particularly susceptible to root damage because they increase soil moisture content and are structurally compromised. Because of these inevitable conflicts, management plans must be put into place to minimize the risks trees may pose. This project focuses only on above-ground tree conflicts which can be mitigated by pruning. Pruning management plans can be defined as the planned removal of plant parts to achieve a predetermined objective (Kane 2017).

This section makes use terms from the current A300 Part 1 Standard, *Tree, Shrub, and Other Woody Plant Management – Standard Practices (Pruning).* This standard divides pruning practices into separate pruning systems: natural, topiary, pollard, espalier, pleach, fruit production, and bonsai (Anonymous 2018). All seven of these pruning systems focus on their own distinct pruning objectives. Arborist pruning of amenity trees is typically included in the natural pruning system. Natural pruning is used by arborists to retain and promote the characteristic form of a species or cultivar in its current location. This process may involve branch removal or reduction cuts to avoid conflict with infrastructure, encourage stable tree structure, allow desirable views, or provide clearance for cars and pedestrians. However, natural pruning does not mean that a pruned tree may will have a completely natural appearance as if it were grown in an open field. The topiary pruning system is a formal practice where shrubs, vines, or trees are pruned into a specified shape through either shearing or pruning. These can include geometrically shaped hedges, or artistically shaped trees. Pollarding is used to maintain trees in a predetermined size range, however, this system should not be confused with topping. This type of pruning uses heading cuts to generate epicormic shoots for continued and frequent removal, generally annually. After several pruning cycles, pollard heads (also referred to as knobs or knuckles) form, which aid in compartmentalization to reduce decay movement down the parent stems. These pollard heads are the key difference between pollarding, an acceptable pruning system, and the unacceptable practice of topping. Espalier is a formal system for managing plants in a two-dimensional plane, such as along a fence or wall. Branches are selectively pruned and tied to a vertical framework to encourage the desired two-dimensional structure. Pleaching involves horizontally weaving branches to form an arching tunnel, an arbor, a wall, or an alee. Fruit production pruning systems are specific to fruit producing tree species, and many species have their own specialized needs. However, the intent of all fruit pruning regimes is to maximize fruit production. Bonsai is a general term for the maintenance and art of styling container-grown trees at a small size. In arboriculture, this system is used when trees have confined root space, yet a natural form is desired, and where the tree is intended to be maintained at a fixed limited size. While these seven systems may differ in their objectives, they use many of the same techniques to achieve them. Under all pruning systems described, branches are reduced or removed through making pruning cuts to achieve their intended objective.

Pruning cuts can be grouped into two categories: proper and improper. Cuts which damage or remove parts, or all, of the branch collar, leave a stub beyond the branch collar, or do not occur at a node are typically referred to as improper cuts (Kane 2017). Proper cuts include branch removal cuts and branch reduction cuts. Branch removals removes a branch back to a parent stem at the point of attachment. Removal cuts retain the branch collar and bark ridge, and do not create a stub beyond the branch collar. Branch reduction removes the larger of two or more branches or stems to a live lateral branch or stem of at least one-third the diameter of the stem being removed (Lilly et al. 2019). This retained portion of the pruned limb or stem should assume apical control of the remaining part (Harris et al 2004, Grabosky and Gilman 2007). Heading, or internodal, cuts can be labeled as proper or improper depending on whether they are placed near an appropriately sized lateral branch or bud. Internodal cuts which are not placed near an appropriately sized lateral branch or bud are referred to as topping cuts, which are not proper practice. In the case of topping, no remaining bud or lateral can assume the role of apical control of the remaining piece (Harris et al 2004). Trees respond to this with epicormic shoot growth, which are weakly attached and have higher incidence of failure under loading (Dahle 2006a).

Pruning has physiological effects on trees. Regardless of whether cuts are proper or improper, they cause wounds to a tree which may create dysfunctional wood at the cut point as well as an entry for decay microorganisms into the branch or stem. Decay, over time, creates a cavity which compromises the physiological health and mechanical structure of a tree (Dujesiefken and Stobbe 2002). Wound occlusion occurs after pruning through the CODIT (compartmentalization of decay in trees) model established by Shigo and Marx (1977). Trees surround an injury to functional sapwood with 4 walls. Walls 1 to 3 compartmentalize decay to prevent internal spread, and wall 4 closes the exposed wound area (Shigo and Marx 1977). Additionally, pruning can invigorate existing growth on branches which were not pruned (Gilman and Grabosky 2009, Findlay et al. 1997), and encourage watersprouts, suckers, or epicormic branching (Grabosky and Gilman 2007, Gilman et al. 2008, Fini et al. 2013, Hipps et al. 2014, Fini et al. 2015). It can also slow growth of pruned branches (Gilman and Grabosky 2009, Kristoffersen et al. 2010, Gilman 2015a, Gilman 2015b) as well as reduce trunk growth rates post-pruning (Gilman 2015a). Photosynthesis of non-pruned branches is also affected by pruning, often showing temporary increases. The magnitude of this compensatory photosynthesis is usually related to the amount of leaf area removed during pruning operations (Pinkard and Beadle 1998, Medhurst et al. 2006).

Utility pruning, while a part of the larger natural pruning system, has specialized pruning objectives which separate it from other types of pruning. However, the tools and methods used in utility arboriculture are similar to those used to attain other pruning objectives. The most common type of pruning encountered around overhead electric distribution lines is directional pruning (also known as natural pruning) in modern utility vegetation management programs. Directional pruning has been the favored pruning practice over topping for decades (Ulrich 1987; Shigo 1990; Kempter 2004; Kuhns and Reiter 2007) for many reasons.

Topping, or rounding over, occurs when trees are trimmed to a pre-determined plane of height at a set number of feet below electrical conductors, and is imprudent for several reasons. Topping cuts are generally internodal cuts which are not made at a branch collar, which allow for greater chance of decay or disease pathogens entering the wounds than properly placed cuts. Internodal topping cuts also encourage prolific watersprout growth back up towards conductors (Dahle et al 2006a). These watersprouts are often more weakly attached to the parent stem than a normal branch, leading to a greater risk of failure under loading (Dahle et al 2006b).

Directional pruning involves selecting limbs growing towards overhead electrical facilities and cutting them back to the next limb growing laterally away from the lines (Johnstone 1988, Miller 1998, Kempter 2004, Dahle et al 2006a). Carefully placed cuts in directional utility pruning removes or reduces the potentially interfering branches and leaves the compatible branches intact. This type of clearance pruning is best conducted at regular, cyclical intervals. Cyclical pruning enhances utility reliability with more frequent inspections of facilities and the trees which could affect them. It also reduces aesthetic and biological impact on trees and neighborhoods, and can stabilize or even reduce tree maintenance budgets (Kempter 2004). Cycle length as well as pruning clearance distances should be established to ensure that tree growth will not overtake electrical conductors before the next cycle. For example, areas with long growing seasons or a high proclivity for fast-growing tree species should have a shorter maintenance cycle length that those with short growing seasons or many slower-growing tree species. However, growing conditions do not solely govern pruning cycle length. In urban areas, comparatively large clearances are not possible due to aesthetic reasons or constricted easement rights. In rural areas, longer pruning cycles may be possible due to the possibility of achieving greater clearance distances with pruning.

There are some limitations on existing research of tree pruning. Pruning to achieve one objective, such as utility clearance, may adversely affect another objective, like ecosystem service delivery. The contradiction of the ideal season to prune highlights this trade off effectively; early summer pruning expedites would occlusion (Perry and Hickman 1987) and stimulates a greater level of carbohydrate storage (Clair-Maczulajtys et al. 1999), yet at the same time, increases the likelihood of attracting bark beetles or other insects which may be vectors of disease such as Dutch elm disease or oak wilt. The effect of utility pruning of trees on assessed likelihood of failure or ecosystem service delivery was not encountered in the preceding literature review. The main objectives of this study are to determine what effect, if any, that utility pruning has on: i) tree size and crown condition, ii) likelihood of failure, iii) and ecosystem service delivery.

CHAPTER 3

MATERIALS AND METHODS

To better understand potential differences in forest structure and function between utility and non-utility forests, trees in utility easements were compared to street trees or privately-owned trees adjacent to the utility easement. To investigate forest structure, diameter at breast height (DBH), total tree height, percent crown missing, percent twig dieback, and likelihood of failure (assessed at level 1 inspection level, as outlined in the *Utility Tree Risk Assessment Best Management Practices*) were measured and assessed for trees in each sample population. Using morphometric inputs as well as site condition inputs, i-Tree Eco estimated the contribution ecosystem services delivered by trees at each sampling site, quantifying the function and value of each forest sample.

Study Area and Site Selection:

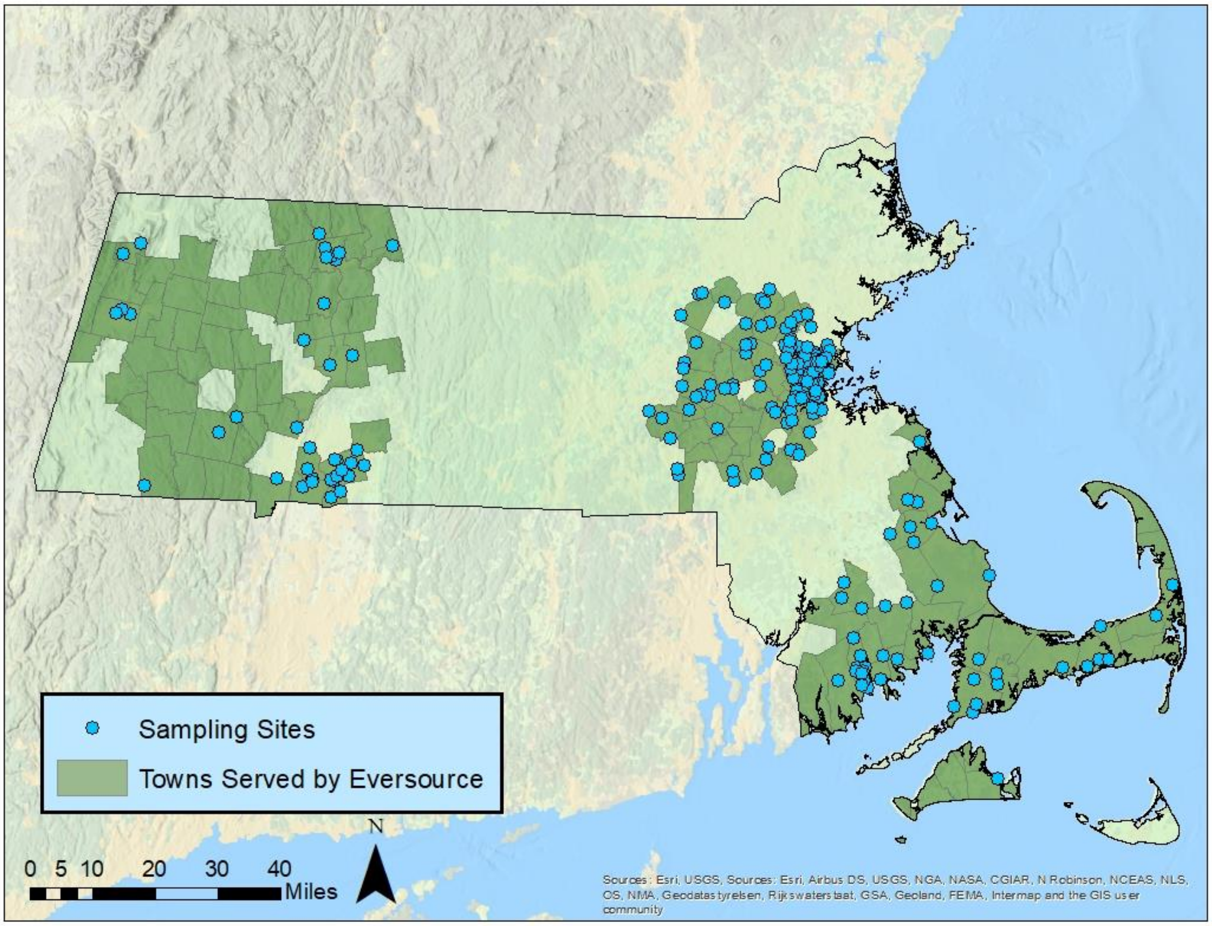
All sampling sites in this study were in the state of Massachusetts, and more specifically, within towns whose electricity is provided by Eversource Energy. The scope of this project was limited to trees around roadside electrical distribution lines. Vegetation management near transmission lines differs dramatically from distribution lines regarding their associated pruning practices. Furthermore, both sides of a transmission line right-of-way (ROW) receive similar management, so there is not a convenient control plot location for comparison. Distribution lines generally range from 2.4kV to 23kV for localized distribution of power, while transmission lines range from 23kV up to an excess of 765kV (Miller and Kempter 2018). Because of this inequity, transmission lines require far more strict vegetation management standards. Often, incompatible tree species are simply removed rather than pruned when in proximity to the higher voltage transmission lines due to the greater consequence of potential tree conflict.

The overhead facilities in this study consist of roadside distribution lines managed by Eversource throughout their Massachusetts service areas. The sample included a plot trees located near electrical distribution lines (referred to as utility forest or utility trees) and a control plots of trees which have similar site conditions but are not maintained by Eversource's vegetation management program. For the utility forest plots, only trees near primary distribution electric lines were considered, excluding transmission corridors, secondary distribution electric lines, service drops leading from primary lines to individual building structures, or any other type of utility line. These other facilities have their own unique vegetation management standards and combining groups together may potentially skew results.

GIS generation of sampling sites

Sampling sites were randomly selected throughout each of Eversource's service areas in the state of Massachusetts, using ESRI ArcMap to randomly choose census tracts within each service area's towns. Census tracts are relatively small statistical subdivisions of counties, averaging approximately 4000 inhabitants (United States Census Bureau 2010). By using census tracts rather than town subdivisions, randomized sampling increased the likelihood of selecting more populous areas where a tree caused electrical outage would have a higher consequence in terms of total customer hours without power.

Using a road shapefile from MassGIS as a guide, 200 sampling sites along roads located within Eversource served census tracts were selected. Figure 1 depicts all randomly selected locations within these census tracts. ArcMaps automatically assigns these sites with GPS information, which were reverse geocoded to assign each sampling site a street address for easy navigation by the field technicians. If no roadside distribution lines were present at any particular site, or if the lines are not deemed suitable via in person or Google Streetview confirmation (e.g., are not capable of having a plot consistent with sample plot area procedure due to insufficient line length), the field technician moved north to search for suitable lines within the same town. If moving north was impossible, cardinal directions were cycled through in a clockwise fashion until suitable distribution lines were found.



Sources: Esri, USGS, Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community

Figure 1: Sampling site distribution (blue) throughout Eversource service territories (green) in the state of Massachusetts.

These sites were split into three generation iterations. Due to uncertainty regarding the availability of field assistance in the early weeks of the Covid-19 epidemic, adjustments were made to the way sites were assigned to field technicians. First, 100 sites were geocoded and assigned to the first field technician. Second, the next 100 sites were geocoded and assigned to the second technician. A total of 14 replacement sites were generated in the third iteration, as some inappropriate sites needed to be replaced to reach the desired sample size of 200 sites. At each address, the technician placed a utility plot along roadside distribution lines, and turned 180 degrees to place an identically sized control plot across the street away from overhead lines.

1. ***Utility Plot:***

   Utility plots sampled trees in proximity to primary overhead electric distribution lines. While this study retained the 0.1 ac plot footprint outlined in the i-Tree Eco protocol (Nowak et al. 2008), the circular plot shape was not appropriate for sampling utility ROWs. A 37.2 ft radius plot would encapsulate trees which are not included in utility vegetation management plans for pruning and include a large proportion of impermeable road surface within each plot. This study's plot dimensions measured 12ft (3.66m) by 363ft (110.64 m) along distribution lines to achieve the same 0.1 ac (404.686m^2) footprint while targeting trees which Eversource has pruned for line clearance. Trees located outside of the sampling plot that had also been pruned for overhead electrical utilities were included in the data gathering process and noted as being outside of the determined plot.

2. ***Control Plot:***

Control plots were located immediately across the road from ROW plots and were identical in dimension. By having control and utility plots near one another, the potential influence of site condition differences between utility and control plots was limited.

Sample Site Distribution:

Because of the possibility of bias between the two surveyors, each gathered data in territories across the state. By deliberately not assigning geographic regions per inspector, I aim to avoid potential geographic trends based on possible technician bias. This was accomplished with the 3-iteration ArcGIS geocoding process previously described.

Equipment:

Field technicians used a laser rangefinder to measure tree crown dimensions (Forestry Pro Rangefinder / Hypsometer, Nikon USA, Melville, NY), a DBH tape to measure trunk diameter, and a contractors measuring wheel (12.5 in Contractors Measuring Wheel, Model PSMW48CL, Lufkin, Missouri City, TX) to measure plot dimensions as well as tree data.

Field Data Collection:

Field technicians used i-Tree Eco v6 to collect tree data at sample plots. Developed by the U.S. Forest Service, i-Tree has been widely used in surveys of urban tree populations (Früchtenicht et al. 2018, Morani et al. 2014, Nowak et al. 2016, Raum et al. 2019). Data gathering occurred when trees were in full leaf in the Spring and Summer of 2020, concluding before leaf drop to avoid potential influence of seasonal defoliation on measurements of percent dieback, or percent of crown missing. Field technicians gathered a range of data for each site and tree sampled (Table 1).

Table 1: Variables collected in field by technicians and a description of each variable

Variable	**Description**
Site ID	Unique site number
Tree ID	Unique tree number
Species	Species of tree
DBH	Diameter at breast height (in/cm) measured at 4.5ft (1.37m) above ground. Measured with DBH tape
Total height	Height to top of tree crown (ft/m), measured with Nikon Forestry Pro Laser Rangefinder
Height to crown base	Height to base of live crown (ft/m), measured with Nikon Forestry Pro Laster Rangefinder
Crown Width	Recorded by 2 measurements: North-South, and East-West. Measured with Nikon Forestry Pro Rangefinder or Lufkin contractors measuring wheel
Percent Canopy Missing (figure 2)	Percent of crown volume that is not occupied by leaves; two perpendicular measures of missing leaf mass are made, and the average result is recorded; rounded to nearest 5%
Dieback (Figure 1)	Percent crown dieback to nearest 5%
Likelihood of Failure (Smiley et al. 2017)	**1-Improbable** (some minor defects present); **2-Possible** (Several moderate defects present); **3-Possible** (Multiple **or** significant defects present); **4-Imminent** (Multiple **and** significant defects present)
Managed or unmanaged	Status of whether the tree being measured has been pruned or not. For utility plots, only trees previously pruned for overhead electrical utility lines were marked as ‘managed’. This status will be given to any non-utility trees that have been previously pruned, regardless of pruning objective
In or out of plot	Position of trunk of tree being measured to plot. Only trees that are outside of the 12 ft x 363 ft plot and pruned for overhead lines will be marked “out”, all other measured trees were inside of plot

Percent crown missing was measured as a comparison of whole tree crown to an estimated completely full crown silhouette. Snag branches and large holes or gaps in crown were not included in the estimation, along with natural, normal branch dieback (i.e., self-pruning due to crown competition or shading in the bottom portion of crown). Branch dieback on sides and top of crown area due to shading from another building or tree were included in the estimation. The final measurement was expressed as a percentage of entire crown (Table 1 and Figure 2) (USDA Forest Service 2019)**.**

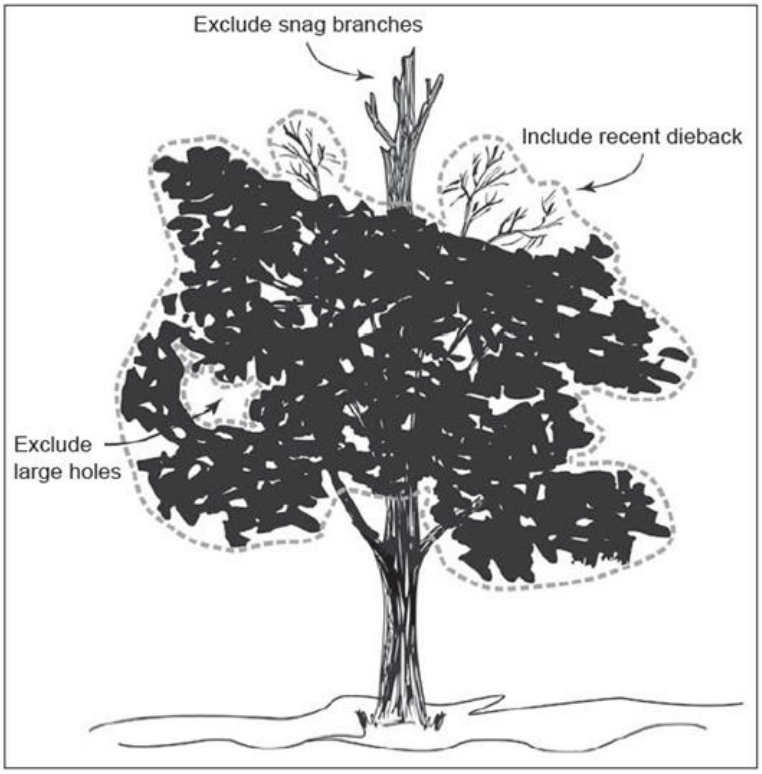


Figure 2: Visualization of how percent dieback will be estimated by technicians.

Percent crown missing was based on the amount of foliage absent due to pruning, dieback, defoliation, uneven crown, or dwarf or sparse leaves. Interior crown voids as a result of leaf shading were not considered in this measurement (Figure 3) (USDA Forest Service 2019).

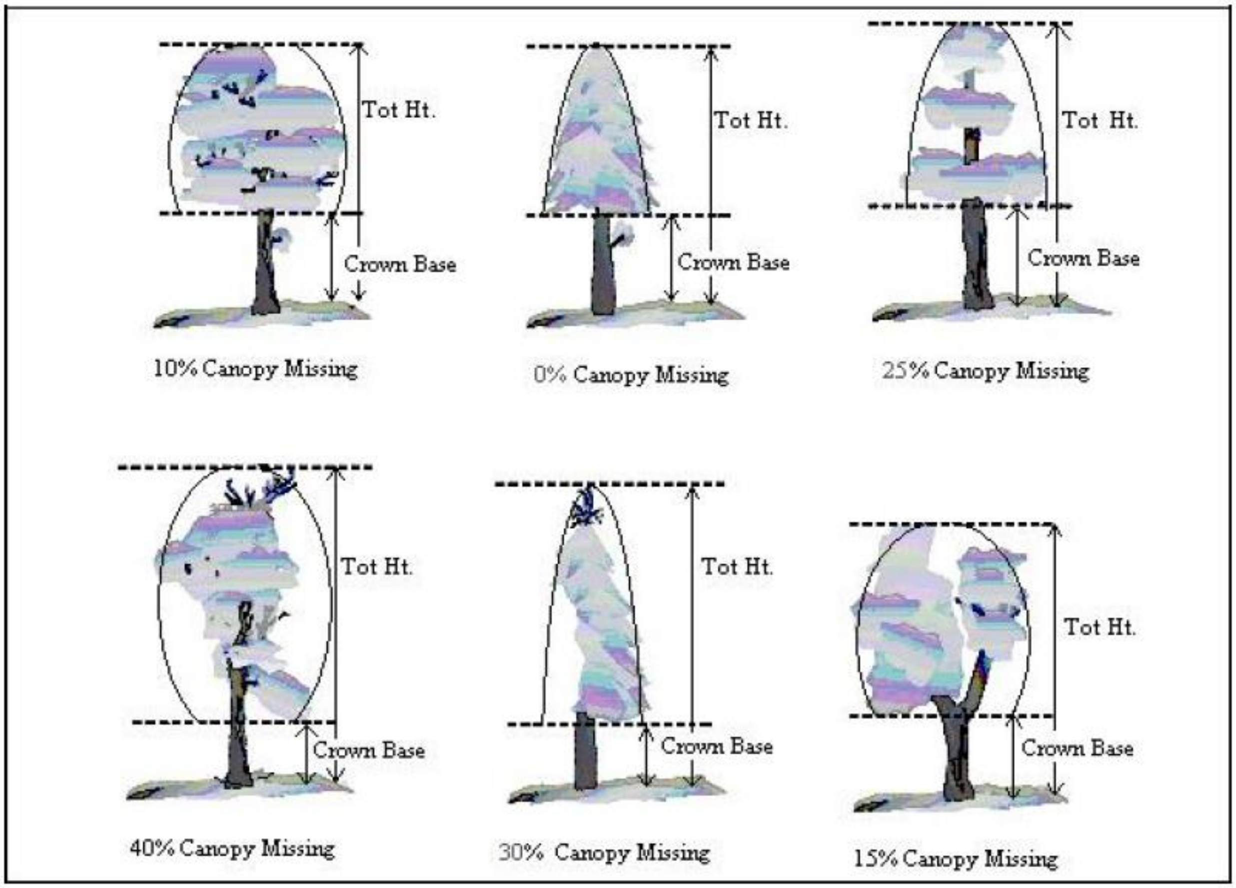


Figure 3: **-** Visualization of how percent crown missing was estimated by field technicians (USDA Forest Service 2019).

Likelihood of failure assessments followed the "Level 1" methods outlined in the second edition of the International Society of Arboriculture's (ISA) Tree Risk Assessment Best Management Practices (Smiley et al. 2017) and ISA's Utility Tree Risk Assessment Best Management Practices (Goodfellow 2020). This method is commonly used to assess trees in the United States. A level 1 assessment was selected for this study because: (1) individual risk assessments may be prohibitively expensive at higher orders, i.e. Level 2 or Level 3 (Smiley et al. 2017), given the hundreds of thousands of trees utilities must manage across territory areas; (2) utility rights-of-way (ROW) easements may not allow utility inspectors full access to trees in practical application of higher order risk assessment procedure if the trees are beyond the edge of the ROW (Goodfellow 2020); (3) studies have shown reasonable efficacy of limited basic visual assessment techniques in identifying more severe tree defects (Rooney et al. 2005, Koeser 2016) which lead to greater likelihood of failure ratings. The four categories of likelihood of tree failure, which are always considered in a stated time frame, are defined as follows (Smiley et al. 2017).

1. *Improbable*- the tree or tree part is not likely to fail during normal weather conditions and may not fail in extreme weather conditions within the specified time frame.
2. *Possible*- Failure may be expected during extreme weather conditions, but it is unlikely during normal weather conditions within the specified time frame.
3. *Probable*- Failure may be expected in normal weather conditions within a specified time frame.
4. *Imminent*- Failure has started or is most likely to occur in the near future, even if there is no significant wind or increased load. This is a rare occurrence for a risk assessor to encounter, and may require immediate action to prevent people from harm. The *imminent* category overrides the stated time frame.

Likelihood of failure was judged based on the standards put forth by the International Society of Arboriculture for tree risk assessment. This metric was recorded as ordinal data, ranging from 1, delineating *improbable* trees, to 4, delineating *imminent* trees. Likelihood of tree failure was determined by examining structural conditions, defects, response growth, and anticipated loads to anticipate tree failure occurring within a specified time frame. Technicians used Eversource's maintenance interval of three years as a baseline for our assessment of likelihood of failure for this study, however, this time span may not be interpreted as a guarantee period for failure assessment. The likelihood of failure per tree was characterized into the previously stated four levels, and in this section, language from the International Society of Arboriculture Best Management Practices: Tree Risk Assessment, Second Edition 2017 (Smiley et al. 2017), as well as the American National Standards Institute (ANSI) A300 Part 9-2017: Tree, Shrub, and Other Woody Plant Management – Standard Practices (Tree Risk Assessment: Tree Failure) (Anonymous 2018) is used to describe the factors assessed in this study. The highest likelihood of failure recorded on each tree, either for whole or partial tree failure, was used as that tree's rating. Certain defects or conditions present in trees can more likely lead to failure than others.

Dead or dying trees and branches were of obvious concern when considering likelihood of failure. Dead branches ranged from *possible* to *imminent* depending on specific conditions of the tree such as species, branch size, type and extent of decay, etc. Similarly, broken or hanging branches were also considered *probable* or *imminent*.

Cracks in either longitudinal or transverse directions were also considered defects which affect tree likelihood of failure. Trunks or branches were cracked completely through or that have partially failed were considered *imminent* risks, and so ranked. Transverse cracks were considered a sign of localized failure, and ranged from *possible* to *imminent* depending on potential loading forces and tree response growth. Response growth may compensate for cracks present in tree stems, thus lowering an individual tree's likelihood of failure. Internal cracks indicated by seams and ribs where response growth was added at the edges were considered *improbable* or *possible* failure risks depending on the amount of solid wood behind the seam. However, if seams cover decay and depending on load exposure, failures at seams may become *possible* to *probable.* Given the limited level of detail possible in this study's scope, this was not always possible to assess. Growth cracks that form in the outer bark during periods of rapid trunk growth were not considered structural defects, and did not impact assessment of likelihood of failure.

Weakly attached branches, including adventitious branches, multiple branches originating at a single location on the stem, codominant stems, and included bark were also associated with higher failure rates. Codominant stems, or stems with nearly equal size, typically have weak attachments. Included bark causes these to be considered *possible to probable*. However, if there was decay in or near the union, likelihood of failure increased to *probable* or *imminent* depending on weight distribution and potential branch or stem loading. At these branch unions, presence of response wood reduced likelihood of failure, while presence of associated cracks increased likelihood of failure. The shape of a branch union was also considered when estimating likelihood of failure; stems which divide in a sharp V-shape tend to be weaker than those with a gentler U-shape. Codominant stems with a V-shape union were considered *possible* to *probable*, while U-shaped unions were considered *improbable* to *possible*. Adventitious branches are generally weakly attached, and were considered *possible* if decay is absent, and *probable* in the presence of decay. If significant holding wood had developed, the likelihood could decrease to *possible* or *improbable*. When several branches originate from one place on a stem, they tend to be more weakly attached than branches of the same size that are alone. Under these conditions, there is not enough space for adequate holding wood to develop around each branch, creating weak unions. Likelihood of failure in this instance was considered *possible* to *probable*, increasing if decay was present near the point of multiple branch attachments.

Missing or decayed wood also increased likelihood of failure. Missing wood refers to anything which reduces the cross-sectional area of solid wood in a trunk or branch. This includes decay, cankers, or mechanical injuries which result in future weakening. Two categories of decay indicators informed the assessor of missing or decayed wood – potential indicators and definite indicators. The most common potential indicators of decay, strength loss, or missing wood include: (1) presence of old wounds and branch stubs which may allow decay fungi to enter the tree; (2) swelling, ridges, bulges, or other response growth patterns that form to compensate for wood strength loss (3); seams or cracks; (4) oozing through exterior bark; (5) dead or loosely attached bark, or abnormally colored bark; (6) sunken areas in the bark; (7) termite trails. The most common definite indicators of internal voids or decay include: (1) cavity openings, nesting holes, and other openings or voids on the tree's exterior; (2) mushrooms, conks, brackets, or other fungal fruiting structures attached to the tree; (3) carpenter ants inhabiting or emerging from defect regions; (4) termite emergence from tunnels or internal nests.

Tree growth and structural characteristics change how trees move in the wind, and thusly, how the load in the crown is distributed. When architectural defects are present in tree structure, other structural defects are considered more significant in likelihood of failure. Leaning trees may be less stable than vertical trees due to uneven loading. Trees with increased lean over a short amount of time are especially likely to fail. While this study's single inspection did not capture any changes over time, surveyors inspected for certain signs of recent leaning: (1) uncorrected lean; (2) soil depression on the side of the lean or lifting on the opposite side of the lean. Recently leaning trees were considered *probable* or *imminent*. Corrected leans, or sweeps, are not as significant of a failure risk, and will be considered to have a likelihood of *improbable* to *possible*, increasing with lower trunk angle and as crown weight increased. Bows are characterized by the top of a tree extending more than the lower trunk, creating a curve. If they have not increased stem diameter via response growth, the likelihood of a bowed tree was considered *possible* to *probable*. Bowed trees were examined specifically for longitudinal cracks, and if present, was considered *probable* to *imminent*. Live crown ratio may also increase likelihood of failure if other structural defects are present. When ratios are less than 50% (i.e., only the upper 50% of the tree has live branches) there may be reason for concern. Similarly, poor taper can also increase likelihood of failure. Degree of taper can be calculated by dividing tree height by trunk diameter. However, reported critical values vary from 50:1 to 90:1. Because of this wide range, this was not used in isolation to classify likelihood of failure.

Root defects also contribute to higher likelihoods of failure; they can be decayed, restricted, severed, or otherwise undermined, leading to inadequate anchorage. Other root-related problems, such as stem-girdling roots, can affect response growth further up the stem, potentially increasing likelihood of failure. Given the logistical limitations of this study at a Level 1 risk assessment classification, root assessment will be limited to visual indicators: (1) fungal fruiting structures; (2) lack of root flare; (3) stem-girdling roots; (4) wounded roots; (5) root cuts; (6) adventitious roots. Visual indicators of response growth included wide root flare and fused buttress roots.

Survey Team

Two surveyors collected field data over the summer 2020 field season between May and September. With the subjective nature of visual crown assessment methods, there was a potential for subjective individual-surveyor influence on estimated percentage values and classes. Using the standard protocols described in the above sections, inter-rater reliability pilot samples were conducted while training prior to the sending each technician into the field separately to ensure uniformity in data gathering between them. Two inter-rater reliability tests were conducted after the training period and before sending the second technician out into the field solo, with two more follow up reliability testing rounds later in the field season to assess continued congruence of measuring procedures. In these tests, each technician measured and assessed the same group of trees independently of one another on the same day, using the same tools, and the data were compared to assess potential biases of each technician

Data Analysis:

To analyze data gathered in the field, CSV files were be exported individually by site from i-Tree Eco v6, consolidated, and processed in R statistical software as a single dataset containing all sampled trees and sites. Generalized linear model (GLM) frameworks were used to model variables, followed by two-ways ANOVA tests.

Potential tree size differences between populations

Both DBH and height were compared to investigate potential size differences between each of the study groups. These data will be analyzed using GLM's accounting for the influence of plot type, pruning status, and their interaction.

Potential tree condition differences between populations

Both percent crown dieback and percent crown missing were compared to investigate potential size differences between each of the study groups. These data was be analyzed using GLM's accounting for the influence of plot type, pruning status, and their interaction.

Data for both of these two response variables were converted from a categorical variable of 5% bins to a numerical variable from 0 (0% dieback) to 21 (100% dieback, dead tree).

Comparing Likelihood of Failure Ratings

Data were coded as an ordinal variable, recoding the likelihood categories depicted in Smiley 2017 and Goodfellow 2020 with a 1-4 scale. 1 represented *improbable* trees and 4 represented *imminent* trees. Analysis of this ordinal variable required the use of an ordinal logistic regression model.

Comparing results from outputs of i-Tree Eco models:

Ecosystem services calculated by i-Tree Eco v6 in this study include: structural value ($), carbon storage (kg), annual carbon sequestration (kg), annual runoff avoided (m^3), annual air pollution removed (g), structural value ($), and value for annual ecosystem service delivery ($) per tree. This study used GLM's to investigate whether a significant relationship exists between plot type (utility vs non-utility), and pruning type (pruned, unpruned) on each ecosystem service delivery response, and potential interaction between the two predictor variables. These GLM's were also tested using two-way ANOVA tests.

Modeled Regression Distributions:

Visual analysis of residuals plots (Appendix I) indicated non-normality of several response variables. In some cases, there was a pronounced right skew in the distribution. For these variables, a gamma distribution with a log link was often used because the data were non-negative, non-integers, and were often right skewed (Bolker 2008, Akresh 2020). A small value of 0.001 was added to each response variable contained 0 values in order to be able to fit these 0 values to a gamma distribution with a log link function. Exploratory analyses found that adding this value provided good model fits for the various responses under gamma distribution generalized linear models (Appendix 1), and that 0.001 produces a small effect size (Kalies et al. 2010). Table 2 contains the response variables and the regression distributions used to analyze them. Appendix I indicates that distributions of the following response variables exhibited a right skew: diameter at breast height, total tree height, structural value, total carbon storage, annual carbon sequestration, avoided stormwater runoff, annual air pollution removal, and total dollar value of cumulative ecosystem service delivery. Likelihood of failure, however, was treated differently than other variables. Being an ordinal variable, it was analyzed using an ordinal linear regression model. After fitting models for each response variable, each model was validated using a two-way ANOVA test, as well as a Tukey HSD piecewise comparison test.

Table 2: Response variables (left) and the regression distributions used to analyze them (right)

Response Variable	Regression Distribution
Diameter at breast height	Gamma distribution GLM with log link
Tree height	Gamma distribution GLM with log link
Slenderness	No suitable distribution found
Crown width	Gamma distribution GLM with log link
Crown Height	Poisson distribution GLM with log link
Crown Volume	Gamma distribution GLM with log link
DBH / ht^2	No suitable distribution found
Percent crown missing	Gaussian distribution GLM with log link
Percent crown dieback	No suitable distribution found
Total carbon storage	Gamma distribution GLM with log link
Carbon sequestration per year	Gamma distribution GLM with log link
Runoff avoided per year	Gamma distribution GLM with log link
Air pollution removal per year	Gamma distribution GLM with log link
Structural value	Zero-inflated negative binomial GLM with log link
Total dollar value in ecosystem services per year	Gamma distribution GLM with log link
Likelihood of failure	Ordinal linear regression

CHAPTER 4

RESULTS

Diameter at Breast Height

Mean DBH (cm) varied among plot type, pruning status, and their interaction. Table 3 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on DBH; Figure 4 shows the distribution of DBH classified by plot type and pruning status in a box and whisker plot. Mean DBH of trees in control plots was greater than tree in utility plots, and mean DBH of pruned trees was greater than unpruned trees. The magnitude of difference was greater between pruned and unpruned trees in utility plots than between pruned and unpruned trees in control plots.

Table 3. ANOVA (type III) table for the gamma distribution model for the effects of plot type, pruning status, and their interaction on DBH (cm); within each main effect and interaction, means followed by the same letter are not significantly ($p < 0.05$) different; Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	22.04	1	2.67E-06		
				Control	35 (±1.05) a
				Utility	31 (±0.65) b
Pruning status	146.86	1	<2.2E-16		
				Pruned	39 (±0.71) a
				Unpruned	18 (±0.65) b
Plot type * Pruning status	18.99	1	1.38E-05		
				Control Pruned	46 (±1.58) a
				Control Unpruned	23 (±1.07) b
				Utility Pruned	37 (±0.77) c
				Utility Unpruned	13 (±0.66) d

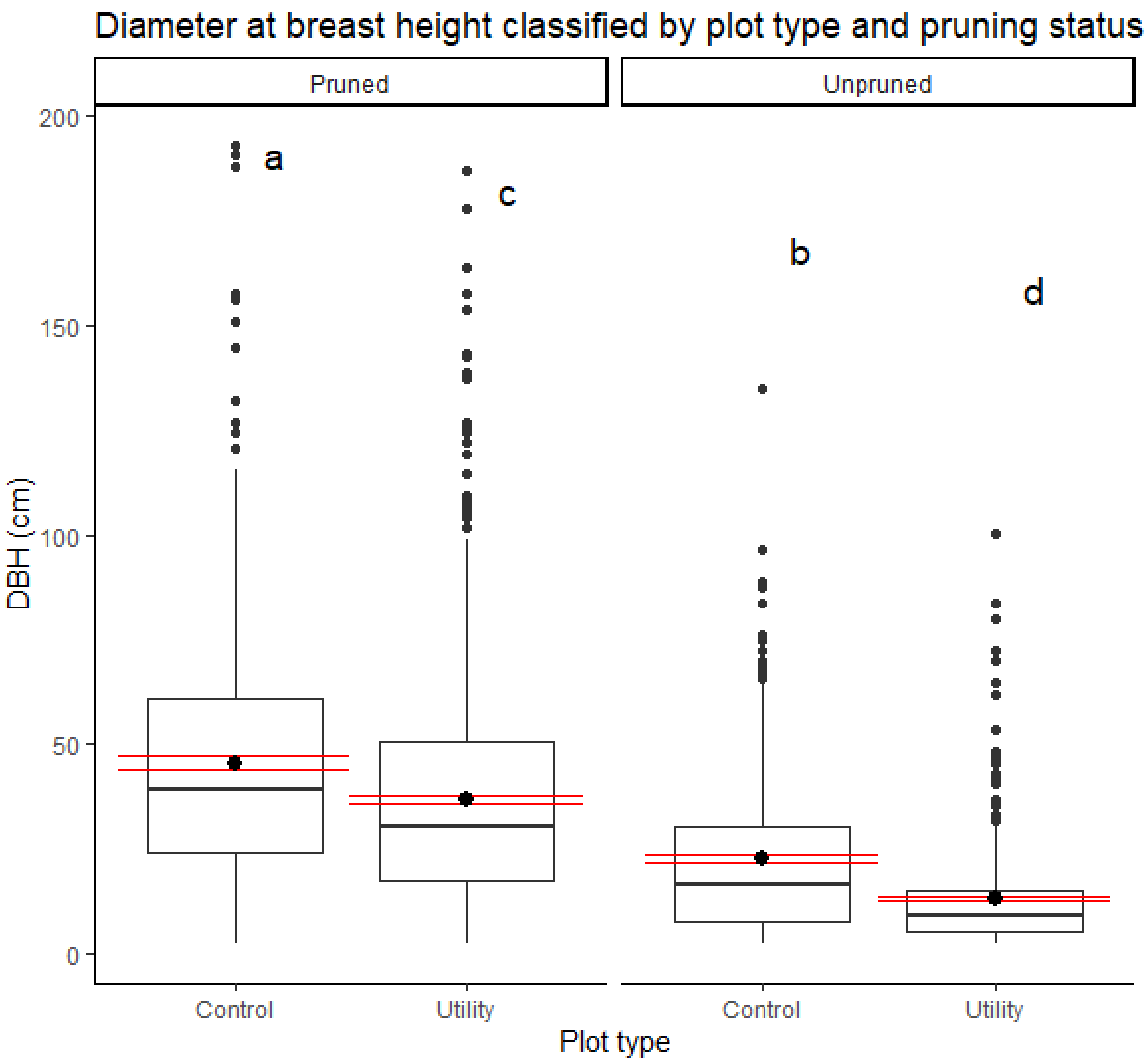


Figure 4. Box and whisker plot of diameter at breast height (DBH, cm) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whiskers are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Tree Height

Mean tree height (m) varied by pruning status and its interaction with plot type. Table 4 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on mean tree height; Figure 5 shows the distribution of tree height classified by plot type and pruning status in a box and whisker plot. Mean height of trees in control plots was similar to that of trees in utility plots, but mean height of pruned trees was greater than that of unpruned trees. While mean height of pruned trees in both utility and control plots was similar, the mean height of unpruned trees was greater for trees in control plots than trees in utility plots.

Table 4. ANOVA (type III) table for the gamma distribution model for the effects of plot type, pruning status, and their interaction on tree height (m); within each main effect and interaction, means followed by the same letter are not significantly ($p < 0.05$) different. Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	0.007	1	0.932		
				Control	11.2 (±0.22) a
				Utility	10.9 (±0.16) a
Pruning status	64.192	1	1.129E-15		
				Pruned	12.7 (±0.16) a
				Unpruned	7.4 (±0.18) b
Plot type * Pruning status	146.34	1	<2.2E-16		
				Control Pruned	12.8 (±0.28) a
				Control Unpruned	9.5 (±0.32) c
				Utility Pruned	12.7 (±0.19) a
				Utility Unpruned	5.4 (±0.11) b

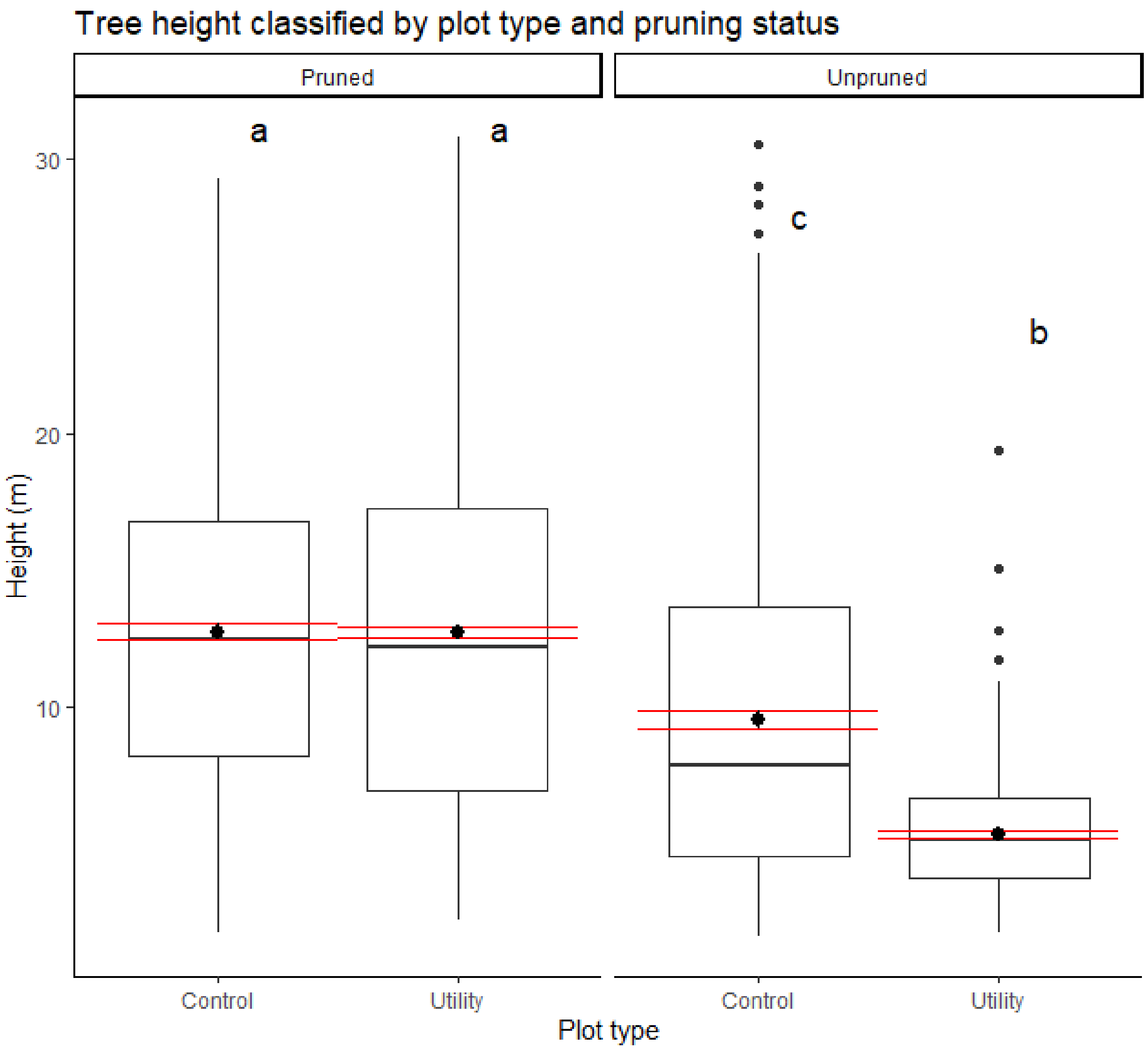


Figure 5. Box and whisker plot of tree height (m) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whiskers are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Crown Width

Mean crown width (m) varied among plot type, pruning status, and their interaction. Table 5 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on crown width; Figure 6 shows the distribution of crown width classified by plot type and pruning status in a box and whisker plot. Mean crown width of trees in control plots was greater than for utility plots, and mean crown width of unpruned trees was greater than pruned trees. The magnitude of difference was greater between pruned and unpruned trees in utility plots than between pruned and unpruned trees in control plots.

Table 5. ANOVA (type III) table for the gamma distribution model for the effects of plot type and pruning status on mean crown width (m); within each interaction, means followed by the same letter are not significantly ($p < 0.05$) different; Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	42.948	1	5.621E-11		
				Control	7.73 (±0.17) a
				Utility	6.94 (±0.11) b
Pruning status	228.881	1	<2.2E-16		
				Pruned	8.48 (±0.11) a
				Unpruned	4.57 (±0.10) b
Plot type * Pruning status	12.393	1	0.0004		
				Control Pruned	9.77 (±0.24) a
				Control Unpruned	5.44 (±0.18) b
				Utility Pruned	8.02 (±0.13) c
				Utility Unpruned	3.75 (±0.09) d

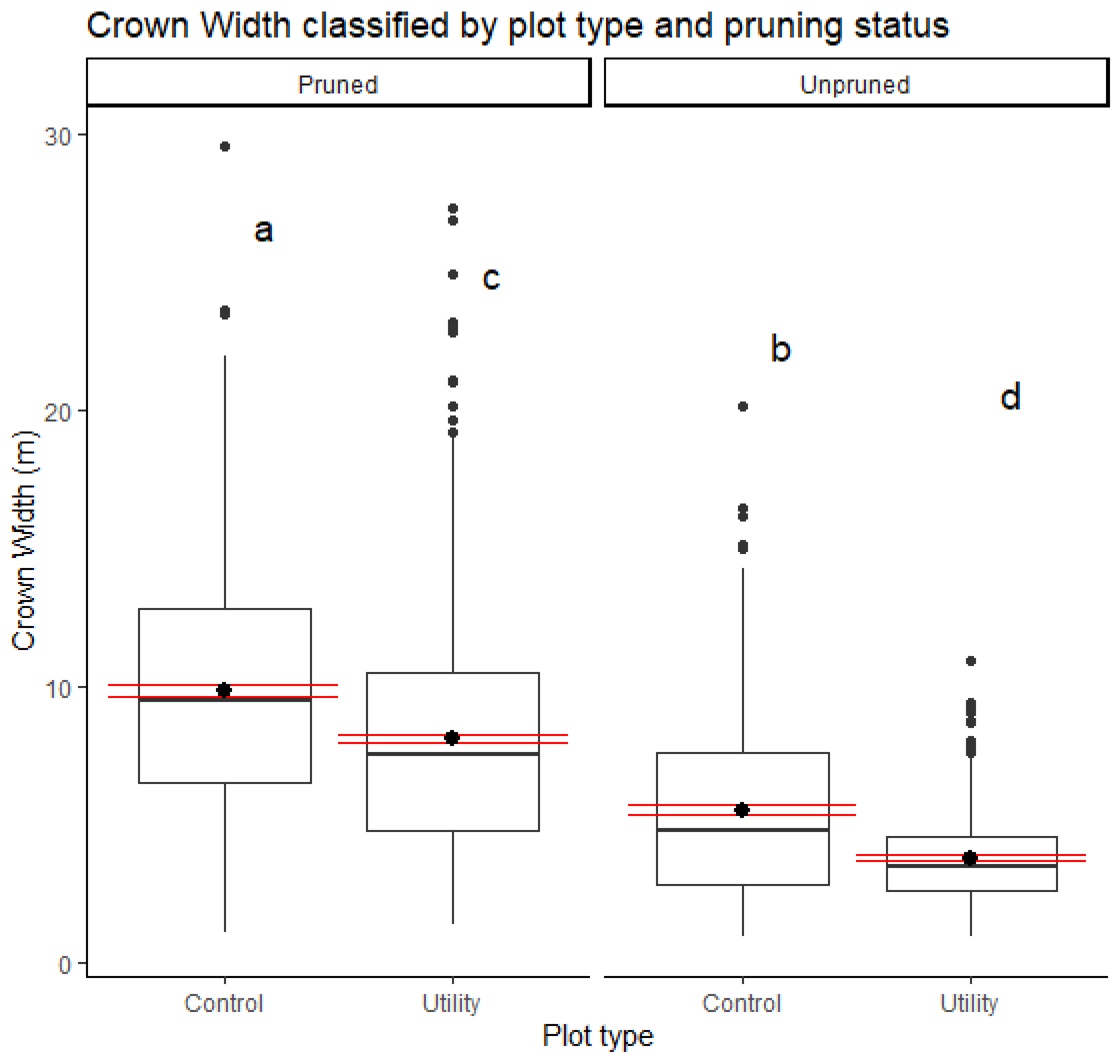


Figure 6. Box and whisker plot of mean crown width (m) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whiskers are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Crown Length

Mean crown length (m) varied among plot type, pruning status, and their interaction. Table 6 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on crown length; Figure 7 shows the distribution of crown length classified by plot type and pruning status in a box and whisker plot. Mean crown length of trees in control plots was greater than for utility plots, and mean crown length of pruned trees was greater than unpruned trees. The magnitude of difference was greater between pruned and unpruned trees in utility plots than between pruned and unpruned trees in control plots.

Table 6. ANOVA (type III) table for the poisson distribution model for the effects of plot type and pruning status on mean crown length (m); within each interaction, means followed by the same letter are not significantly ($p < 0.05$) different; Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	12.817	1	0.00034		
				Control	8.46 (±0.13) a
				Utility	7.89 (±0.19) b
Pruning status	194.909	1	<2.2E-16		
				Pruned	9.39 (±0.13) a
				Unpruned	5.36 (±0.14) b
Plot type * Pruning status	163.454	1	<2.2E-16		
				Control Pruned	9.88 (±0.25) a
				Control Unpruned	6.87 (±0.25) b
				Utility Pruned	9.22 (±0.15) c
				Utility Unpruned	3.93 (±0.11) d

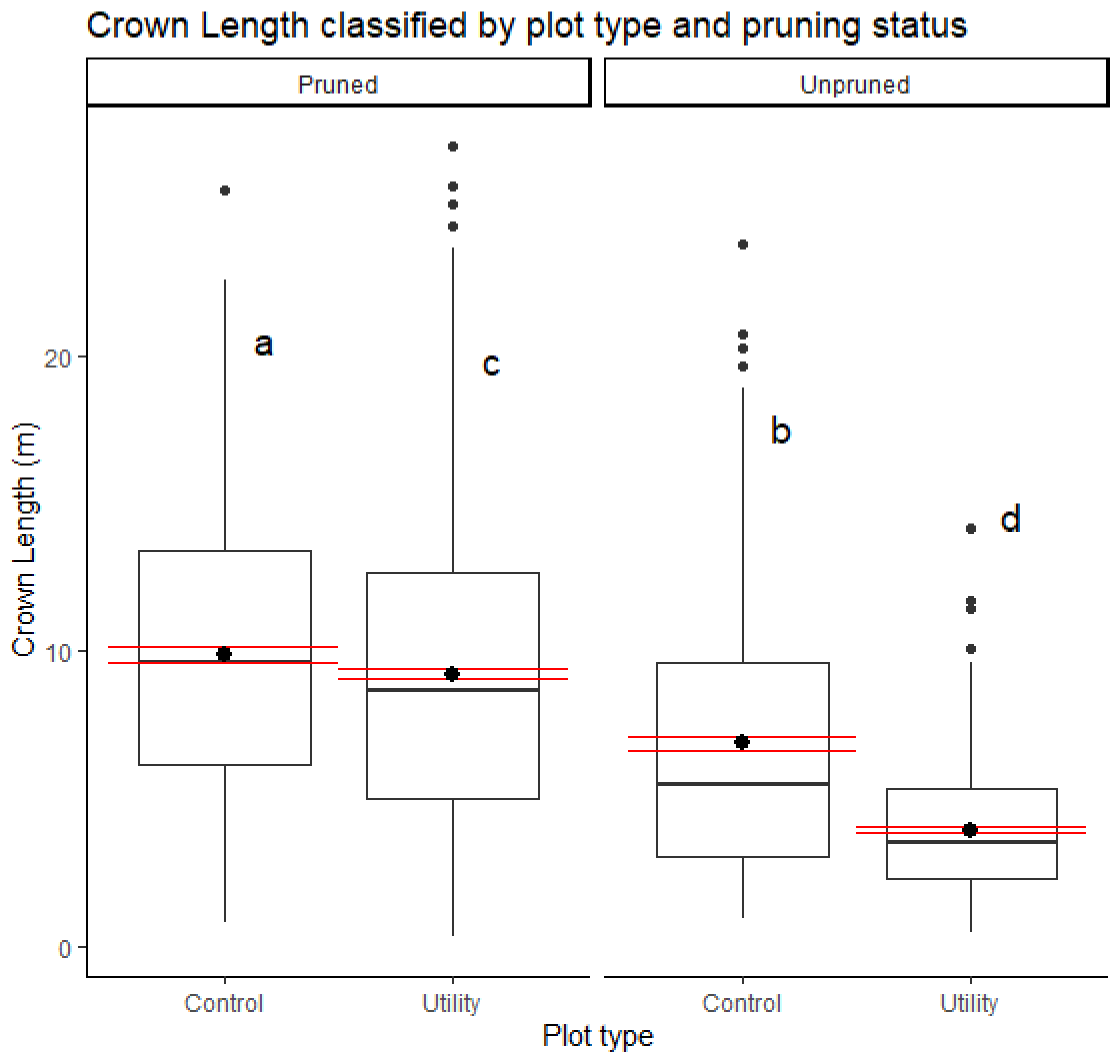


Figure 7. Box and whisker plot of mean crown length (m) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whiskers are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Crown Volume

Mean crown volume (m^3) varied among plot type, pruning status, and their interaction. Table 7 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on crown volume; Figure 8 shows the distribution of crown volume classified by plot type and pruning status in a box and whisker plot. Mean crown volume of trees in control plots was greater than for utility plots, and mean crown volume of pruned trees was greater than unpruned trees. The magnitude of difference was greater between pruned and unpruned trees in utility plots than between pruned and unpruned trees in control plots.

Table 7. ANOVA (type III) table for the gamma distribution model for the effects of plot type and pruning status on mean crown volume (m^3); within each interaction, means followed by the same letter are not significantly ($p < 0.05$) different; Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	28.912	1	7.57E-08		
				Control	355.89 (±13.95) a
				Utility	240.70 (±23.51) b
Pruning status	90.260	1	<2.2E-16		
				Pruned	373.46 (±17.09) a
				Unpruned	84.22 (±8.75) b
Plot type * Pruning status	23.625	1	1.17E-06		
				Control Pruned	549.41 (±39.18) a
				Control Unpruned	138.81 (±17.31) b
				Utility Pruned	310.70 (±18.13) c
				Utility Unpruned	32.63 (±2.77) d

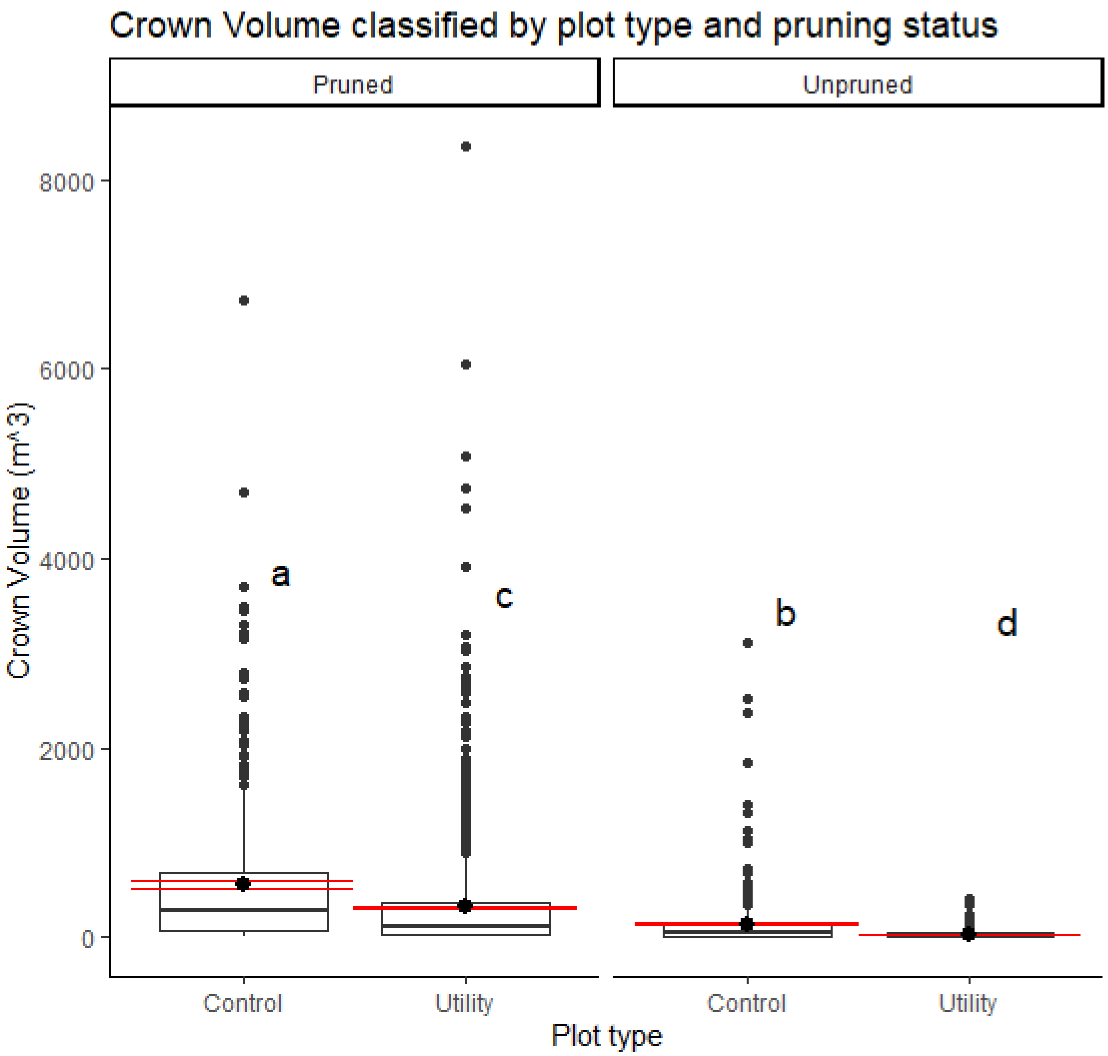


Figure 8. Box and whisker plot of mean crown volume (m^3) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whiskers are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Percent Crown Missing

Mean percent crown missing (in bins of 5%) varied among plot type, pruning status, and their interaction. Table 8 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on mean percent crown missing; Figure 9 shows the distribution of percent crown missing classified by plot type and pruning status in a box and whisker plot. Mean percent crown missing for trees in utility plots was greater than for trees in control plots, and mean percent crown missing for pruned trees was greater than for unpruned trees. The mean value for unpruned trees growing in utility plots was similar to both unpruned trees growing in control plots as well as pruned trees in control plots. Mean percent crown missing was greater for pruned trees in utility plots than for unpruned trees in utility plots, but greater for unpruned trees in control plots than pruned trees in control plots. The magnitude of difference was greater between pruned and unpruned trees in utility plots than between pruned and unpruned trees in control plots.

Table 8. ANOVA (type III) table for the gaussian distribution model for the effects of plot type and pruning status on percent crown missing (in bins of 5%); within each main effect or interaction, means followed by the same letter are not significantly ($p < 0.05$) different; Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	149.628	1	<2.20E-16		
				Control	8.4 (±0.21) a
				Utility	11.2 (±0.15) b
Pruning status	7.649	1	0.006		
				Pruned	10.9 (±0.14) a
				Unpruned	8.9 (±0.24) b
Plot type * Pruning status	65.646	1	5.40E-16		

Control Pruned	7.9 (±0.26) a
Control Unpruned	9.0 (±0.34) b
Utility Pruned	12.0 (±0.16) c
Utility Unpruned	8.8 (±0.34) ab

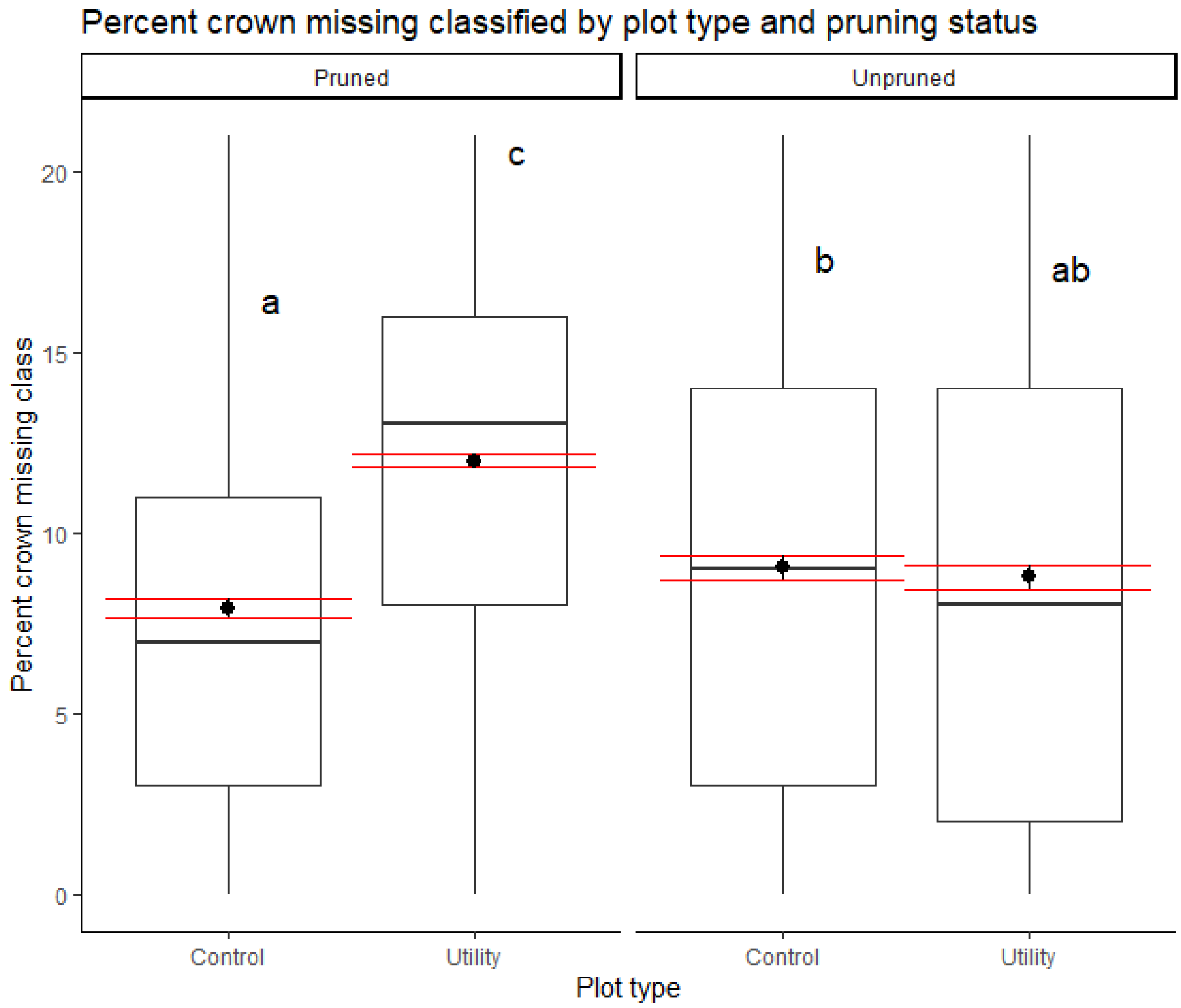


Figure 9. Box and whisker plot of total percent crown missing (in bins of 5%) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whisker are outlies; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the

red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Carbon Storage

Mean carbon storage (kg) varied among plot type, pruning status, and their interaction. Table 9 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on mean carbon storage; Figure 10 shows the distribution of carbon storage classified by plot type and pruning status in a box and whisker plot. Mean carbon storage for trees in control plots was greater than for trees in utility plots, and mean carbon storage for pruned trees was greater than for unpruned trees. The magnitude of difference was greater between pruned and unpruned trees in utility plots than between pruned and unpruned trees in control plots.

Table 9. ANOVA (type III) table for gamma distribution model for the effects of plot type and pruning status on total carbon storage (kg); within each main effect or interaction, means followed by the same letter are not significantly ($p < 0.05$) different; Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	15.467	1	8.40E-05		
				Control	455.75 (±31.00) a
				Utility	352.01 (±16.71) b
Pruning status	84.339	1	<2.2E-16		
				Pruned	523.80 (±21.17) a
				Unpruned	107.1 (±11.29) b
Plot type * Pruning status	48.585	1	3.16E-12		
				Control Pruned	706.85 (±53.19) a
				Control Unpruned	184.44 (±21.85) b
				Utility Pruned	459.75 (±21.38) c
				Utility Unpruned	32.97 (±4.71) d

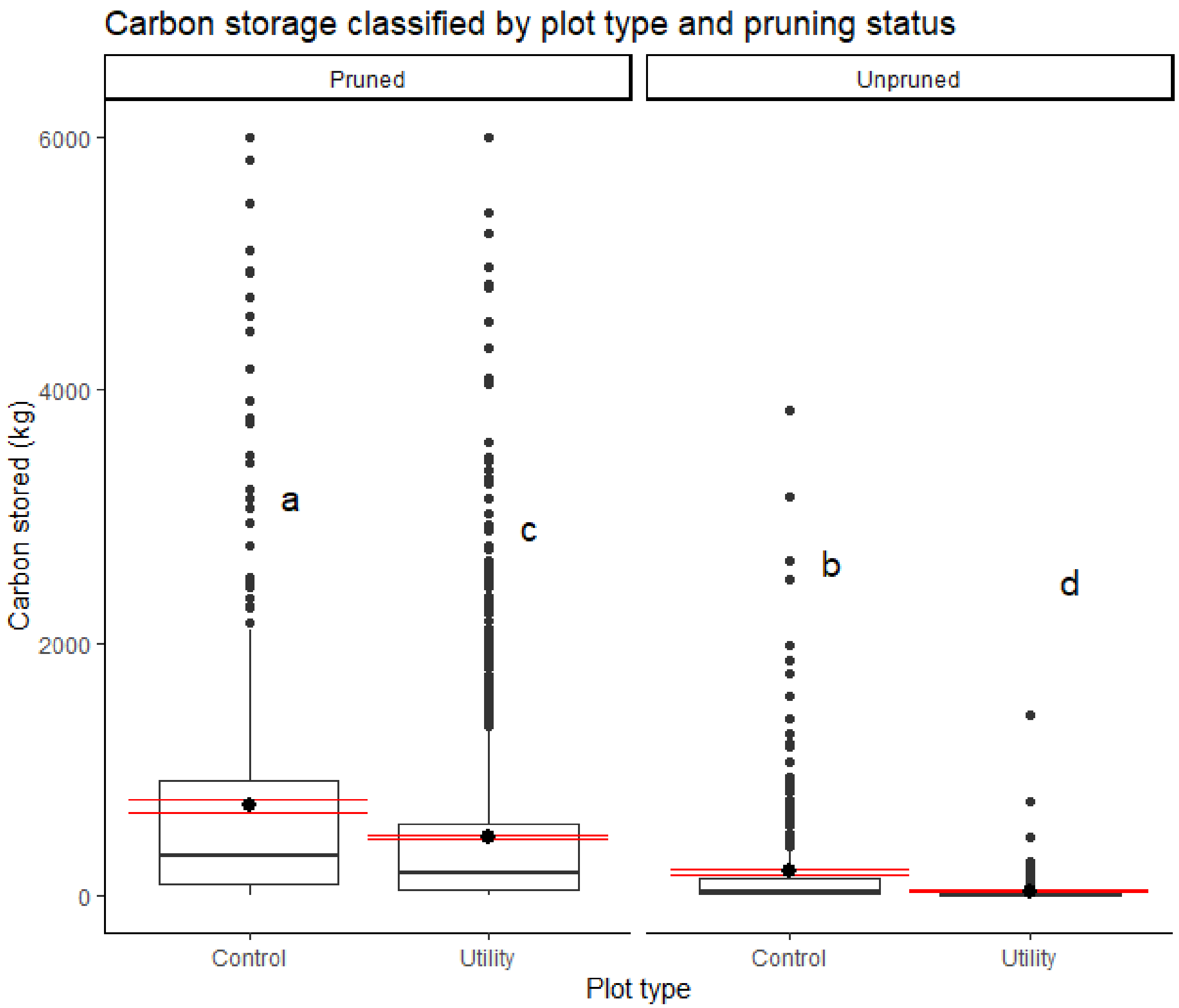


Figure 10. Box and whisker plot of carbon storage (kg) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whisker are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Annual Carbon Sequestration

Mean annual carbon sequestration (kg) varied among plot type, pruning status, and their interaction. Table 10 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on mean annual carbon sequestration, Figure 11 shows the distribution of DBH classified by plot type and pruning status in a box and whisker plot. Mean annual carbon sequestration in control plots was greater than in utility plots, and mean annual carbon sequestration for pruned trees was greater than for unpruned trees. The magnitude of difference was greater for pruned and unpruned trees in utility plots than between pruned and unpruned trees in control plots.

Table 10. ANOVA (type III) table for the gamma distribution model of the effects of plot type and pruning status on annual carbon sequestration (kg); within each main effect or interaction, means followed by the same letter are not significantly ($p < 0.05$) different; Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	**LR Chi-sq**	**Df**	**P-value**	**Level**	**Mean (±std err)**
Plot type	25.192	1	5.189E-07		
				Control	12.80 (±0.58) a
				Utility	10.81 (±0.35) b
Pruning status	159.028	1	<2.20E-16		
				Pruned	14.93 (±0.41) a
				Unpruned	4.43 (±0.27) b
Plot type * Pruning status	8.691	1	0.000320		
				Control Pruned	19.14 (±0.91) a
				Control Unpruned	5.96 (±0.49) b
				Utility Pruned	13.46 (±0.44) c
				Utility Unpruned	2.97 (±0.23) d

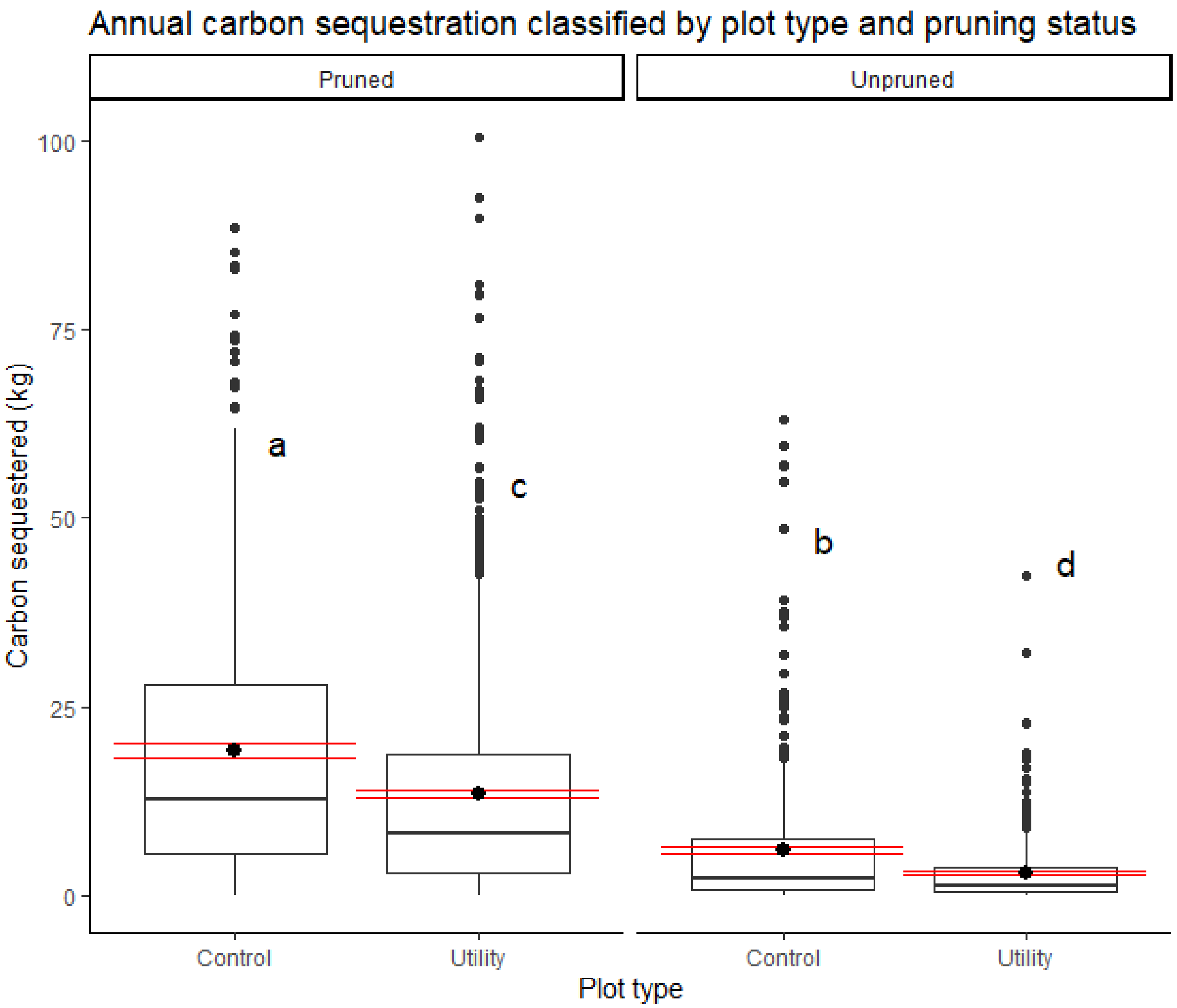


Figure 11. Box and whisker plot of annual carbon sequestration (kg) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whisker are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Annual Runoff Avoided

Mean annual runoff avoided (m^3) varied with plot type and pruning status. Table 11 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on mean runoff avoided; Figure 12 shows the distribution of DBH classified by plot type and pruning status in a box and whisker plot. Mean annual runoff avoided for trees in control plots was greater than for trees in utility plots, and mean annual runoff avoided for pruned trees was greater than for unpruned trees. The magnitude of difference between pruned and unpruned trees was greater than the difference between trees in control plots and trees in utility plots.

Table 11. ANOVA (type III) table for gamma distribution model for the effects of plot type and pruning status on annual runoff avoided (m^3); within each main effect, means followed by the same letter are not significantly ($p < 0.05$) different.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	34.417	1	4.448E-09		
				Control	1.06 (±0.05) a
				Utility	0.80 (±0.03) b
Pruning status	104.678	1	<2.20E-16		
				Pruned	1.12 (±0.03) a
				Unpruned	0.41 (±0.03) b
Plot type * Pruning status	3.509	1	0.061		

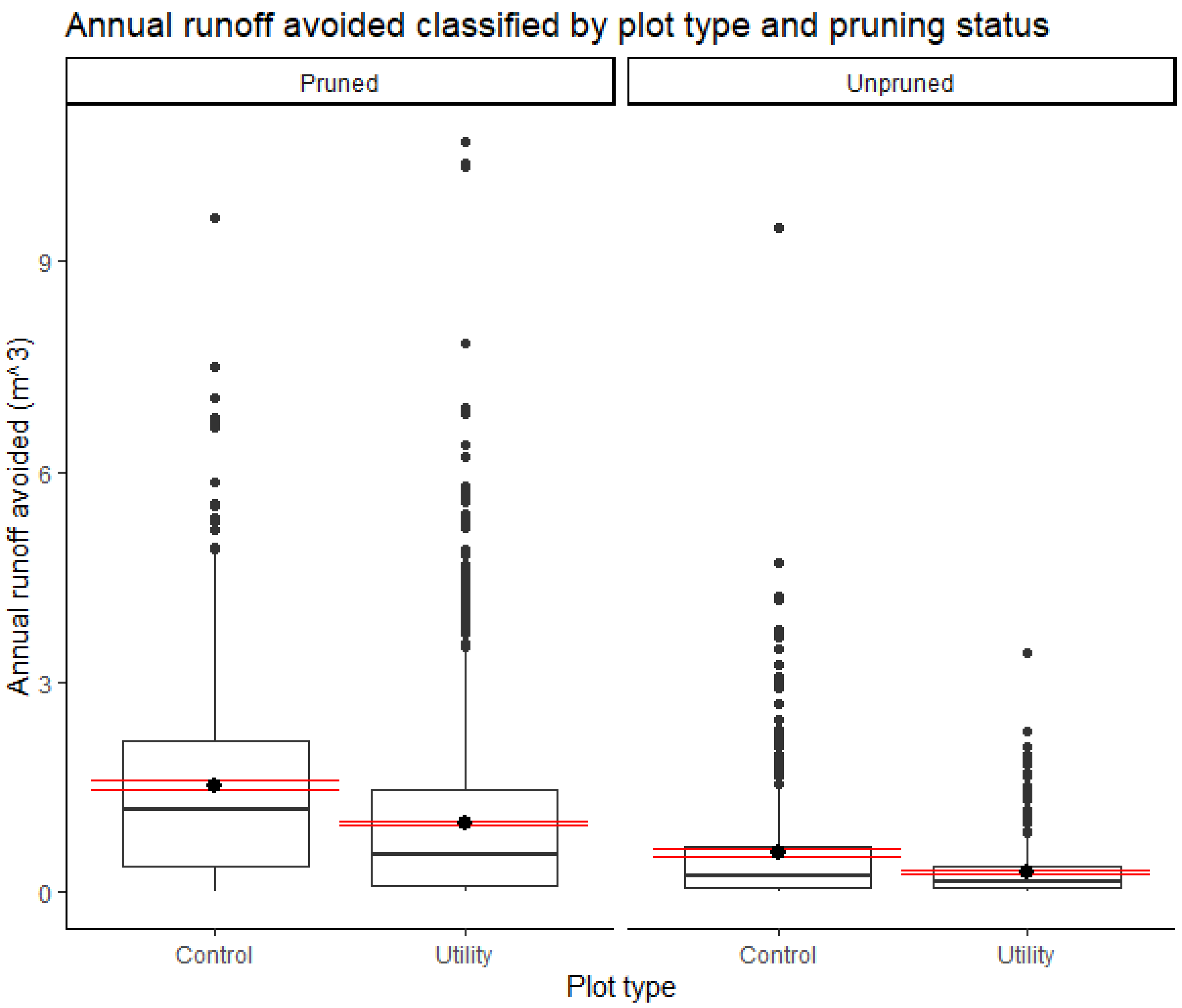


Figure 12. Box and whisker plot of annual runoff avoided (m^3) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whiskers are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean.

Annual Air Pollution Removed

Mean annual air pollution removed (g) varied with plot type and pruning status. Table 12 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on mean annual air pollution removed; Figure 13 shows the distribution of DBH classified by plot type and pruning status in a box and whisker plot. Mean annual air pollution removed in control plots was greater than in utility plots, and annual air pollution removed by pruned trees was greater than for unpruned trees. The magnitude of difference was greater between pruned and unpruned trees than between trees in utility plots and trees in control plots.

Table 12. ANOVA (type III) table for gamma model for effects of plot type and pruning status on annual air pollution removed (g); within each main effect or interaction, means followed by the same letter are not significantly ($p < 0.05$) different.

Parameter	LR Chi-sq	Df	P-value	Level	Mean (±std err)
Plot type	39.864	1	2.723E-10		
				Control	135.85 (±5.88) a
				Utility	102.80 (±3.51) b
Pruning status	106.741	1	<2.2E-16		
				Pruned	141.66 (±4.11) a
				Unpruned	57.15 (±3.21) b
Plot type * Pruning status	2.301	1	0.129		

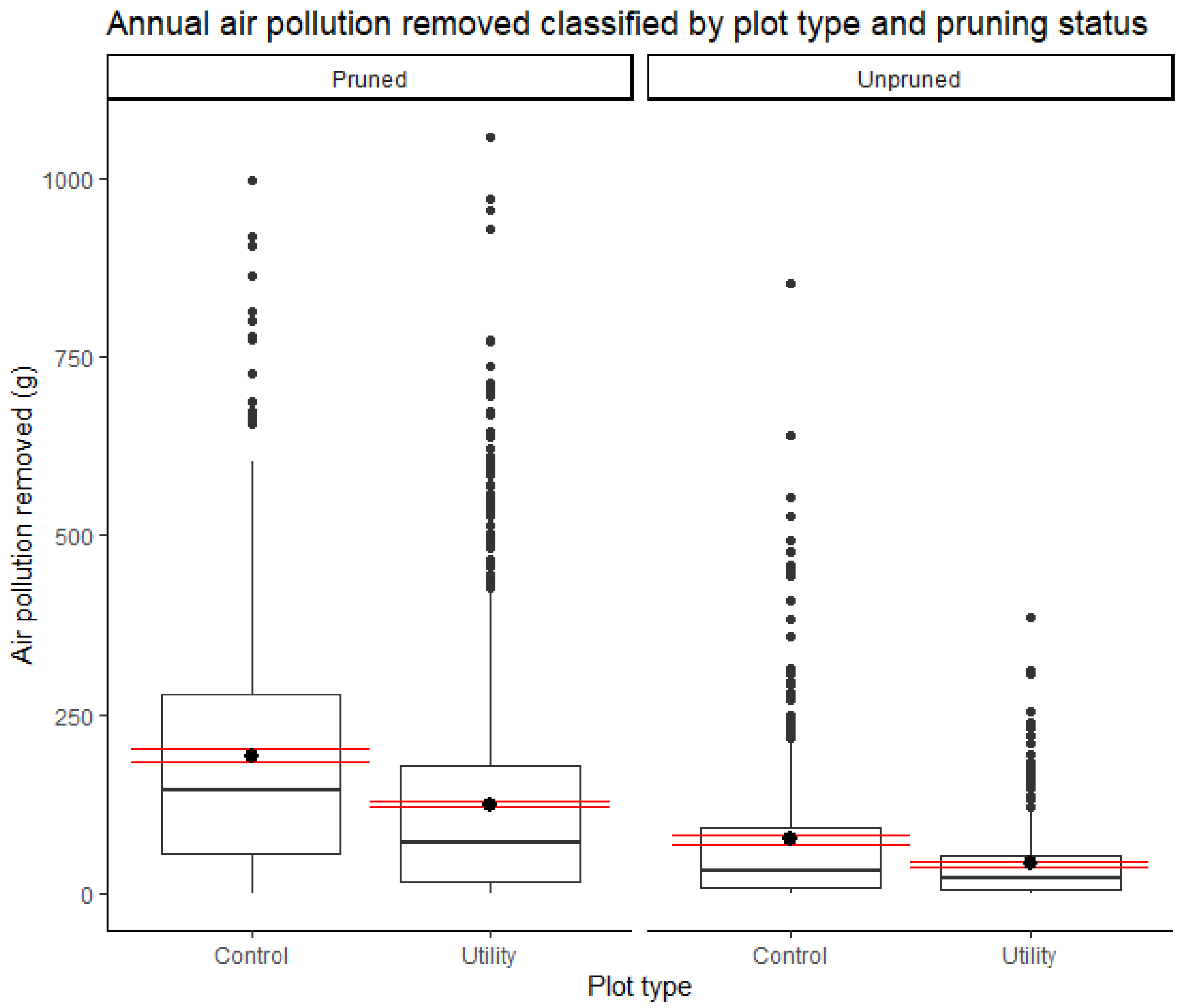


Figure 13. Box and whisker plot of annual air pollution removed (g) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whisker are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean.

Structural Value

Mean structural value ($) varied among plot type, pruning status, and their interaction. Table 13 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on structural value; Figure 14 shows the distribution of DBH classified by plot type and pruning status in a box and whisker plot. Mean structural value of trees in control plots was greater than for trees in utility plots, and mean structural value of pruned trees was greater than unpruned trees. The magnitude of difference was greater between pruned and unpruned trees in utility plots than between pruned and unpruned trees in control plots.

Table 13. ANOVA (type III) table for the zero-inflated negative binomial modeled effects of plot type and pruning status on structural value ($); within each main effect or interaction, means followed by the same letter are not significantly ($p < 0.05$) different; Tukey's Honestly Significant Difference test was used for multiple comparisons of interaction terms.

Parameter	**LR Chi-sq**	**Df**	**P-value**	**Level**	**Mean (±std err)**
Plot type	20.736	1	5.271E-06		
				Control	1850.58 (±90.92) a
				Utility	1645.52 (±53.44) b
Pruning status	234.887	1	2.2E-16		
				Pruned	2258.24 (±63.04) a
				Unpruned	603.88 (±36.16) b
Plot type * Pruning status	25.656	1	4.08E-07		
				Control Pruned	2793.25 (±148.85) a
				Control Unpruned	831.68 (±67.47) b
				Utility Pruned	2071.03 (±66.47) c
				Utility Unpruned	385.50 (±24.23) d

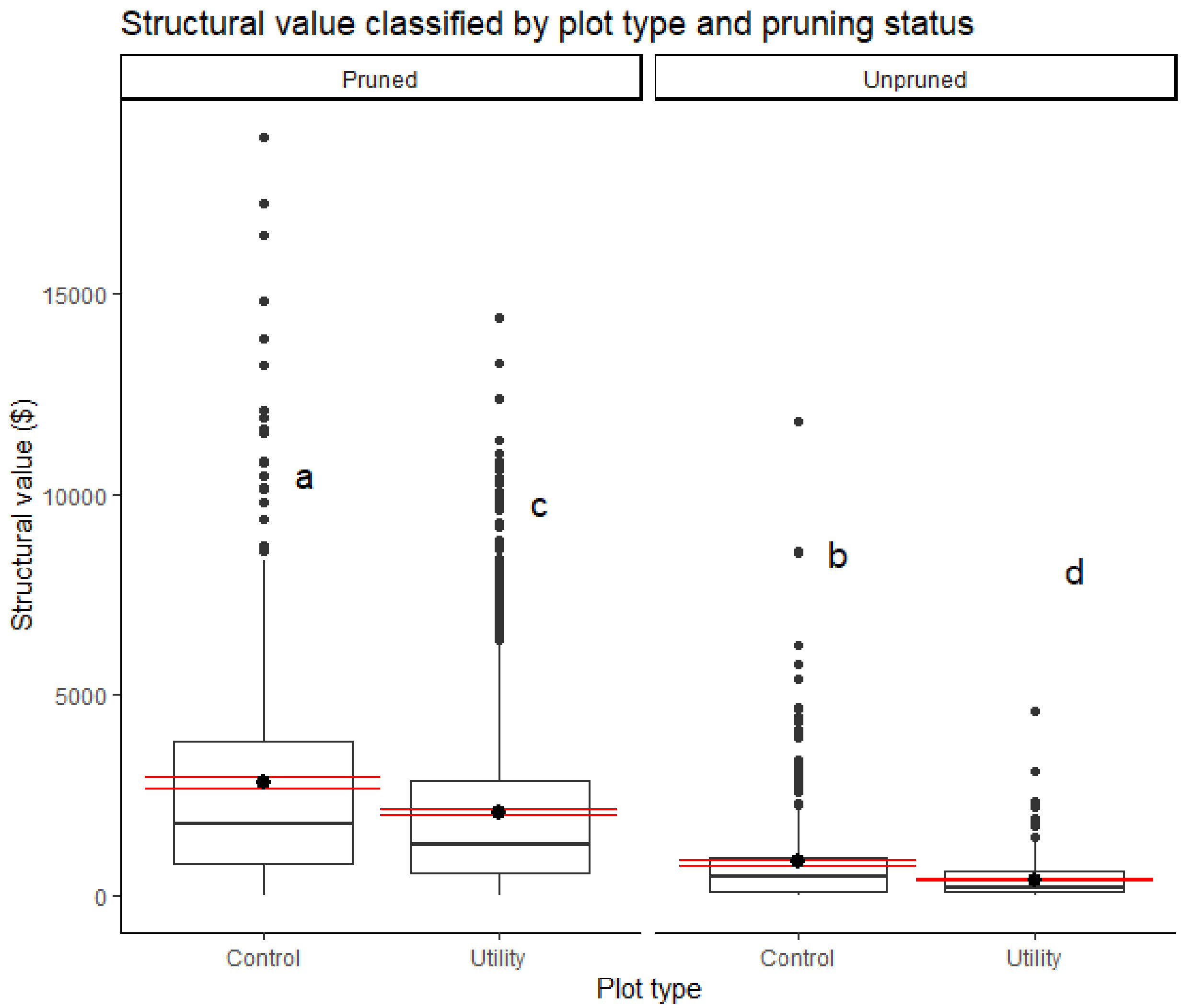


Figure 14. Box and whisker plot of structural value ($) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whisker are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean; letters to the right of upper outliers or whiskers indicate significantly different ($p < 0.05$) means.

Value of Annual Ecosystem Services Delivery

Mean value of annual ecosystem services delivery ($) varied significantly across plot type and pruning status. Table 14 presents the ANOVA output for the effects of plot type, pruning status, and their interaction on mean value of annual ecosystem services delivery; Figure 15 shows the distribution of value of annual ecosystem services delivery classified by plot type and pruning status in a box and whisker plot. Mean value of annual ecosystem services delivery for trees in control plots was greater than for trees in utility plots, and greater for pruned trees than unpruned trees. The magnitude of difference was greater between pruned and unpruned trees than between trees in control plots and trees in utility plots.

Table 14. ANOVA (type III) table for the gamma distribution model of effects of plot type and pruning status on value of annual ecosystem services delivery ($); within each main effect or interaction, means followed by the same letter are not significantly ($p < 0.05$) different.

Parameter	**LR Chi-sq**	**Df**	**P-value**	**Level**	**Mean (±std err)**
Plot type	51.299	1	7.933E-13		
				Control	5.65 (±0.28) a
				Utility	4.18 (±0.15) b
Pruning status	161.791	1	<2.2E-16		
				Pruned	5.99 (±0.19) a
				Unpruned	1.99 (±0.12) b
Plot type * Pruning status	1.606	1	0.2051		

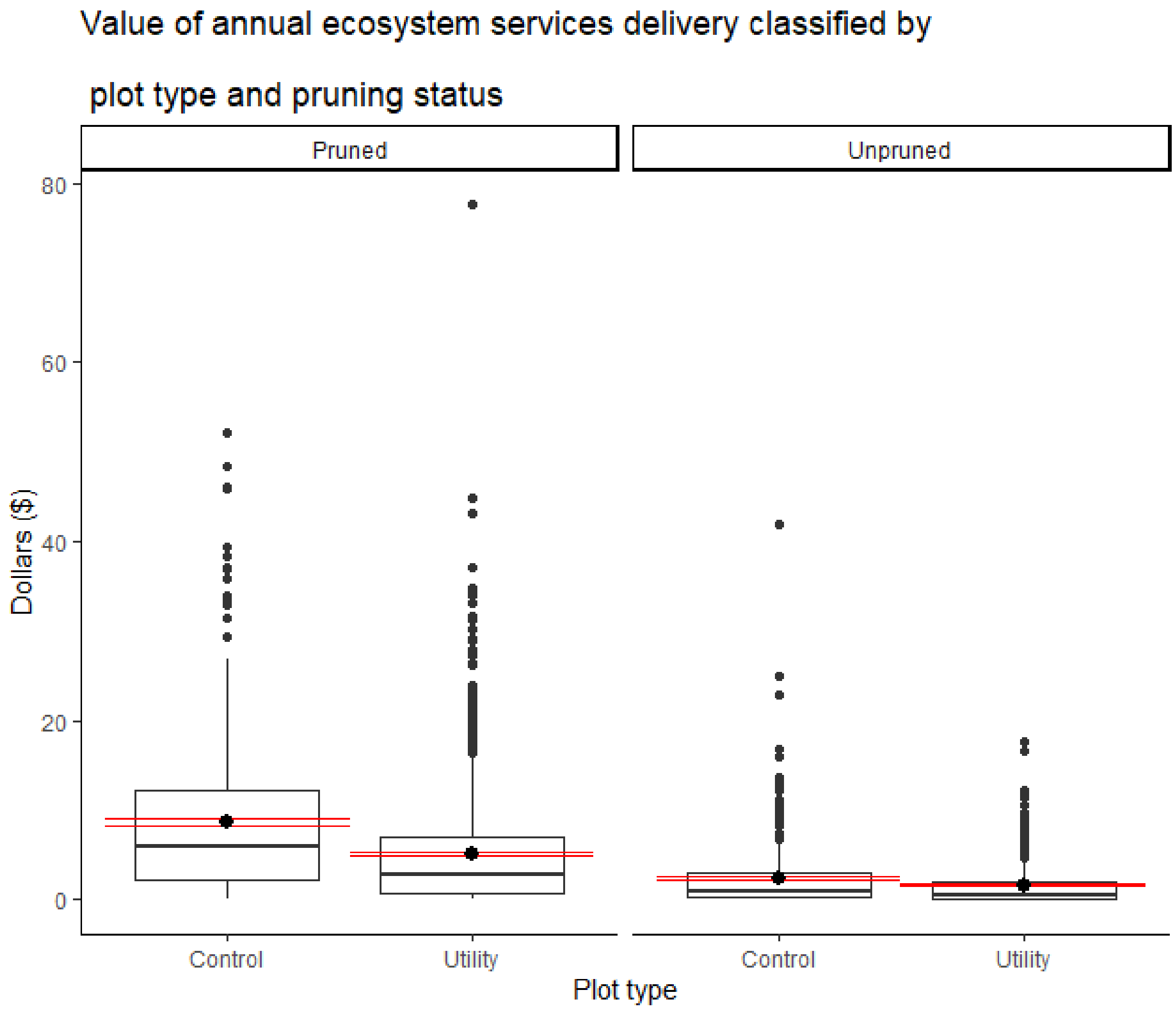


Figure 15. Box and whisker plot of value of annual ecosystem services delivery ($) classified by plot type and pruning status. The box indicates upper and lower quartiles, representing one interquartile range (IQR) between the 25th percentile (Q1) and 75th percentile (Q3); whiskers indicate 1.5 IQR above Q3 and below Q1; the black dots beyond the whisker are outliers; the heavy black line indicates the median; the black dot in the box indicates the sample mean; the red lines represent 1 standard error above and below the sample mean.

Likelihood of Failure

Likelihood of Failure was analyzed with an ordinal logistic regression model including the predictor variables DBH, plot type, pruning statues, and percent crown dieback. Table 15 reports the model summary table, and Table 16 reports the ANOVA output for the effect of each predictor variable and their interactions. Figure 16 visualizes the relationship between these four predictor variables on the proportional response of likelihood of failure.

Variation in likelihood of failure was not significantly associated with plot type alone, nor with any interaction terms including plot type. However, its inclusion in the model improved both the Akaike Information Criteria score as well as the calculated McFadden's PseudoR2 value, thus plot type was retained in the final model (Table 15). Likelihood of failure varied significantly with DBH, percent crown dieback, and pruning status, as well as the interaction between pruning status and DBH, and the interaction between dieback and DBH (Table 16).

Trees with larger DBH had higher likelihood of failure ratings than trees with smaller DBH (Table 16). The magnitude of difference was greatest between small DBH unpruned trees and large DBH unpruned trees regardless of plot type or dieback. As percent crown dieback increased, differences in likelihood of failure between large DBH trees and small DBH trees increased in magnitude (Figure 16). The difference in likelihood of failure between small DBH trees and large DBH trees is greater in magnitude for unpruned trees than pruned trees.

Trees with higher levels of percent crown dieback had a higher likelihood of failure rating than trees with lower levels of percent crown dieback (Table 16). As DBH increased, the magnitude of difference in likelihood of failure between trees with higher and lower levels of percent crown dieback increased in magnitude (Figure 16). The magnitude of difference between large DBH trees with high levels of percentage crown dieback and large DBH trees with low percentage of crown dieback was greater than the difference between small DBH trees with high levels of percentage crown dieback and small DBH trees with low percentage of crown dieback (Figure 16).

Pruned trees had a higher likelihood of failure than unpruned trees (Table 16), however this relationship is not constant at all values of DBH (Figure 16). Small DBH pruned trees had a higher likelihood of failure than small DBH unpruned trees. As DBH increased, the relationship between likelihood of failure of pruned and unpruned trees reversed; large diameter unpruned trees were more likely to be classified in the higher categories of likelihood of failure than large diameter pruned trees, while smaller diameter pruned trees were similar to smaller diameter unpruned trees.

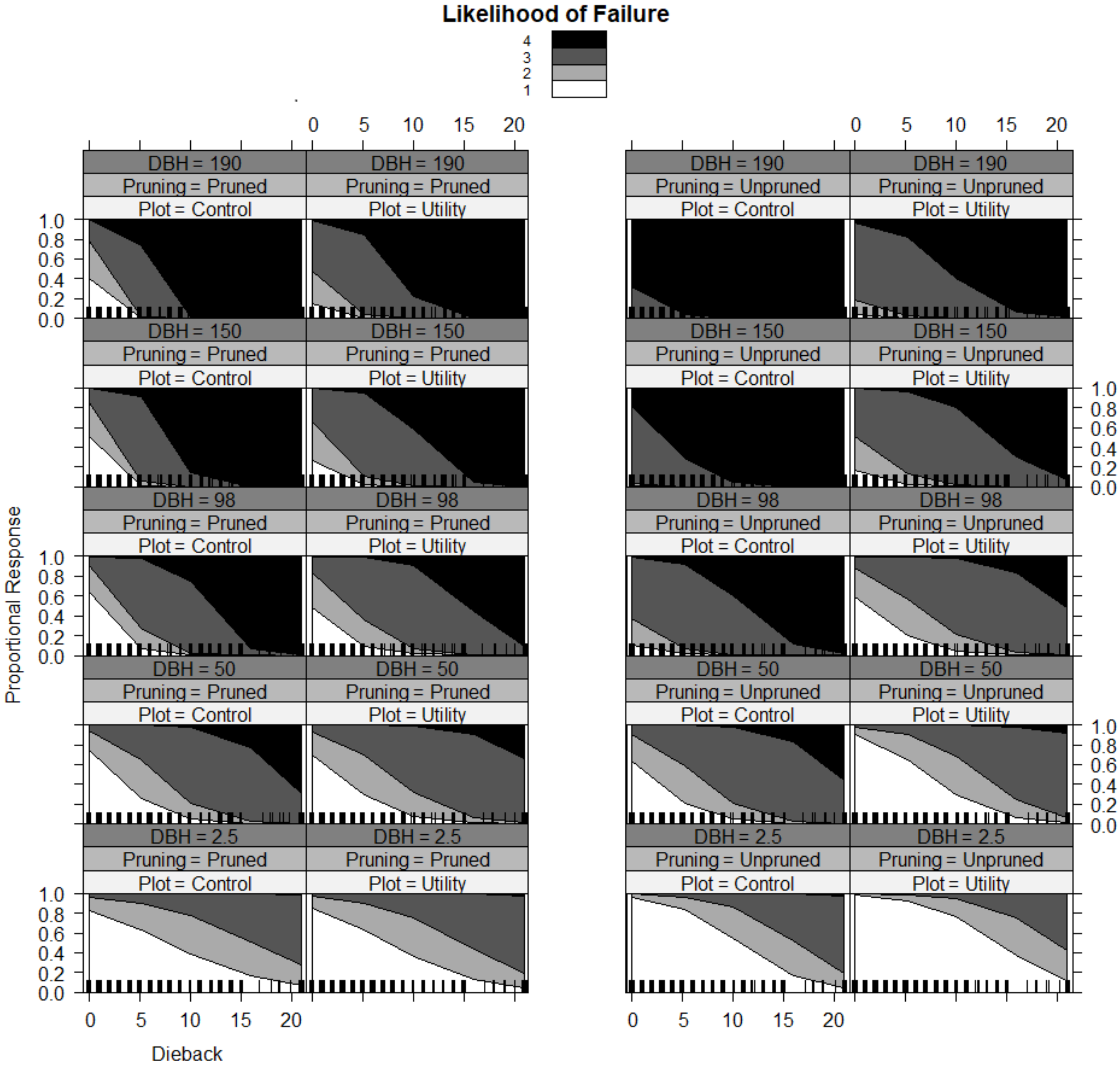


Figure 16. Visualization of ordinal linear regression model of effect of plot type (Plot= Utility or Control), pruning status (Pruning = Pruned or Unpruned), diameter at breast height (DBH, cm), and dieback class (Dieback) on the proportional response of assessed likelihood of failure (1-4, white-black).

Table 15. Output table for ordinal logistic regression modeling the effects of predictor variables plot, pruning status, DBH, and percent crown dieback on response of likelihood of failure. Response given on the model (log) scale, not of response. Values are compared to base case of Control:Pruned. Fitted McFadden pseudo-r2 value: 0.2511

Coefficients	Value	Std. Error	t value	p value[z]		Odds Ratio	2.5% CI	97.5% CI
Utility:Pruned	-0.153	0.260	-0.59	0.5553		0.86	0.52	1.44
Control:Unpruned	-1.799	0.387	-4.65	3.32E-06	***	0.17	0.08	0.35
Control:Pruned:Dieback	0.189	0.065	2.92	0.00348	*	1.21	1.07	1.37
Control:Pruned:DBH	0.010	0.004	2.47	0.01358	.	1.01	1.00	1.02
Utility:Unpruned	-0.617	0.581	-1.06	0.2885		0.54	0.17	1.66
Utility:Pruned:Dieback	0.033	0.069	0.48	0.63338		1.03	0.90	1.18
Control:Unpruned:Dieback	0.112	0.077	1.46	0.14535		1.12	0.96	1.30
Utility:DBH	0.008	0.005	1.64	0.10023		1.01	1.00	1.02
Control:Unpruned:DBH	0.047	0.009	5.09	3.58E-07	***	1.05	1.03	1.07
Control:Pruned:Dieback:DBH	0.004	0.002	2.24	0.02541	*	1.00	1.00	1.01
Utility:Unpruned:Dieback	-0.048	0.090	-0.54	0.59093		0.95	0.80	1.14
Utility:Unpruned:DBH	-0.027	0.016	-1.69	0.09033		0.97	0.94	1.00
Utility:Pruned:Dieback:DBH	-0.002	0.002	-1.07	0.28276		1.00	0.99	1.00
Control:Unpruned:Dieback:DBH	-0.003	0.002	-1.33	0.18197		1.00	0.99	1.00
Utility:Unpruned:Dieback:DBH	0.002	0.005	0.38	0.70509		1.00	0.99	1.01

Intercepts[y]					
1|2	1.589	0.2252	7.0585	1.68E-12	***
2|3	3.267	0.238	13.725	7.15E-43	***
3|4	8.266	0.4629	17.856	2.60E-71	***

[z] Significance Codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’

[y] Intercepts, or cutpoints, indicate where the response variable is cut to make the four levels of likelihood of failure. 1|2 can be interpreted as the log odds of a tree falling into **1** vs **2** level of likelihood of failure; 2|3 can be interpreted as the log odds of a tree falling into **2** vs **3** level of likelihood of failure; 3|4 can be interpreted as the log odds of a tree falling into **3** vs **4** level of likelihood of failure. This number is combined with the value of the coefficient in the upper section of this table to view the coefficient’s relationship to the base case of Control:Pruned at leach level of likelihood of failure.

Table 16. ANOVA (Type III) table for response of assessed likelihood of failure.

Effect	**LR Chisq**	**Df**	**Pr(>Chisq)**	
Plot	0.34565	1	0.55658	
Pruning	23.552	1	1.22E-06	***
Dieback	9.50892	1	0.00204	**
DBH	6.12412	1	0.01333	*
Plot:Pruning	1.14822	1	0.28392	
Plot:Dieback	0.22618	1	0.63437	
Pruning:Dieback	2.07085	1	0.15014	
Plot:DBH	2.68904	1	0.10104	
Pruning:DBH	27.7733	1	1.36E-07	***
Dieback:DBH	5.10899	1	0.0238	*
Plot:Pruning:Dieback	0.28671	1	0.59234	
Plot:Pruning:DBH	3.00461	1	0.08303	.
Plot:Dieback:DBH	1.15997	1	0.28147	
Pruning:Dieback:DBH	1.70777	1	0.19128	
Plot:Pruning:Dieback:DBH	0.14293	1	0.70538	

Signif. Codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’

CHAPTER 5

DISCUSSION

This study contributes to the relatively limited but growing body of research focused on utility arboriculture. Utilities often collect and analyze data necessary to improve vegetation management programs, but studies are typically not published in peer-reviewed journals – evident from the comparatively small proportion of utility-specific research found in a literature review on tree pruning (Vogt et al. 2016). Recent studies have focused specifically on utility forest management on compatible right-of-way species richness (Mahan et al. 2020) and the effects of main stem reduction pruning on small stature trees in a nursery setting (Perrette et al. 2020, 2021), but the effect of utility pruning on larger trees in the landscape has not been as deeply investigated outside of the implications of converting previously topped crowns to directionally pruned V-shaped crowns (Dahle et al. 2006a; Dahle et al. 2006b). Furthermore, at the time of writing, utility forests have not been compared to the greater urban forest to investigate differences between the two populations. The current study investigated how trees growing near overhead utility lines differed from trees growing away from them. Additionally, the current study utilized a novel and specific utility forest i-Tree Eco assessment to investigate how trees growing near overhead utility lines may functionally differ from trees growing elsewhere in terms of calculated ecosystem service delivery capacity.

However, the current was mensurative in nature; trees were not measured before and after manipulative pruning treatments, thus limiting the ability to empirically demonstrate the effects of utility pruning at an individual tree level. With the allowed budget and time scale of the current study, though, a manipulative study design was not possible. Manipulative studies of large stature trees are relatively rare in arboricultural literature, and to an even greater extent when narrowing the focus to utility pruning. Hiring qualified professionals to safely conduct this pruning and monitoring the trees over the course of several utility pruning cycles, which are typically three to five years in the United States, would be prohibitively costly and out of the scope of reasonable expectation for a master's thesis project. Similarly, estimations of ecosystem services delivery by i-Tree Eco are admittedly uncertain at the individual tree level, and errors are likely sizeable due to its calculation structures (Nowak 2020). To address these constraints, a large sample was collected to analyze trends in each response variable within the study populations. Despite the observational nature of the current study, the results still provided interesting and valuable insight for the practice of utility arboriculture.

Morphological and i-Tree Eco response variables

Several broad trends were evident in analysis of the data in this study. Firstly, all morphological variables (DBH; tree height; crown width; crown length; crown volume; percent crown missing) had greater means for pruned trees than for unpruned trees. This outcome was originally counterintuitive because previous studies have shown that pruning generally slows growth (Gilman and Grabosky 2009, Kristoffersen et al. 2010, Gilman 2015a, Gilman 2015b), especially when pruned with increasing severity (Clair-Maczulajtys et al. 1999, Víquez and Pérez 2005). This initially unexpected set of results, though, benefits from consideration of how arborists generally prune trees in an industry setting, leading to an alternative plausible explanation. Since there were large disparities in some morphological aspects (DBH; tree height; crown width; crown length; crown volume), it is plausible that large trees were more likely to have been pruned than smaller trees. This was intuitive because larger trees often present greater risk or are more likely to conflict with infrastructure, and pruning can mitigate both.

Since pruned trees were larger than unpruned trees, their estimated delivery of ecosystem services was also greater because i-Tree uses morphological data inputs (DBH; tree height; crown size; calculated leaf area; projected growth rates) to estimate ecosystem service delivery. Further and more detailed descriptions of which specific variables i-Tree Eco utilizes in each calculation can be found in Nowak (2020). Since all response variables from i-Tree are directly proportional to one or more aspects of tree size, it follows that pruned trees were more productive than unpruned trees in all i-Tree models.

Additionally, unpruned trees differed from each other across each plot type. Unpruned trees in control plots were nearly twice as tall as those in utility plots. This may plausibly be explained by the hazardous consequences of tree conflict with overhead utility lines and the nature of the scale of conflict they present. Municipal and commercial arborists also manage tree risk and trees in utility plots and trees in control plots had similar likelihood of failure ratings (all other variables held constant) despite apparently different pruning strategies.

However, utility lines are continuous over long distances, and tree conflict may lead to immediately hazardous or life-threatening scenarios such as power outages, fires, or electrocution far beyond the localized conflict location. This may compel utility arborists to initiate pruning of all trees in proximity to the overhead lines when trees are shorter. Commercial and municipal arborists also consider tree conflicts with infrastructure, but their commonly considered infrastructure conflicts are typically not continuous for long distances (e.g. blocking streetlights, impeding pedestrian or vehicular traffic, obscuring signage, etc.). Given this notion, it seems that utility arborists may identify and mitigate risk more proactively than commercial or municipal arborists.

In further support of this idea, utility companies have larger tree care budgets than municipalities do. This plausibly allows them to identify and mitigate potential conflicts more proactively. A technical report by Hauer and Peterson (2015) describes a survey of 668 municipalities across the United States. Mean budgets for municipal tree care in 2014 were approximately $801,595. Of this total, approximately half dedicated to tree pruning and removal (Hauer and Peterson 2015). While no similar survey exists for utility companies' tree-related budgets, a technical report by Lovelace (1996) asserts that a rural utility managing only 12,000 line-miles of distribution infrastructure spent up to $1,000,000 per year on line clearance pruning activities (Lovelace 1996). When adjusted to 2014 dollars, this figure inflates to roughly $1,500,000. A similar technical report conducted in 2011 maintains that a larger utility company, spanning over 16,000 line-miles of distribution infrastructure and an unspecified amount of transmission infrastructure, invested $28,314,000 on vegetation management alone for both distribution and transmission operations (Goodfellow 2012). Lastly, a study by Radmer et al. (2002), although not specifying dollar amounts exactly, asserted that an unspecified utility in the Northwest U.S. annually spends approximately 30% of the total distribution system maintenance budget and 8% of the total distribution system operations and maintenance budget on line clearance pruning. These raw dollar amounts and budgetary expenditure percentages for utility companies eclipse those described by Hauer and Peterson (2015) for municipalities, which is intuitive because many utility companies are multi-county or multi-regional for-profit corporations rather than local government departments. This wide budgetary discrepancy further contextualizes differences in unpruned tree height between control and utility plots, as utility companies would presumably be empowered by their large budgets to identify and mitigate tree conflicts when trees are smaller. This speculation is further supported by the interactive effect in the current study's modeling of tree height. The magnitude of difference between heights of pruned and unpruned trees in utility plots was more than twice that of the difference between pruned and unpruned trees in control plots.

For all morphological models and ecosystem service delivery models where the interaction of plot type and pruning status was significant, the difference between pruned and unpruned trees in utility plots exceeded the difference between pruned and unpruned trees in control plots. Given the idea that utility arborists start pruning trees when they are smaller as compared to municipal or commercial arborists, this result was anticipated. Further study investigating these claims may be useful in better understanding how action thresholds for pruning may differ between utility and municipal managers, and whether the presumed greater budget of utilities or greater risk from neglected trees over continuous distances are indeed drivers of these seemingly earlier action thresholds. A future survey-based study may be an effective way of gauging these qualitative differences between utility and municipal tree management strategies and budget availability and demand.

Mean values for all response variables related to tree morphology, except tree height and percent crown missing, were also greater for trees in control plots than for trees in utility plots. Although the relationship between trees in utility plots and trees in control plots was inverted for percent crown missing, this finding directly corroborated observed trends in crown size between the two study populations. Presumably, trees which were pruned more severely, as evidenced by higher mean percent crown missing, would have smaller crown heights, lengths, and volumes. i-Tree Eco response variables were also greater for trees in control plots than for trees in utility plots, aligning with the noted trends in DBH and percent crown missing. However, tree height did not behave similarly to other variables across plot type.

Given the observed differences in crown morphology and DBH between trees in utility and control plots, it was somewhat surprising to observe that trees in control plots and trees in utility plots were similar in height. One may have expected that, having potentially reduced photosynthetic capacity as compared to trees in control plots which had larger crowns, trees in utility plots may have grown more slowly and thus reached shorter heights. Similarly, one may have expected the presence of utility lines, often roughly seven to nine meters above ground level (Millet and Bouchard 2003), to have encouraged pruning practices which maintained trees shorter than line height. However, the current study's findings evidently did not support either presumption when comparing means across plot type alone. Through the synthesis of the interaction term between plot type and pruning status in the current study's tree height model, observed trends in DBH, and additional context provided by previously conducted studies into various pruning intensities' effect on both vertical growth and trunk growth, this initially surprising response can be plausibly explained.

In models of tree height, the interaction term between pruning status and plot type was the most impactful predictor as evidenced by the highest chi-sq value. While mean heights were similar across plot type for pruned trees, unpruned trees in control plots were nearly twice as tall as unpruned trees in utility plots. This was seemingly incongruous with the results observed in DBH models; mean DBH for pruned trees in control plots was greater than that of pruned trees in control plots.

Víquez and Pérez (2005) provide some helpful context to this situation, monitoring height and trunk diameter of forest plantation trees subjected to three increasing intensities of crown raising treatments and comparing them to a control group of unpruned trees. Two years following treatment, all pruning severity groups were distinct from one another and from the unpruned control group in height, with control trees being the tallest and the most severely pruned trees being the shortest (Víquez and Pérez 2005). After four years post-pruning, the only difference in height among groups was between the control group and the second most severe pruning treatment group. Trunk diameter, though, did not equalize to the same degree over the study period; four years following treatment, the most severely pruned group remained significantly smaller in DBH than both the control and the lowest intensity pruning group. Gilman (2015a) also noted no significant difference between the height of pruned and unpruned after three seasons under nursery settings, even though pruned trees had smaller DBH measurements than unpruned trees.

Considering their observed relationships in DBH, tree height, and pruning severity (i.e. percent crown missing), pruned trees in control plots and utility plots in the current study grew similarly to the control and high intensity pruning treatment groups described by Víquez and Pérez (2005). Trees in the current study have also grown in urban areas and thus have likely been pruned for longer periods of time than the study period of four years presented in Víquez and Pérez (2005). Potentially, any effect of differing pruning severity on the height of sampled pruned trees in the current study may have already been compensated for by growth of unpruned sections of the trees, while differences in diameter between pruned trees in utility plots and pruned trees in control plots remained significant. Indeed, pruning has previously been linked to increased terminal growth rates of unpruned remaining branches (Findlay et al. 1997, Gilman and Grabosky 2009), and this increased growth of non-pruned tree portions is a critical mechanism in the natural pruning system, under which utility pruning falls (Kempter 2004). It seems, given the context of these two previous studies, utility pruning in the current study may have been associated with a slower rate of growth for a tree’s trunk, but was not associated with any decrease in vertical growth rate as compared to trees pruned for other objectives.

Carbon sequestration modeling in the current study, due to the i-Tree Eco mechanism used to estimate this response, anecdotally presents some interesting findings which may corroborate potentially slower trunk growth rates observed for trees in utility plots than for trees in control plots. Using inputs including tree species, DBH, tree height, percent crown missing, crown condition, and crown light exposure, i-Tree Eco estimated the annual amount of carbon sequestered by calculating annual growth rates and the resulting biomass increases. A tree’s DBH was incrementally increased by i-Tree based on previous studies’ measurements of street tree growth rates (Flemming 1988, Frelich 1992, Nowak 1994), and the software subtracted modeled carbon storage for the current year from the projected carbon storage for the next year to estimate annual sequestration rates (Nowak 2020). Trees in utility plots were modeled to sequester less carbon than trees in control plots, suggesting slower modeled trunk growth rates for trees in utility plots than for trees in control plots.

These ideas remain speculative, albeit in general alignment with the findings of previously conducted studies and a synthesis of several response variables in the current study. This would be an interesting concept to explore in future research projects, particularly with a manipulative study design utilizing trunk coring to more directly measure trunk growth over time for single trees pruned for varying objectives. In a nursery setting, or perhaps an arboretum setting to target trees of similar size to those repeatedly pruned by utilities in practice, trees could be mock utility pruned with varying degrees of intensity. Trees near live utility lines carrying electricity would not be practical for a manipulative study because of the danger associated with pruning them and the potential for unscheduled emergency pruning on behalf of the utility outside the scope of the proposed study. Three common characteristic shapes of utility pruned trees, ‘V’ shaped, ‘L’ shaped, and a group with one side completely removed back to the parent stem, could serve as varying intensities of utility pruning. These three groups could be repruned on a 3–5-year pruning cycle to mimic a utility pruning program, and measured against similarly sized trees that do not undergo utility pruning as a control. This would more directly investigate the relationship between utility pruning and both trunk growth and vertical growth of individual trees.

Another initially surprising relationship between trees in utility plots and trees in control plots was found in the interaction term of the percent crown missing model. When analyzing multiple comparisons of the interaction effect within the percent crown missing model, pruned trees in control plots were missing less of their crowns than unpruned trees in control plots.

This result was counterintuitive. Sine pruning is the selective removal of portions of a tree to reach a predetermined objective, pruned trees should have been missing a larger proportion of their crown than unpruned trees regardless of plot type and pruning objective. While the difference between pruned and unpruned trees in control plots was statistically significant, the magnitude of this difference was quite small. Furthermore, neither pruned trees nor unpruned trees in control plots were significantly different from unpruned trees in utility plots. This unexpected phenomenon, then, was plausibly an artifact of the imprecise nature of the measurement technique used for this variable in the current study. Five percent visual estimates may not have precicely reflected five percent of actual crown volume. However, true errors and accuracy of this study’s estimates are unknown. Additionally, inter-rater variability may have impacted this response as well. While assessor variability has not been directly studied in terms of percent crown missing estimates, Solberg and Strand 1999 investigates assessor bias in estimations of temporal changes of crown density of forest trees (Solberg and Strand 1999). They identify several potential sources of observer bias: i) different assessment styles between observers; ii) observers tending to assess all trees within a small part of a continuous scale (e.g. often 80-85% crown density in old stands); iii) less trained observers having lower confidence in their assessments, leading to systematically overestimating scores for plots with low crown density and underestimating scores with high crown density; iv) preference for round numbers. Several of those aspects are potentially applicable in the current study, in particular, disparities between individual assessors' training and professional experience, as the two field technicians varied in that respect. In arboricultural studies, considerable variability in visual estimates between assessors for percent foliage removal following reduction and thinning pruning treatments as well (Smiley and Kane 2006, Gilman and Grabosky 2009). Given these several sources of potentially large variability of visual assessment of percent crown missing by multiple individuals, the initially unexpected relationship between pruned and unpruned trees in control plots becomes less surprising: especially given its relatively small magnitude of difference.

Although estimates in the current study for percent crown missing are likely imprecise for similar reasons, they nevertheless provide informative estimates of trends regarding utility pruning. The large magnitude of difference between pruned trees in utility plots and any other study group suggests utility pruning may remove more of a tree's crown than pruning for other objectives. A manipulative pruning experiment would more effectively investigate this notion empirically, and may also prove useful in the greater arboricultural field outside of the utility industry. Regardless of pruning objective, arborists generally strive to remove less than 25% of a tree's crown within one growing season in accordance with the ANSI A300 standard (Anonymous 2018). However, the ability of arborists to accurately gauge 25% crown volume has not been specifically investigated, although pruning percentages have been measured by before-and-after pruning weight (Smiley and Kane 2006, Gilman et al. 2008, Gilman and Grabosky 2009) and image analysis (Pavlis et al. 2008, Gilman and Grabosky 2009). A visual assessment conducted by many arborists on the same tree or group of trees following a manipulative pruning treatment to estimate percent crown removal could be compared to a more precise and nonbiased measuring standard such as weight of removed foliage, three dimensional digital models collected from unoccupied aerial sensing flyovers using simple RGB or LiDAR data gathering techniques. This would be an interesting way to investigate how accurately and precisely arborists are generally able to estimate pruning severity, as well as an insight into consistency among arborists of differing experience levels or industry background and perceptions of different pruning objectives.

In all but two exceptional cases (tree height; percent crown missing), the effect of pruning alone had the greatest chi-sq value in the fitted models. Given the idea that pruned trees tended to be considerably larger than unpruned trees in the landscape, this result was generally expected. However, the two exceptions warrant further discussion.

The model for percent crown missing was more influenced by plot type than pruning status or the interaction between the two. This was anticipated, though, as the magnitude between pruned and unpruned trees in utility plots exceeded the difference between pruned and unpruned trees in control plots so dramatically. Furthermore, three study groups were fairly similar to one another; unpruned trees in utility plots were statistically similar to both groups of trees in control plots. As stated previously, perhaps this model’s anomalous behavior between pruned and unpruned trees in control plots was an artifact of imprecise field measurement techniques based on relatively subjective assessments.

Tree height modeling was also most affected by the interaction of pruning status and plot type than either coefficient on their own. Plot type was not a significant predictor, and unsurprisingly, had a much lower chi-sq value as a result. The interaction's greater chi-sq value as compared to pruning status plausibly results from the fact that pruned trees in control and utility plots were similar in height while unpruned trees varied greatly across plot type. The magnitude of difference between the pruning groups in utility plots was 2.2 times greater than the magnitude of difference between pruning groups in control plots. Additionally, considering the idea that utility arborists often begin pruning trees when they are smaller than municipal or commercial arborists do, this greater disparity between pruned and unpruned trees in utility plots than pruned and unpruned trees in control plots was expected. Given this large disparity between magnitudes of difference in the interaction term, it logically follows that the interaction was the most influential in this model.

For all significant interactions in morphological models, excluding percent crown missing, responses were greater for pruned than unpruned trees within each plot type as well. This observation aligns with the notion that pruning was a more important predictor than plot type for most variables, and that pruned trees were, within each plot type, larger than unpruned trees. As a result, responses for i-Tree response variables were greater for pruned trees than unpruned trees within each plot type. Furthermore, percent crown missing's inverse relationship between pruned and unpruned trees in utility plots reflects trends seen in other models – although the relationship for pruned and unpruned trees in control plots appears to be anomalous.

Likelihood of Failure

Likelihood of failure was modeled differently than the other response variables in the study. Given the distinct modeling technique used for this variable, its unique response was anticipated. Interestingly, trees in utility plots and trees in control plots did not vary significantly on their own, demonstrated by the lack of statistical significance of the interaction between plot type and pruning status in the model. In fact, plot type was not a meaningful predictor on its own, nor in any interaction with additional predictors. while this was a negative result, inclusion of plot type still increased the McFadden's pseudo R^2 value of the model, and it was thus retained in the final model. With all other variables held constant, pruned trees in utility plots were not inherently assessed at a higher likelihood of failure than trees pruned for other objectives which may have more natural looking crowns.

The most impactful modeling coefficient with the highest chi-sq value was the interaction between pruning status and DBH. Interestingly, pruning status alone was the second most impactful predictor in the current likelihood of failure model. This was mostly expected, as tree size (DBH) has been noted as an important predictor in studies assessing previously failed trees in the landscape (Foster 1998, Gibbs and Greig 1990, Duryea et al. 2007, Kane 2008). However, when combined, DBH and pruning status show interesting insight into potential differences in pruning objective for small and large trees in the current study.

Unpruned trees with small DBH measurements were more likely to be assigned lower likelihoods of failure than pruned trees with similar DBH measurements. However, as DBH increased and surpassed approximately 50 cm, this relationship reversed. Once an approximate 50 cm DBH threshold was exceeded, unpruned trees became less frequently assigned lower likelihoods of failure than pruned trees, especially with higher levels of percent crown dieback.

In the author’s professional opinion, this was an anticipated result; one would expect practicing arborists to prune large trees to reduce their likelihood of failure (especially near important targets like utility lines or roads: both targets being present at half or all study sites, respectively) thus reducing later assessed likelihood of failure. Similarly, one may expect arborists to more commonly prune smaller trees for other objectives including structural pruning or directional pruning away from a target – neither of which would prioritize likelihood of failure reduction, and would plausibly result in a trend similar findings in the current study.

The International Society of Arboriculture’s Pruning: Third Edition Best Management Practices describes common pruning objectives including improving structure and reducing likelihood of failure (Lilly et al. 2019). Lilly et al. (2019) recommends structural pruning on young and semimature trees due to a larger proportion of sapwood and smaller sized wounds from pruning cuts than on larger trees, resulting in a greater ability to close pruning wounds than larger more mature trees would. Lilly et al. (2019) also describes risk mitigation pruning (i.e., reducing likelihood of failure) as the primary consideration for large trees in urban areas. It appears, anecdotally, that this may hold true in the current study as well. However, since the current study did not investigate pruning objectives for different sized trees directly, future research investigating this plausible explanation is needed to make this claim with more certainty. A survey sent to different types of many arborists across utility, municipal, and commercial settings, would evaluate which pruning objectives are most commonly prescribed for different sized trees, and whether that may vary based on an arborist’s specific discipline. Additionally, it would be useful to conduct similar likelihood of failure assessments to those presented in the current study with a larger pool of arborists to strengthen the validity of these findings, as well as re-sampling trees after the original time frame of the assessment expires to further investigate arborists' ability to accurately predict tree failure.

Changes in DBH, percent crown dieback, and pruning status were positively associated with significant change in assessed likelihood of failure. Previous studies reporting tree failures, although largely conducted only on forest trees, have noted increased wind-induced failure rate as tree size (DBH) increased (Foster 1998, Gibbs and Greig 1990, Duryea et al. 2007, Kane 2008). More recent research also correlated increases in DBH with greater incidence of failure in an urban setting, as well an increase in perception of likelihood of failure by assessors (Koeser et al. 2020), and if failure does indeed occur, the weight of larger trees can cause significant property damage or injury (Koeser and Smiley 2017). These findings generally held true in the present study; however, results from the current and previous studies (Foster 1998, Gibbs and Greig 1990, Duryea et al. 2007, Kane 2008, Koeser and Smiley 2017, Koeser et al. 2020) do not indicate that DBH alone may explain failure rates. Anecdotally, trees in each plot type were distinct from each other in DBH modeling, an effective predictor for likelihood of failure, even though plot type itself was not an effective predictor for likelihood of failure. Perhaps the difference in DBH between trees in utility plots and trees in control plots was not large enough to cause a significant difference in likelihood of failure between the two study groups in this instance.

Increases in percent crown dieback were also correlated with increased likelihood of failure ratings in the current study. This was both intuitively expected and supported by industry standards and previous research. According to the current edition of tree risk assessment best management practices, trees and tree parts with higher proportions of dead tissue may be assessed at higher likelihoods of failure either due to dead portions failing themselves, or they may indicate possible root decay and other root or soil defects which may affect whole tree stability (Smiley et al. 2017). Additionally, a study of tree failures following tropical storm Matthew in Charleston, South Carolina, and Savannah, Georgia, found that trees with recorded twig dieback failed at a rate of 20.7% (Koeser et al. 2020). But Koeser et al. (2020) did not note how the presence of twig dieback influenced assessors' ratings of likelihood of failure for trees prior to the storm, nor the mode of failure (tree part or whole tree), nor at what percentage, in relation to a tree's entire crown, twig dieback was associated with increased failure rates in the post-storm assessments. Still, the present study generally supports the positive relationship between twig dieback and increased likelihood of failure.

The interaction between percent crown dieback and DBH also influence likelihood of failure rating, which was expected given the individual effect of each variable. DBH and percent crown dieback were positively associated with one another; increases in DBH paired with increases in percent crown dieback increased the modeled likelihood of failure of a tree, signifying that the likelihood of failure of a large tree with high percentages of dieback would be greater than the likelihood of failure of a small tree with the same percentage of dieback. Again, this result is encouraging and intuitive. The potential loading forces on a large tree or parts of a large tree would inherently be greater than the forces exerted on a comparatively smaller tree or tree part. Coupled with the increased risk of dying limbs compared to healthy limbs, and their potential indication of root instability, this should logically be associated with a higher assessed likelihood of failure by observers as confirmed by the current study's model output and visualization.

CHAPTER 6

CONCLUSION

This study successfully achieved its objectives of (i) assessing factors related to both individual trees and the sample populations of trees growing near and away from overhead utility lines, and (ii) determining whether those factors differed between the two groups. The current study also strived for applicability in industry settings. Approaching customer concerns with science-based claims is an important aspect of the career of a utility arborist. In the author's industry experience, electrical utility customers' most common concerns regarding utility pruning generally are threefold: (i) concerns about the aesthetic component of a 'V' shaped, 'L' shaped, or otherwise utility pruned tree, (ii) concerns about the effect that the unusual shape may have on tree health, and (iii) concerns about how the unusual shape may affect the structural integrity of a tree. While the current study did not address the first of these concerns due to its subjectivity, the current study's findings serve as useful references in addressing the latter major concerns through the results morphometric, ecosystem service delivery, and assessed likelihood of failure modeling.

Trees near utility lines are commonly viewed as a cost sink and potential exposure to risk by the utility itself, and synchronously viewed as a public nuisance or eyesore by community members. The results of the current study may be useful in reframing perception of trees near electrical distribution lines as valuable community resources as they were not found to have inherently higher likelihood of failure compared to trees located away from overhead utility lines, and still provided considerable ecosystem service benefits to their surrounding communities while allowing for safe and reliable electrical power delivery. Additionally, preliminary plausible explanations discussed in the current study provide several interesting avenues for future research opportunities regarding utility arboriculture: a discipline of arboriculture which warrants more representation and investigation in peer reviewed literature. As one of the most common forms of pruning practiced on trees in an urban landscape, and also one of the least represented sub-family of arboriculture in scientific literature, utility pruning should be targeted in future manipulative studies investigating how utility pruning affects individual trees. Insights from future study may be useful in reframing how trees near utility lines and the practice of utility pruning are perceived and conducted.

APPENDIX 1
RESIDUALS AND QUANTILE-QUANTILE PLOTS FOR GLM REGRESSIONS

Diameter at breast height

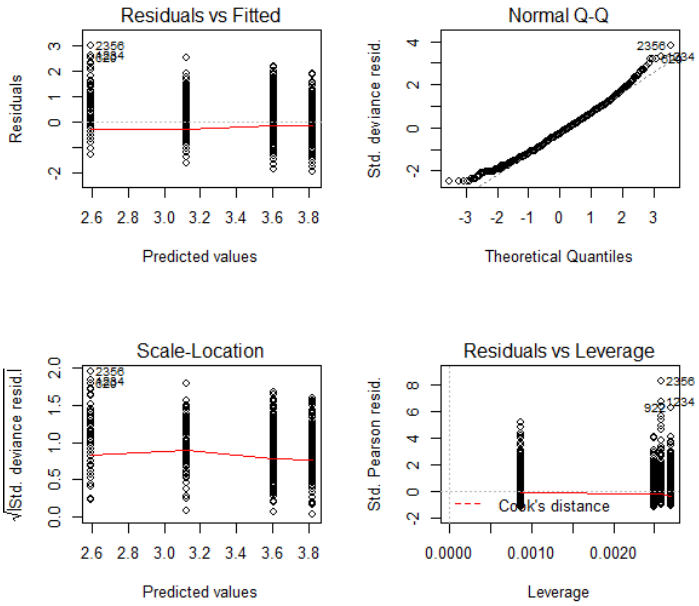


Figure 18: Model plots for gamma distribution generalized linear model with log link function for interactive diameter at breast height model.

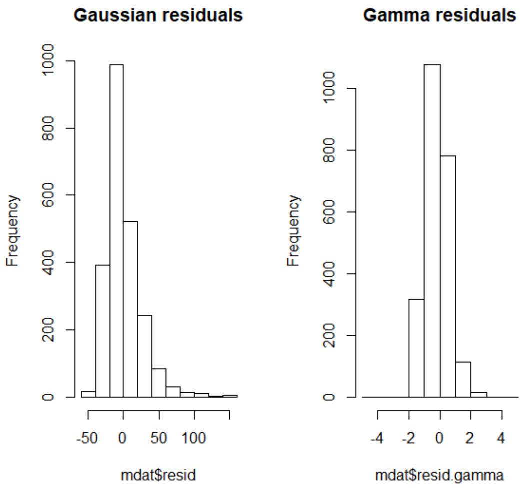


Figure 19: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive diameter at breast height model.

Tree Height

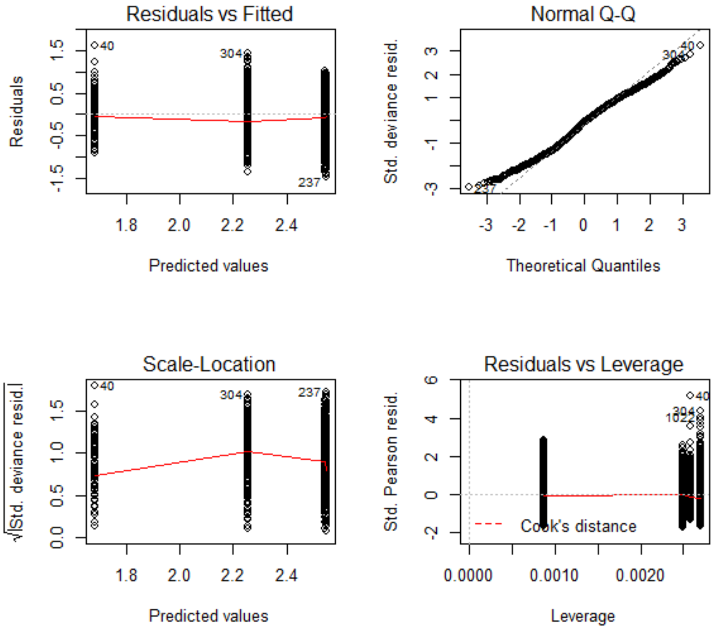


Figure 20: Model plots for gamma distribution generalized linear model with log link function for interactive tree height model.

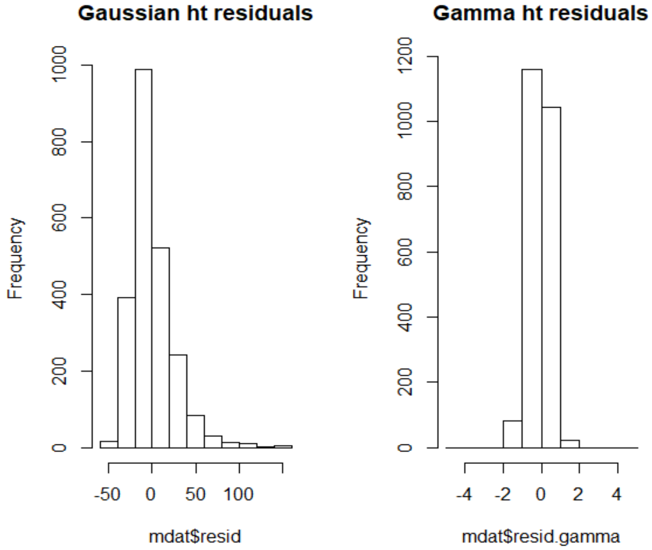


Figure 21: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive tree height.

Percent crown dieback

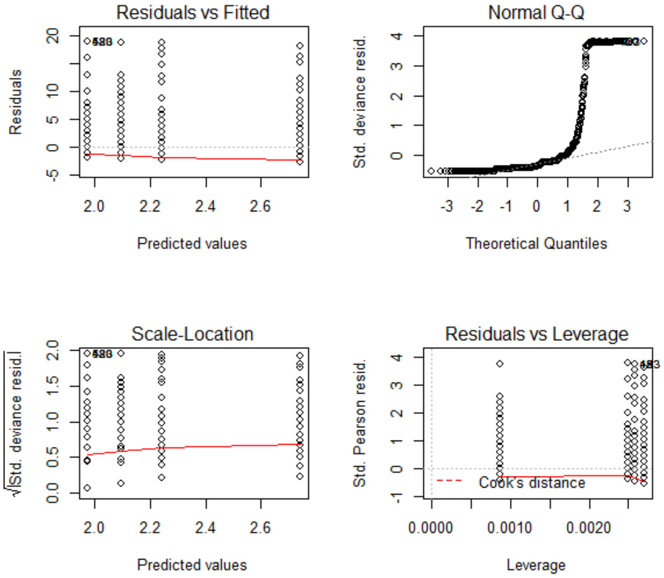


Figure 22: Model plots for gaussian distribution generalized linear model for interactive crown dieback model.

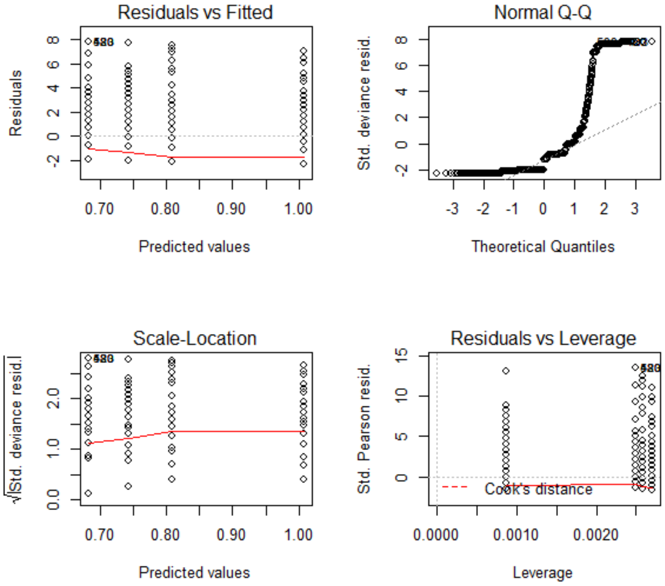


Figure 23: Model plots for poisson distribution generalized linear model for interactive crown dieback model with log link function.

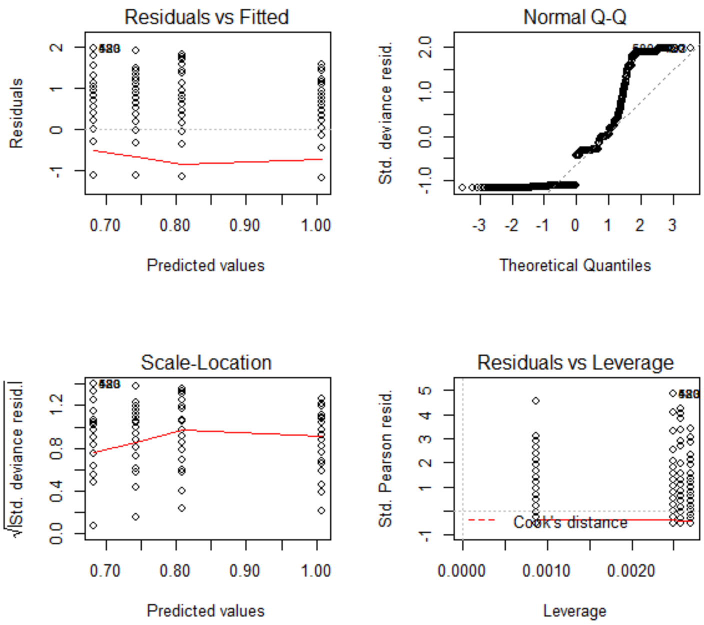


Figure 24: Model plots for negative binomial distribution generalized linear model for interactive crown dieback model with log link function.

These same modeling techniques were conducted for bin sizes of 10%, 20%, 50%, and finally, a binary living or dead grouping of trees. Under none of these groupings was an appropriate modeling distribution found, and this response variable was not pursued further in the modeling process.

Slenderness

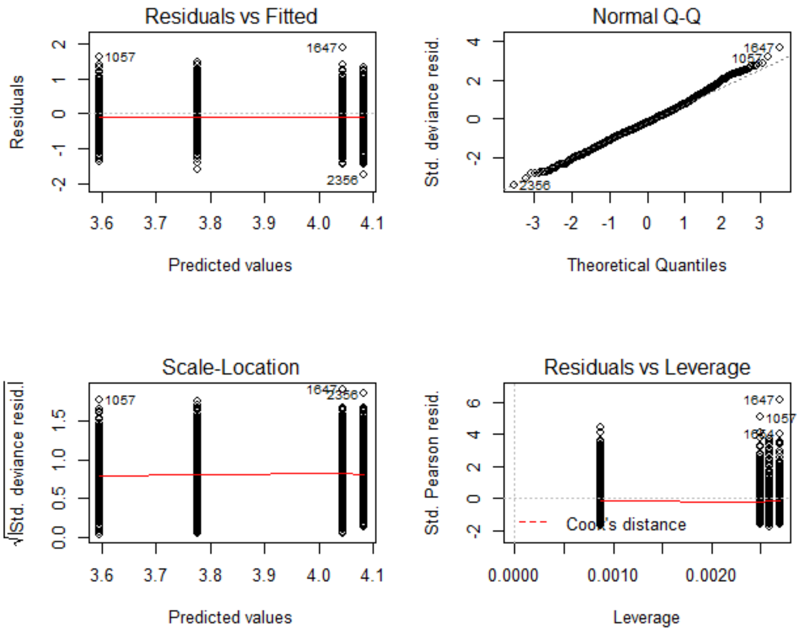


Figure 25: Model plots for gamma distribution generalized linear model with log link function for interactive tree height model.

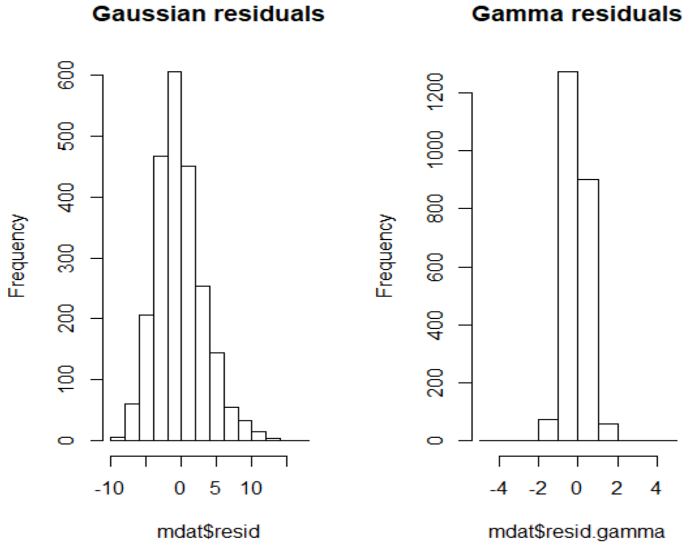


Figure 26: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive slenderness model.

Crown Width

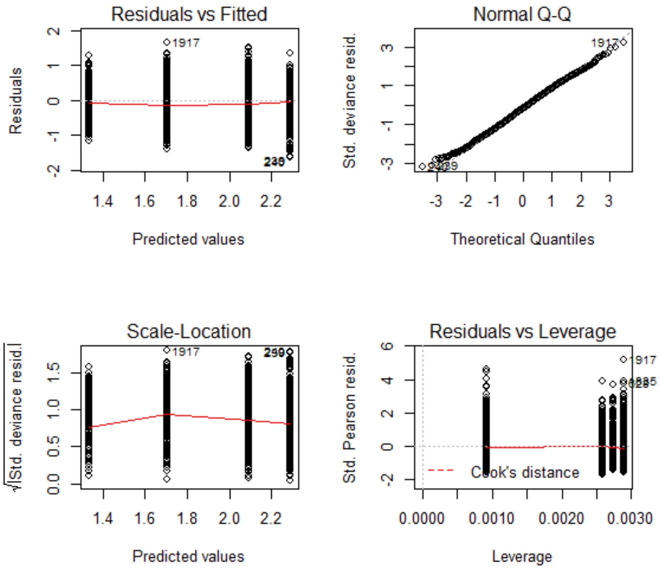


Figure 27: Model plots for gamma distribution generalized linear model with log link function for interactive crown width model.

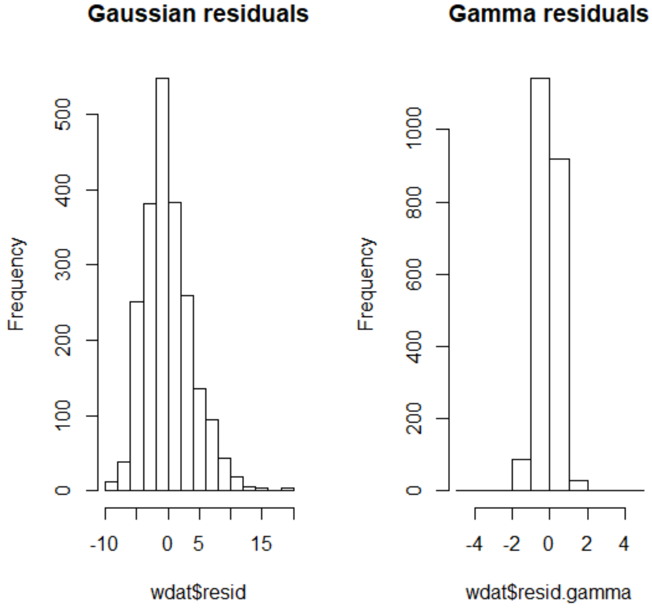


Figure 28: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive crown width model.

Crown Length

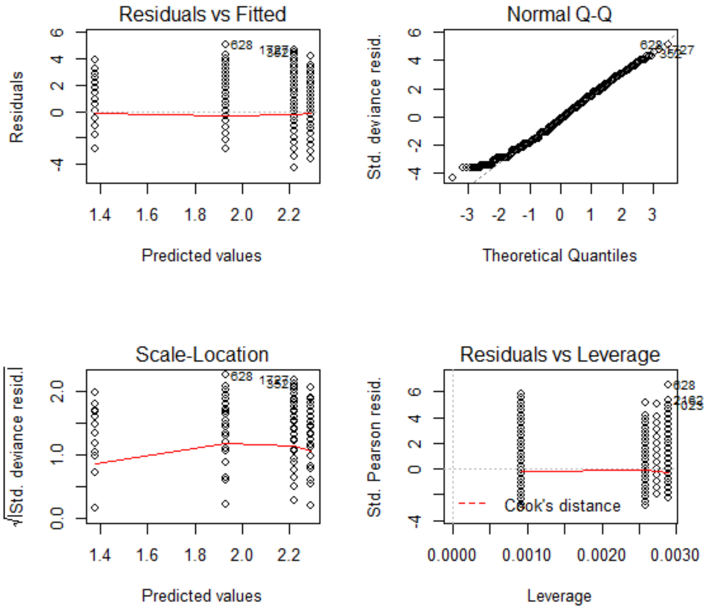


Figure 29: Model plots for poisson distribution generalized linear model with log link function for interactive crown length model.

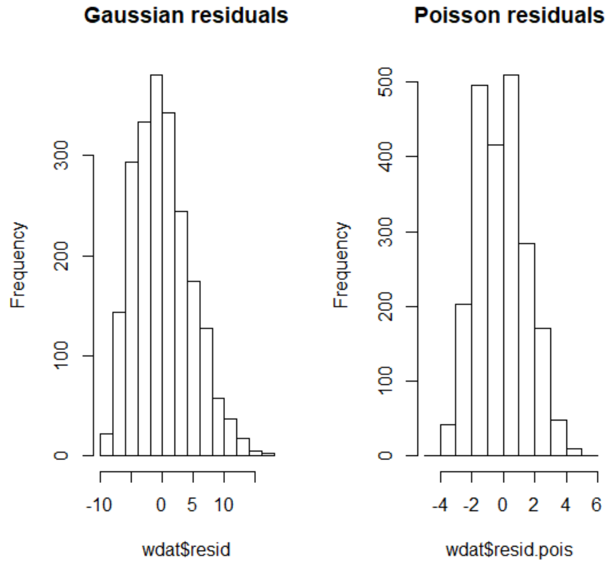


Figure 30: Residuals plots for gaussian (left) and poisson distribution generalized linear model with log link function (right) for interactive crown length model.

Crown Volume

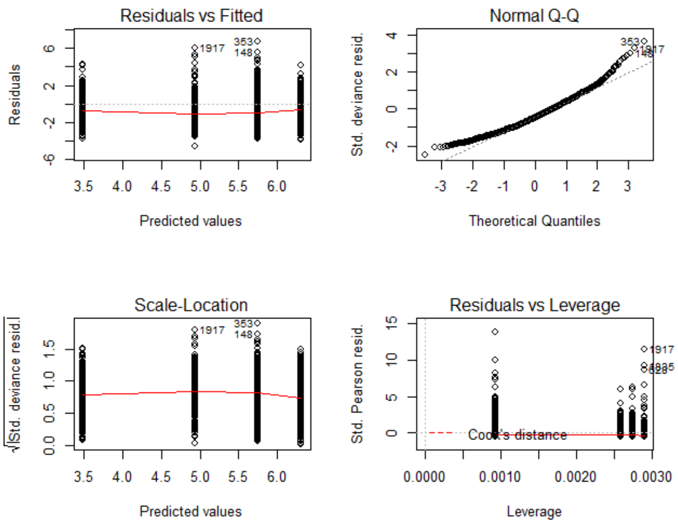


Figure 31: Model plots for gamma distribution generalized linear model with log link function for interactive crown volume model.

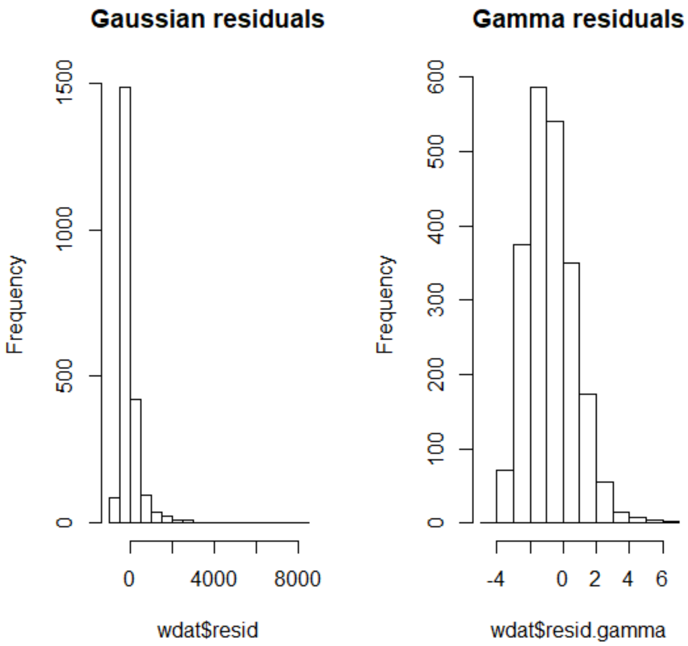


Figure 32: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive crown volume model.

DBH / ht^2

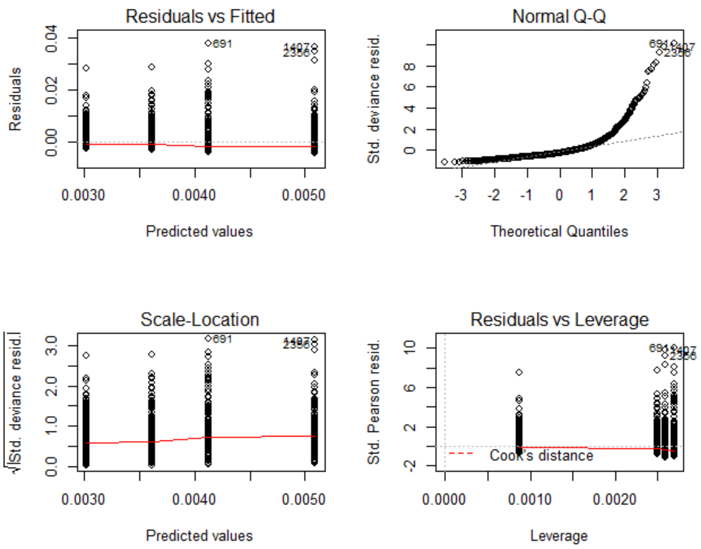


Figure 33: Model plots for gamma distribution generalized linear model with log link function for interactive DBH / ht^2 model.

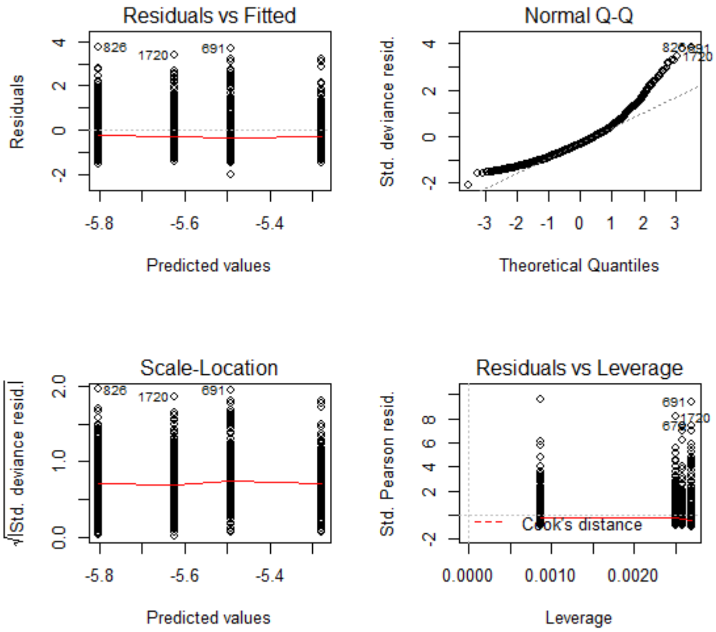


Figure 34: Model plots for gamma distribution generalized linear model with log link function for interactive DBH / ht^2 model.

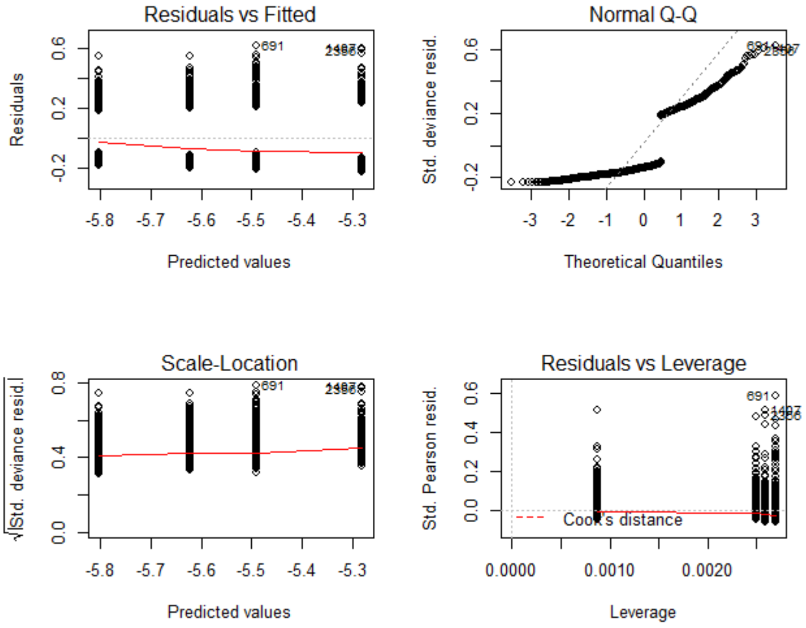


Figure 35: Model plots for gamma distribution generalized linear model with log link function for interactive DBH / ht^2 model.

Modeling was not further continued with this variable. Despite significant outputs, all models were associated with unacceptably low McFadden's pseudo R2 values, and were deemed unfit for further reporting in the results section of this study.

Percent crown missing

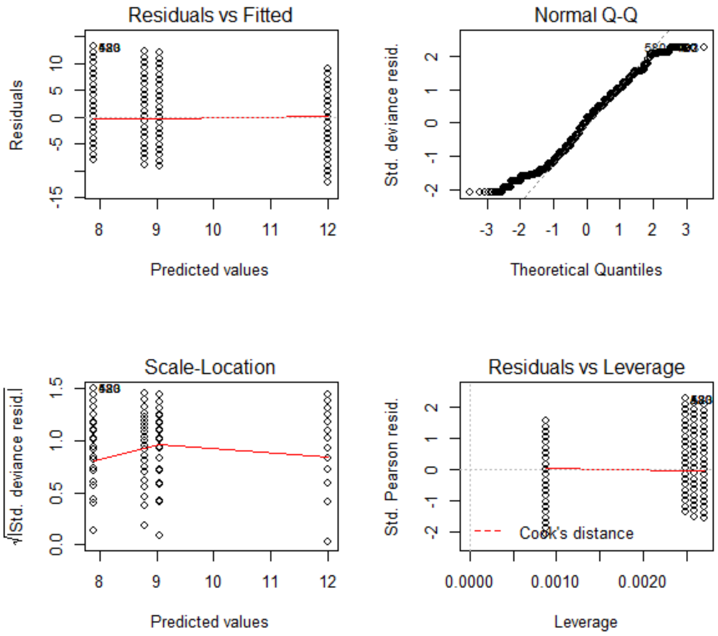


Figure 36: Model plots for gaussian distribution generalized linear model for interactive crown percent missing model.

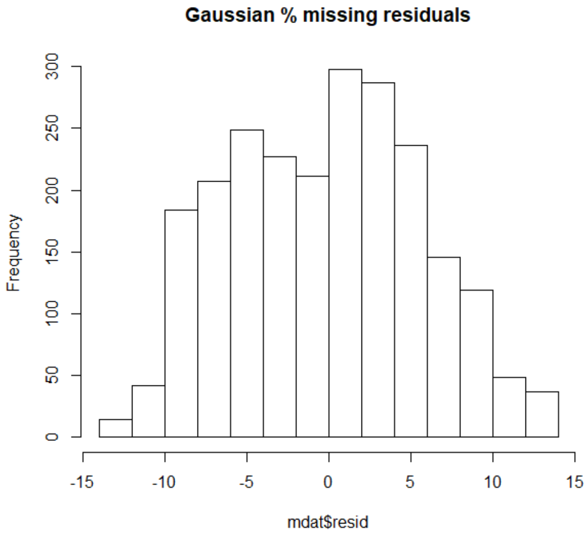


Figure 37: Residuals plots for gaussian distribution generalized linear model for interactive percent crown missing model.

Carbon Storage

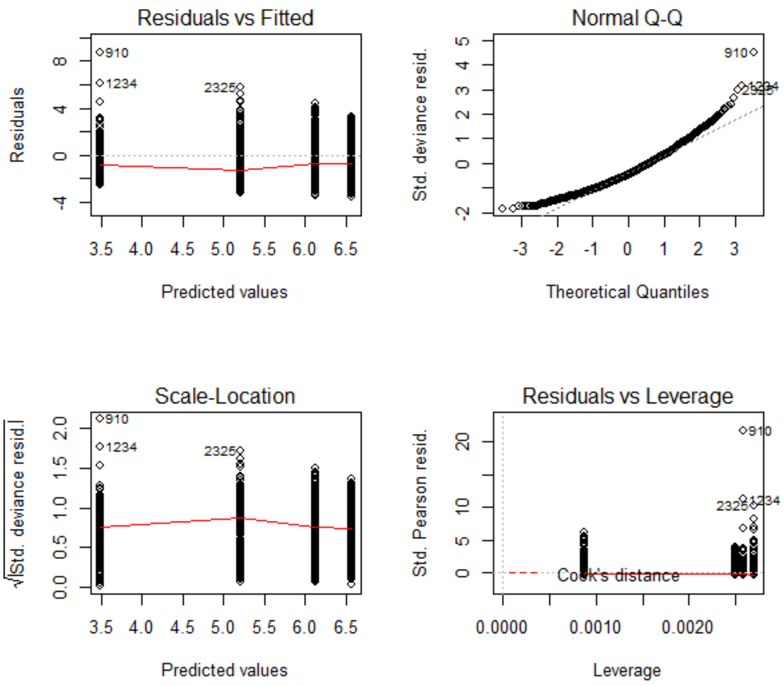


Figure 38: Model plots for gamma distribution generalized linear model with a log link function for interactive carbon storage model.

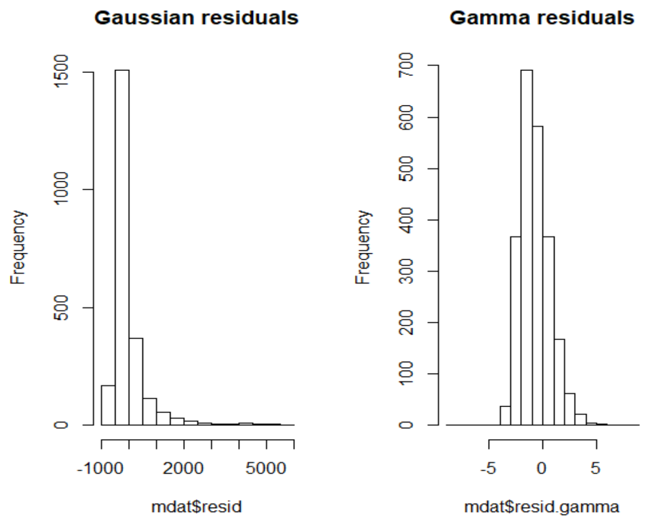


Figure 39: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive carbon storage model.

Annual carbon sequestration

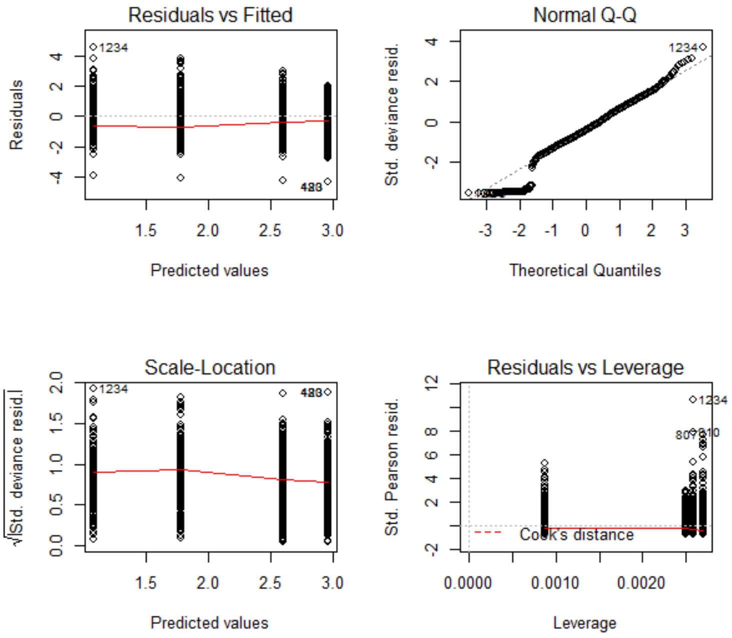


Figure 40: Model plots for gamma distribution generalized linear model with a log link function for annual carbon sequestration model.

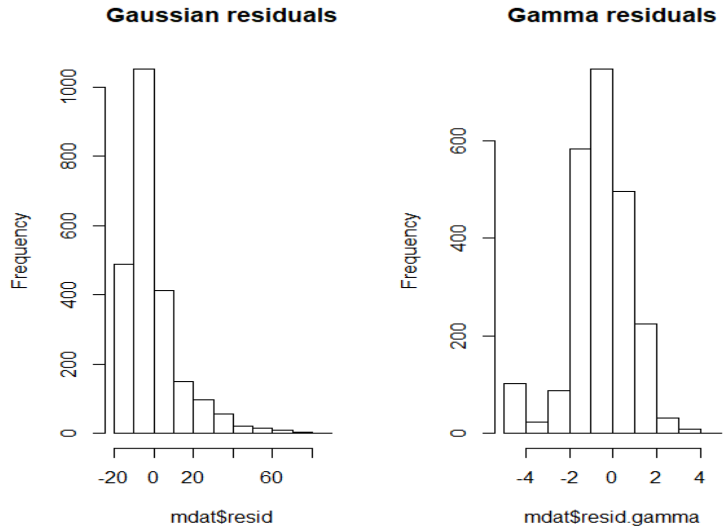


Figure 41: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive annual carbon sequestration model

Annual runoff avoided

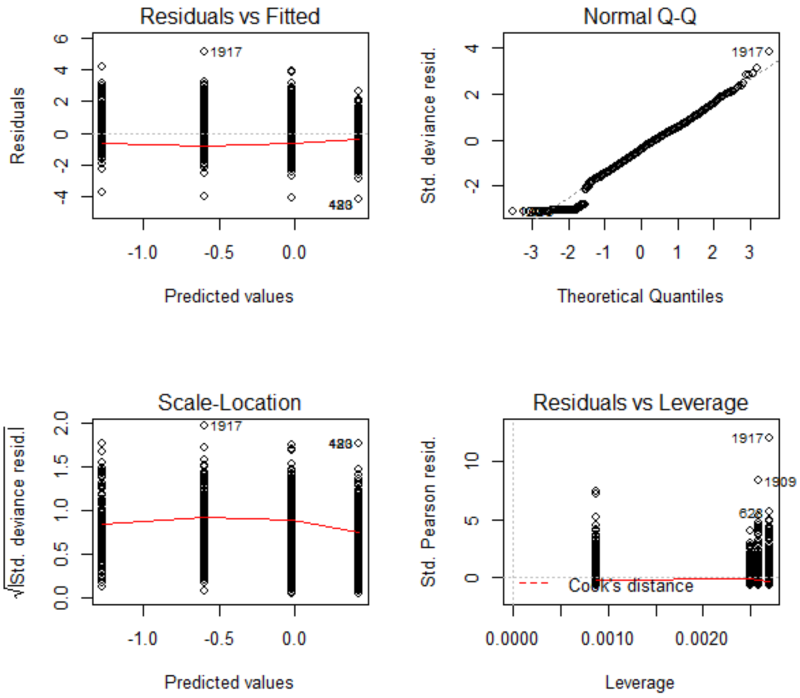


Figure 42: Model plots for gamma distribution generalized linear model with a log link function for interactive model for annual runoff avoided.

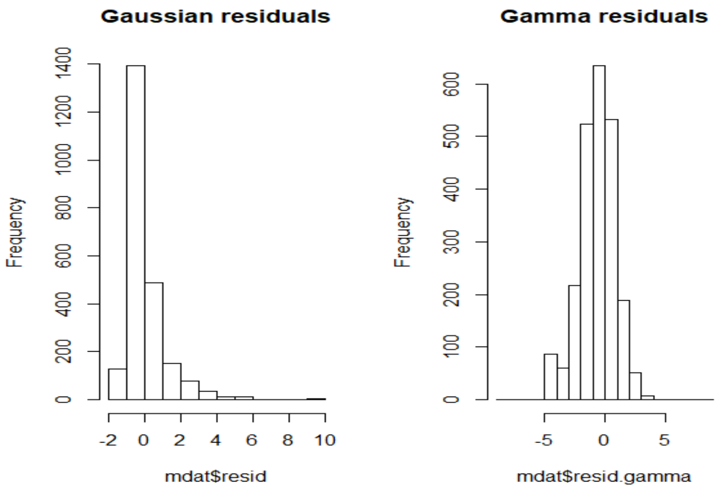


Figure 43: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive model for annual runoff avoided.

Annual air pollution removed

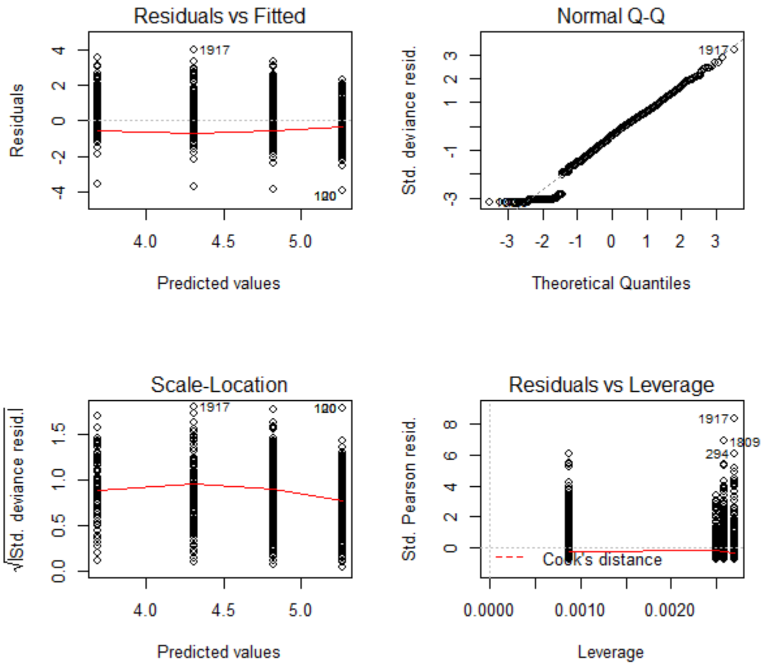


Figure 44: Model plots for gamma distribution generalized linear model with a log link function for interactive model for annual air pollution removed.

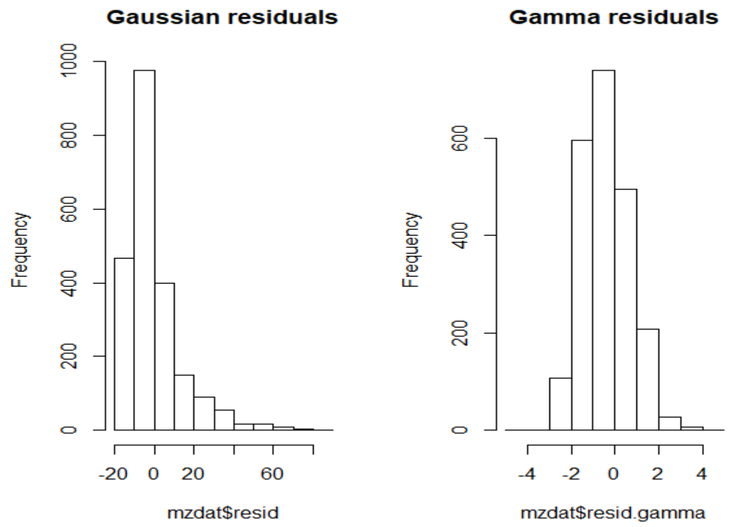


Figure 45: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for interactive model for annual air pollution removed.

Structural value

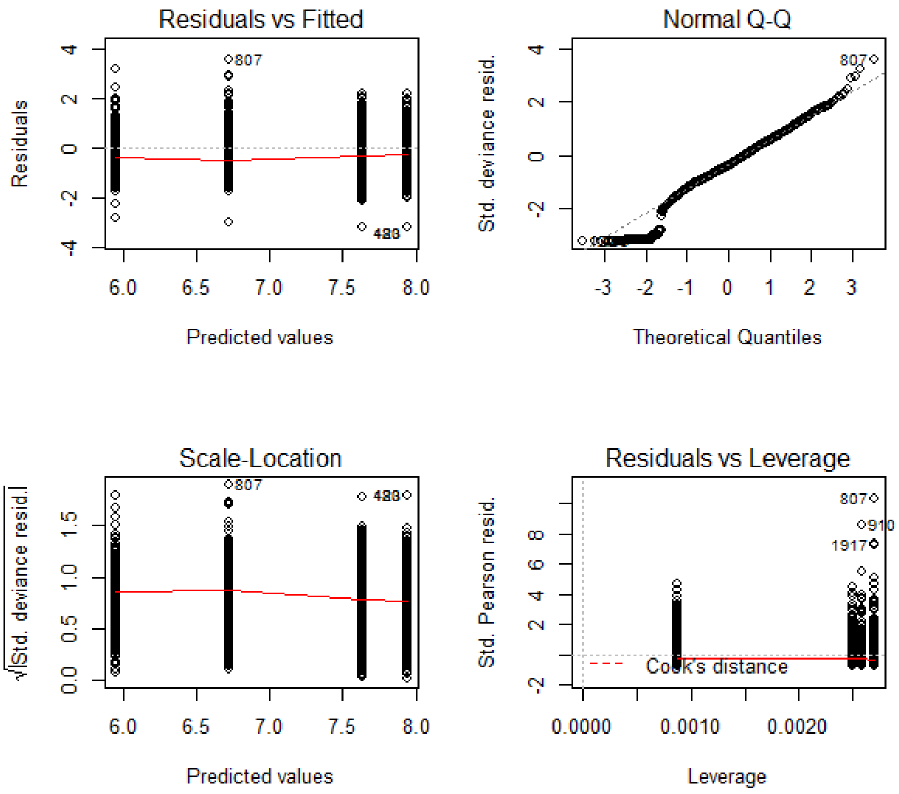


Figure 46 : Model plots for negative binomial distribution generalized linear model with a log link function for interactive structural value model.

A negative binomial regression model with a log link function was the most visually acceptable distribution when compared to gaussian, gamma, or poisson. However, an Akaike information criterion (AIC) comparison suggested that a zero-inflated negative binomial regression model with a log link was a better fit, still (Table 14).

Table 14: Akaike information criterion comparison for various model types for predicting structural value.

Model	AIC	Delta AIC
Interactive zero-inflated negative binomial with log link	37247.63	0.00
Additive zero-inflated negative binomial with log link	37270.84	23.20
Interactive negative binomial with log link	37705.91	445.00
Additive negative binomial with log link	37705.91	458.00

This was validated using a Vuong non-nested hypothesis test comparing a zero-inflated negative binomial model with a log link to a negative binomial model with a log link, each of with being interactive models (Table 15).

Table 15: Vuong non-tested hypothesis test-statistic. Test-statistic is asymptotically distributed under the null hypothesis that the models are indistinguishable (**H_0:** Model 1 = Model 2). Model1 represents zero inflated negative binomial model, while model2 represents a negative binomial model which is not zero inflated.

	Vuong z-statistic	H_A	p-value
Raw	9.67	Model 1 > Model 2	< 2.22E-16
AIC-corrected	9.62	Model 1 > Model 2	< 2.22E-16
BIC-corrected	9.50	Model 1 > Model 2	< 2.22E-16

Dollar value for annual ecosystem service delivery

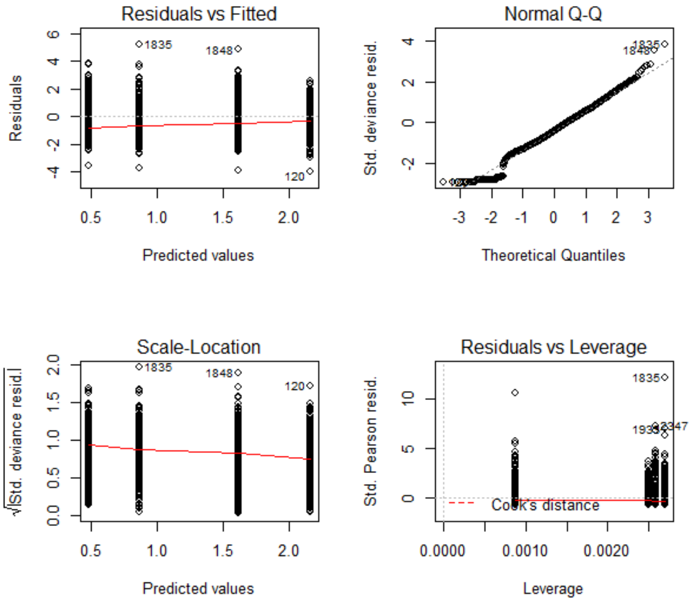


Figure 47: Model plots for gamma distribution generalized linear model with a log link function for model of dollar value for annual ecosystem service delivery.

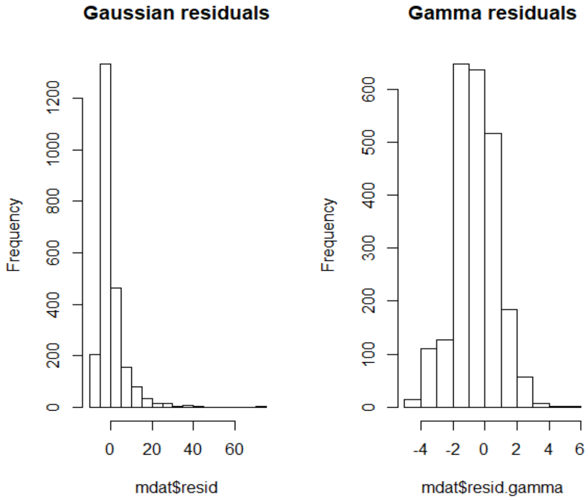


Figure 48: Residuals plots for gaussian (left) and gamma distribution generalized linear model with log link function (right) for model for dollar value for annual ecosystem service delivery.

LITERATURE CITED

Abreu-Harbich, L.V., L.C. Labaki, and A. Matzarakis. 2014. Thermal bioclimate as a factor in urban and architectural planning in tropical climates – The case of Campinas, Brazil. Urban Ecosystems, 17:489-500

Akresh, M.E., King, D.I., Lott, C.A., Larkin, J.L., and A.W.D'Amato. 2020. A meta-analysis of the effects of tree retention on shrubland birds. Forest ecology and management. In press.

Armson, D., Stringer, P., and A. R. Ennos. 2012. The effect of tree shade and grass on surface and global temperatures in an urban area. Urban forestry and urban greening. 11(1):41-49

Anonymous. 2018. American national standard for tree care operations- Tree, shrub, and other woody plant management- Standard practices (pruning). Tree Care Industry Association, Manchester, NH, U.S, 33 pp.

Barker, P.A. (1983) Some urban trees of California: Maintenance problems and genetic improvement possibilities. In *METRIA: 4. Proceedings of the Fourth Biennial Conference of the Metropolitan Tree Improvement Alliance* (H.D. Gerhold, ed.), pp. 47–54. The Pennsylvania State University, School of Forest Resources.

Bolund, P., and S. Hunhammar. 1999. Ecosystem services in urban areas. Ecological economics. 29:293–301.

Bolker, B.M., 2008. Ecological models and data in R. Princeton University Press. New Jersey, USA

Clair-Maczulajtys, D., Le Disquet, I., and G. Bory. 1999. Pruning stress changes in the tree physiology and their effects on tree health. Acta horticulturae. 496: 317-324.

Chow, P., Rolfe, G.L. 1989. Carbon and hydrogen contents of short-rotation biomass of five hardwood species. Wood and Fiber Science. 21(1): 30-36.

Council of Tree and Landscape Appraisers [CTLA]. 1992. Guide for plant appraisal. Savoy, IL: International Society of Arboriculture. 103 p.

Dahle, A.G., Holt, H.H., Chaney, W.R., Whalen, T.M., Grabosky, J., Cassens, D.L., Gazo, R., McKenzie, R.L., and J.B.Santini. 2006a. Decay patterns in silver maple (*Acer saccharinum*) trees converted from roundovers to v-trims. Arboriculture and urban forestry. 32(6): 260-264.

Dahle, A.G., Holt, H.H., Chaney, W.R., Whalen, T.M., Grabosky, J., Cassens, D.L., Gazo, R., McKenzie, R.L., and J.B.Santini. 2006b. Branch strength loss implications for silver maple (*Acer saccharinum*) converted from round-over to V-trim. Arboriculture and urban forestry. 32(4)148-154

Dwyer, J.F., Schroeder, H.W., and P.H. Gobster. 1991. The significance of urban trees and forests: Towards a deeper understanding of values. Journal of arboriculture. 17(10): 276-284

Dochinger, L.S. 1980. Interception of airborne particles by tree plantings. Journal of environmental quality 9:265–268.

Doherty, K.D., Ryan, H.D.P., and D. Bloniarz. 2000. Tree wardens and utility arborists: a management team working for street trees in Massacusetts. Journal of arboriculture 26(1): 38-47

Dujesiefken, D. and H. Stobbe. 2002. The hamburg tree pruning system: A framework for pruning of individual trees. Urban forestry and urban greening. 1(2): 75-82.

Dykes, A.M. 1980. Right-of-way management program. Journal of Arboriculture 6(3):74–76

Escobedo, F. J., Adams, D.C., and N. Timilsina. 2015. Urban forest structure effects on property value. Ecosystem services. 12: 209-217

Findlay, C., F. Last, P. Aspinall, C. Ward Thompson, and N. Rudd. 1997. Root and shoot pruning in root-balled *Acer platanoides* L.: effects of establishment and shoot architecture. Arboricultural Journal 21:215–229

Fini, A., Frangi, P., Faoro, M., Piatti, R., Amoroso, G., and F. Ferrini. 2015. Effects of different pruning methods on urban tree species: a four-year-expiriment scaling down from the whole tree to the chloroplasts. Urban forestry and urban greening. 14(3): 664-674.

Fleming, L.E. 1988. Growth estimation of street trees in central New Jersey. New Brunswick, NJ: Rutgers University. 143 p. M.S. thesis.

Frelich, L.E. 1992. Predicting dimensional relationships for Twin Cities shade trees. St. Paul, MN: University of Minnesota, Department of Forest Resources. 33 p.

Früchtenicht, E., L. Neumann, N. Klein, D. Bonal, and W. Brüggemann. 2018. Response of Quercus robur and two potential climate change winners-*Quercus pubescens* and *Quercus ilex*-To two years summer drought in a semi-controlled competition study: i-Tree water status. Environmental and Experimental Botany 152:107-117

Fox, J. and J. Hong (2009). Effect Displays in R for Multinomial and Proportional-Odds Logit Models: Extensions to the effects Package. Journal of Statistical Software, 32(1), 1-24. <http://www.jstatsoft.org/v32/i01/.>

Fox, J. and S. Weisberg. 2019. An R companion guide to applied regression, third edition. Thousand Oaks, California, USA <https://socialsciences.mcmaster.ca/jfox/Books/Companion/>

Gilman, E.F. 2015a. Pruning *Acer rubrum* at planting impacts structure and growth after three growing seasons. Arboriculture and urban forestry, 41(1): 11-17.

Gilman, E.F. 2015b. Pruning severity and crown position influence aspect ratio change.

Arboriculture and urban forestry. 41(2): 69-74.

Gilman, E.F., J. Grabosky, S. Jones, and C. Harchick. 2008. Effects of pruning dose and type on trunk movement in tropical wind storms. Arboriculture & Urban Forestry 34:13–19.

Gilman, E.F., and J.C. Grabosky. 2009. Growth partitioning three years following structural pruning of *Quercus virginiana.* Arboriculture and urban forestry. 35(6): 281-286

Goodfellow, J. W. 2020. Best management practices: Utility tree risk assessment. International Society of Arboriculture, Champaign Illinois

Goodfellow, J.W. 2012. Condition Assessment of Utility Forests of Massachusetts and Rhode Island. Technical report by Biocompliance Consulting, Inc. Redmond, Washington, U.S.A.

Grabosky, J.C., and Gilman, E.F. 2007. Response of two oak species to reduction pruning cuts. Arboriculture and urban forestry. 33(5):360-366.

Graziano, M., Gunther, P., Gallaher, A., Carstensen, F. V., and B. Becker. 2020. The wider regional benefits of power grids improved resilience through tree-trimming operations evidences from Connecticut, USA. Energy Policy 138 111293

Guggenmoos, S. 2003. Effects of tree mortality on power line security. Journal of Arboriculture 29:181-195

Guggenmoos, S. 2011. Tree-related electric outages due to wind loading. Arboriculture and Urban Forestry 37:147-151

Hall, J.M, Handley, J.F., and A.R. Ennos. 2012. The potential of tree planting to climate proof high density residential areas in Manchester, UK. Landscape and urban planning. 104(3-4):410-417

Harris, R.W., J.R. Clark, and N.P. Matheny. 2004. Arboriculture: Integrated Management of

Landscape Trees, Shrubs, and Vines. 4th ed. Upper Saddle River, NJ, Prentice-Hall. 579 pp.

Hauer, R. and W. Peterson. 2015. Municipal tree care and management in the United States. Technical report in proceedings of the International Society of Arboriculture annual conference and trade show. Orlando, Florida, U.S.

Heisler, G.M., and L.P. Herrington. 1976. Selection of trees for modifying metropolitan climates. Better trees for metropolitan landscapes (Gen. Tech. Rep. NE-22, pp. 31-37). Washington, DC, USDA Forest Service

Hipps, N.A., Davies, M.J., Dunn, J.M., Griffiths, H., and C.J. Atkinson. 2014. Effects of two contrasting canopy manipulations on growth and water use of London plane (*Platanus x acerfolia)* trees. Plant and soil. 382(1-2): 61-74.

International Society of Arboriculture. 2019. Best Management Practices-Pruning Third Edition. International Society of Arboriculture. Atlanta, Georgia, U.S.

Jim, C.Y. 1997. Roadside trees in urban Hong Kong: Tree size and growth space. Arboricultural Journal 21: 146-159.

Johnstone, R.A. 1988. Economics of utility lateral trimming. Journal of Arboriculture 14:74–77.

Kalies, E.L., Chambers, C.L., and W.W. Covington. 2010. Wildlife responses to thinning and burning treatments in southwestern conifer forests: A meta-analysis. Forest ecology and management. 259: 333-342

Kempter, G. 2004. Best management practices: Utility pruning of trees. International Society of Arboriculture, Champaign,IL.

Kristoffersen, P., Buhler, O., Larsen, S.U., and T.B. Randrup. 2010. Growth of newly established *Tilia platyphyllos* ‘Rubra’ roadside trees in response to weed control and pruning.

Arboriculture and urban forestry. 36(1): 35-40.

Koeser, A.K., Smiley, E.T., Hauer, R.J., Kane, B., Klein, R.W., Landry, S.M., and M. Sherwood. Can professionals gauge likelihood of failure? – Insights from tropical storm Matthey. Urban forestry & urban greening. 52(126701)

Koeser, A. K., R.J. Hauer, R. Klein, and J.W. Miesbauer. 2017. Assessment of likelihood of failure using limited visual, basic, and advanced assessment techniques. Urban Forestry & Urban Greening 24:71-79

Koeser, A. K., and E. T. Smiley. 2017. Impact of assessor on tree risk assessment ratings and prescribed mitigation measures. Urban forestry & urban greening 24: 109-115

Kumar, Y., and H.S. Rattanpal. 2010. Effect of pruning in guava planted at different spacings under Punjab conditions. Indian Journal of Horticulture. 67: 115-119.

Kuhns R. M., and D. Reiter. 2007. Knowledge and attitudes about utility pruning and how education can help. Arboriculture and Urban Forestry 4:264-274

Kuntz, P.A., Christie, R.D., and S.S. Venkata. 2002. Optimal vegetation maintenance scheduling of overhead electric power distribution systems. IEEE Transactions on power delivery: 17(4) 1164-1169

Lenth, R. 2020. emmeans: estimated marginal means, aka least-squares means. R package version 1.4.6. <https”//CRAN.R-project.org/package=emmeans>

Lilly, S., Gilman, E.F., and Smiley, E. 2019. Best management practices: pruning, third edition. International Society of Arboriculture, Champaign Illinois

Livesly S. J., E. G. McPherson, and C. Calfapietra. 2016. The urban forest and ecosystem services: Impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. Journal of environmental quality

Lovlace, W. R. 1996. Vegetation management of distribution line right-ofway: Are you getting top value for your money?, in Proc. 39th Annu. Rural Electric Power Conf.

Maczulajtys, C. 1999. Pruning stress: changes in the tree physiology and their effects on the tree health. Acta horticulturae 496:317-324

Mahan, C.G., Ross, B.D., and R.T. Yahner. 2020. The effects of integrated vegetation management on richness of native compatible flowering plants and abundance of noncompatible tree species on a right-of-way in central Pennsylvania, USA. Arboriculture of urban forestry. 46(6): 395-401.

McPherson, E.G. and Peper, P.J. (1996) Costs of infrastructure tree damage to infrastructure. *Arboricultural Journal* 20, 143–160.

Medhurst, J.L., Pinkard, E.A., Beadle, C.L., Worledge, D., 2006. Photosyntheticcapacity in Acacia melanoxylon following form pruning in a two-species plantation. Forest ecology and management. 233, 250–259.

Miller, R. 1998. Why utilities V-out trees. Arborist News 7:9–14.

Miller, R. H., and G. Kempter. 2018. Utility Arboriculture. International Society of Arboriculture. Champaign, Illinois, U.S. 129 pp.

Morani, A., D. Nowak, S. Hirabayashi, G. Guidolotti, M. Medori, V. Muzzini, S. Fares, S.G. Mugnozza, and C. Calfapietra. 2014. Comparing i-Tree modeled ozone deposition with field measurements in a periurban Mediterranean forest. Environmental Pollution 195:202-209

Morgenroth, J., and J. Östberg. 2017. Measuring and monitoring urban trees and urban forests. In F. Ferrini, C. C. Konijnendijk, & A. Fini (Eds.). Routledge handbook of urban forestry. London: Routledge.

Napoli, M., L. Massetti, G. Brandani, M. Petralli, and S. Orlandini. 2015. Modeling tree shade effect on urban ground surface temperature. Journal of Environmental Quality. 45:146-156

Neilsen, W.A., and E.A. Pinkard. 2003. Effects of green pruning on growth of Pinus radiata. Canadian Journal of Forest Research 33:2067–2073.

Nowak, C.A., and B.D. Ballard. 2005. A framework for applying integrated vegetation management on rights-of-way. Journal of Arboriculture 31(1): 28-37

Nowak, D.J. 1994. Atmospheric carbon dioxide reduction by Chicago's urban forest. In: McPherson, E.G; Nowak, D.J.; Rowntree, R.A., eds. Chicago's urban forest ecosystem: Results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 83–94.

Nowak, D.J. 1996. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. 4 Forest Service 42(4)

Nowak, D.J. 2020. Understanding i-Tree: Summary of programs and methods. Technical report of the USDA Forest Service Northern Research Station. Madison, Minnesota, U.S.

Nowak, D.J., D.E. Crane, and J.C. Stevens. 2006. Air pollution removal by urban trees and shrubs in the United States. Urban forestry and urban greening. 4:115–123.

Nowak, D. J., D.E. Crane, J.C. Stevens, R.E. Hoehn, J.T. Walton, and J. Bond. 2008. A ground-based method of assessing urban forest structure and ecosystem services. Arboriculture and Urban Forestry 34:347-358

Nowak, D.J. and M. Lear. 2009. Briefing paper: assessing urban forest canopy cover: a primer for state foresters. A briefing paper prepared by the urban and community forestry committee of the national association of state foresters

Nowak, D.J., R.E. Hoehn, Bodine, A.R., Greenfield, E.J., and J. O'Neil-Dunne. 2016. Urban forest structure, ecosystem services and change in Syracuse, NY. Urban ecosystems. 19:1455-1477.

Olienyk, D. 1988. The network between utility forestry and municipal forestry: it does exist. Journal of Arboriculture 14:265-268

Ordóñez, C., and P.N. Duinker. 2013. An analysis of urban forest management plans in Canada: Implications for urban forest management. Landscape and Urban Planning, 116, 36–47.

Pavlis, M., Kane, B., Harris, J. R., and J. R. Seiler. 2008. The effect of pruning on drag and bending moment of shade trees. Arboriculture and urban forestry. 34(4): 207-215.

Perry, P.B. 1977. Management's view of the tree trimming budget. Journal of Arboriculture 3(8):157–160

Perry, E. and G. Hickman. 1987. Wound closure in *Eucalyptus.* Journal of arboriculture. 13(8): 201-202.

Perrette, G., Delagrange, S., and C. Messier. 2020. Optimizing reduction pruning of trees under electrical lines: The influence of intensity and season of pruning on epicormic branch growth and wound compartmentalization. Arboriculture and urban forestry. 46(6): 432-449

Pinkard, E.A., and C.L. Beadle. 1998. Effects of green pruning on growth and stem shape of *Eucalyptus nitens*. New Forests 15:107–126.

Pokorny, J. 2003. Urban tree risk management: a community guide to program design and implementation. Technical report of the USDA Forest Service Northeastern Area. St Paul, Minnesota, U.S. 204 pp.

Radmer, D.T., Kuntz, P.A., Christie, R.D., Venkata, S. S., and R.H. Fletcher. 2002. Predicting vegetation-related failure rates for overhead distribution feeders. IEE transactions on power delivery. 17(4): 1170-1175.

Randrup, T.B., McPherson, E.G., and L.R. Costello. 2001. A review of tree root conflicts with sidewalks, curbs, and roads. Urban ecosystems. 5:290-225.

Raum, S., Hand, K.L., Hall, C., Edwards, D.M., O’Brien, L., and Doick, K.J. 2019. Achieving impact from ecosystem assessment and valuation of urban greenspace: The case of i-Tree eco in Great Britain. Landscape and urban planning. 190.

Robinette, G. O. 1972. Plants, people, and environmental quality: a study of plants and their environmental functions. Washington, DC: US Department of the interior, National parks service

Ryan, H.D.P. 1985. Vegetation’s impact on urban infrastructure. Journal of Arboriculture 11(4): 112-115.

Ryder, C.M., and G.M. Moore. 2013. The arboricultural and economic benefits of formative pruning street trees. Arboriculture and urban forestry. 39(1): 17-24.

Schomaker, M. E., Z.J. Stanley, W.A. Bechtold, D.J. Latelle, W.G. Burkman, and S.M. Cox. 2007. Crown-condition classification: a guide to data collection and analysis. General Technical Report SRS-102 of the USDA Forest Service Southern Research Station. Ashville, North Carolina, U.S. 92 pp.

Schwarz, C.F., and J.A. Wagar. 1987. Street tree maintenance: How much should you spend now to save later? Journal of Arboriculture 13(11): 257-261

Shigo, A., and H. Marx. 1977. Compartmentalization of decay in trees. Agricultural Information Bulletin No. 405. USDA Forest Service.

Shigo, A.L. 1990. Pruning trees near electric utility lines. Shigo and Trees Associates, Durham, NH.

Simpson, P., and R. Van Bossuys. 1996. Tree-caused electric outages. Journal of Arboriculture, 22:117-121

Smiley, E.T., Matheny, N., Lilly, S., 2017. Best Management Practices: Tree Risk Assessment Second Edition. International Society of Arboriculture, Champaign, IL, pp. 81.

Smiley, E. T., and Kane, B. 2006. The effects of pruning type on wind loading of acer rubrum. Arboriculture and Urban Forestry, 32(1), 33-40.

Soares, A. L., Rego, F. C., McPherson, E. G., Simpson, J. R., Peper, P. J., & Xiao, Q. (2011). Benefits and costs of street trees in Lisbon, Portugal. Urban Forests and Urban Greening, 10(2): 69–78.

Solberg, S. and L. Strand. 1999. Crown density assessments, control surveys and reproducibility. Environmental monitoring and assessment. 56: 75-86

Solecki, W.D., C. Rosenzweig, L. Parshall, G. Pope, M. Clark, J. Cox, and M. Wiencke. 2005. Mitigation of the heat island effect in urban New Jersey. Environmental hazards. 6:39–49.

Ulrich, R. S. 1984. View through a window may influence recovery from a surgery. Science. 224:420-421

Ulrich, E.S. 1987. Utility line clearance in our urban forests. Journal of Arboriculture 13:62–64.

United States Census Bureau. 2010. Census Tracts. Accessed 10/15/2019. <https://www2.census.gov/geo/pdfs/education/CensusTracts.pdf>

USDA Forest Service. 2019. i-Tree eco field guide. Accesssed 10/15/2019. <http://www.itreetools.org/resources/manuals/Ecov6_ManualsGuides/Ecov6_FieldManu

al.pdf>

Víquez, E. and D. Pérez. 2005. Effect of pruning on tree growth, yield, and wood properties of *Tectona grandis* plantations in Costa Rica. Silva Fennica 39(3): 381-390

Vogt, J., Hauer R. J., and B.C. Fischer. The cost of maintaining and not maintaining the urban forest: a review of urban forestry and arboriculture literature. Arboriculture and Urban forestry. 41(6):293-323

Venables, W. N. and B.D. Ripley. 2002. Modern Applied Statistics with S. Fourth Edition. Springer, New York. ISBN 0-387-95457-0

Wickham, H. 2016, ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, USA

Wong, T.W., Good, J.E.G. and Denne, M.P. (1988) Tree root damage to pavements and kerbs in the City of Manchester. *Arbroricultural Journal* **12**, 7–34.

Wu, J., Y. Wang, S. Qiu, and J. Peng. 2019. Using the modified i-Tree Eco model to quantify air pollution removal by urban vegetation. Science of the Total Environment 688:673-683