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Comparing the Structure, Function, Value, and Risk of Managed and Unmanaged Trees along Rights-of-Way and Streets in Massachusetts

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Abstract: Trees provide numerous benefits in urban areas, including improving stormwater retention and filtration, removing gaseous and particulate pollutants from the air, sequestering atmospheric carbon, and reducing ambient temperature. However, trees also pose risks in urban areas. Trees growing near overhead electrical utility lines cause a large proportion of electrical power outages. To mitigate this risk, arborists frequently and sometimes severely prune trees near overhead utilities for clearance and to reduce the likelihood of failure. Ostensibly, urban trees distant from utility lines are not pruned as frequently or severely. This study aimed 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. In total, 200 utility easement plots and 200 non-utility control plots were distributed in Eversource Energy's distribution territories, encompassing 2361 trees in total. Diameter at breast height (DBH), crown height and spread, percent crown missing, percent twig dieback, and likelihood of failure were gathered for each tree in the study. These variables were compared individually among study groups, and used as inputs to calculate estimated ecosystem service delivery using USFS iTree Eco v6. Overall, trees in control plots were larger and delivered more ecosystem services, per tree, than trees in utility plots. However, on a population level, trees in utility plots were more populous and delivered more aggregate ecosystem services than those in control plots. Although the aesthetics of utility tree pruning is often debated, there were no differences in likelihood of failure ratings between trees in control and utility plots. These findings may help to frame trees near overhead utility lines, commonly seen as risks or eyesores, as valuable green infrastructure and community assets.

Keywords: urban forestry; utility forestry; tree risk assessment; ecosystem services; arboriculture; utility arboriculture

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1. Introduction

Electrical distribution grids are an integral component in the safe and reliable delivery of energy from producers to end consumers. Trees are also indispensable to communities and provide many important ecosystem services in urbanized areas globally [1]. However, trees cause a large proportion of unplanned outages on electric distribution systems [2]. Because of this risk, it is necessary to prune or remove trees to ensure reliable delivery of electricity [3], and to reduce (i) the risk and cost associated with outages [4], and (ii) downstream lost revenue from the consumer's perspective [5].

Commercial, municipal, and utility arborists have assessed tree risk for many years in an attempt to mitigate it. In the past 20 years, there has been a greater emphasis on standardizing risk assessment methods to reduce uncertainty [6]. Since the context in which arborists assess risk can vary between commercial, municipal, and utility sectors, best practices particular to the latter have also been developed [7]. In all cases, assessing risk involves the assessment of three factors: likelihood of tree failure, likelihood of impact on a target should the tree or tree part fail, and severity of consequences of the impact of the tree or tree part on a target. Targets include people who may be injured, property that may be damaged, or activities that may be disrupted [7,8]. Once the risk level has been determined, arborists recommend options to mitigate it; risk managers–not arborists–ultimately decide on a management strategy that aligns with a stated risk tolerance [7,8].

Utility arborists manage risk–specifically, the safety and reliability of electrical power distribution systems–by cyclically pruning or removing trees that have a greater likelihood of failure or interfering with power lines [9–11]. However, cyclically repeated pruning to remove branches growing near power lines sometimes creates unnatural crown shapes atypical of open grown trees [12,13] and reduces leaf area; and removing trees–especially large individuals–reduces tree cover. Both can reduce the value of benefits that community trees provide. For example, many ecosystem services provided by trees are proportional to leaf area including air pollution reduction [14], stormwater mitigation [1,15], reduction in building energy use [16] and temperatures in cities [17]. Additionally, tree cover is positively correlated with home sale price [18] and property values [19]. For trees that are not in proximity to utility wires, pruning may be less severe because there is no imperative to clear branches near the wires and best practices for pruning large and mature trees discourage removal of live foliage [20,21].

Repeated pruning also creates more wounds from branch reduction and removal cuts, even within a natural pruning system. Making good branch removal cuts are intended to preserve the branch protection zone [20] and reduce the incidence of decay [22,23], but when many cuts occur, wound occlusion may be slowed, and decay can still form [24]. Reduction cuts, which are often used to shorten interfering branches [20], do not preserve the branch protection zone and can also result in decay over time [13]. Depending on its extent and severity, decay in stems or branches can increase the likelihood of tree failure in the future.

Very few studies have examined the long-term effects of utility pruning on trees in situ [25], although recent work has explored the response of nursery trees to utility pruning [26,27]. Understanding how more severe pruning of trees in proximity to utility lines is essential to modeling ecosystem services provided by trees in towns and cities–an important aspect of urban forest management globally, as shown by the many studies that use i-Tree Eco [28]. As the frequency and severity of storms increases with a changing climate, utilities will be more inclined to pursue more aggressive proactive risk management to avoid service disruptions during inclement weather [29]. The objective of this study was to determine whether trees pruned for overhead utility line clearance differed from trees pruned for other objectives with respect to tree size, crown condition, delivery of ecosystem services, and likelihood of failure.

2. Materials and Methods

Using ArcMap (ESRI, Redlands, CA, USA) and a road shapefile [30], we placed 200 sampling sites along roads throughout Massachusetts, USA in a stratified random fashion using the *Create Random Points* tool [31] in ArcMap (Figure 1). Points were randomly generated in census tracts within Eversource Energy's service territory. Since census tracts correspond to population rather than geographical area, this approach created a greater number of sampling sites in more densely populated areas. At each site, we defined two rectangular plots that were 3.7 m wide, 110 m long, and parallel to the road. Plot width was based on the intended lateral dimension for line clearance pruning; plot length was selected to create the standard plot area (0.40 ha) used in i-Tree Eco [32], adjusted for a rectangular rather than circular area to align with the orientation of electrical distribution lines. One plot was located on the side of the road with electrical distribution lines (the "utility plot"); the other was located on the opposite side of the road without utility lines (the "control plot"). We measured any tree whose trunk was entirely or partially in the plot. In the event that (i) a randomly generated site did not contain electrical distribution lines or (ii) the paired control plot did not contain any trees, we headed north (or east) along the road until appropriate utility and control plots were present.

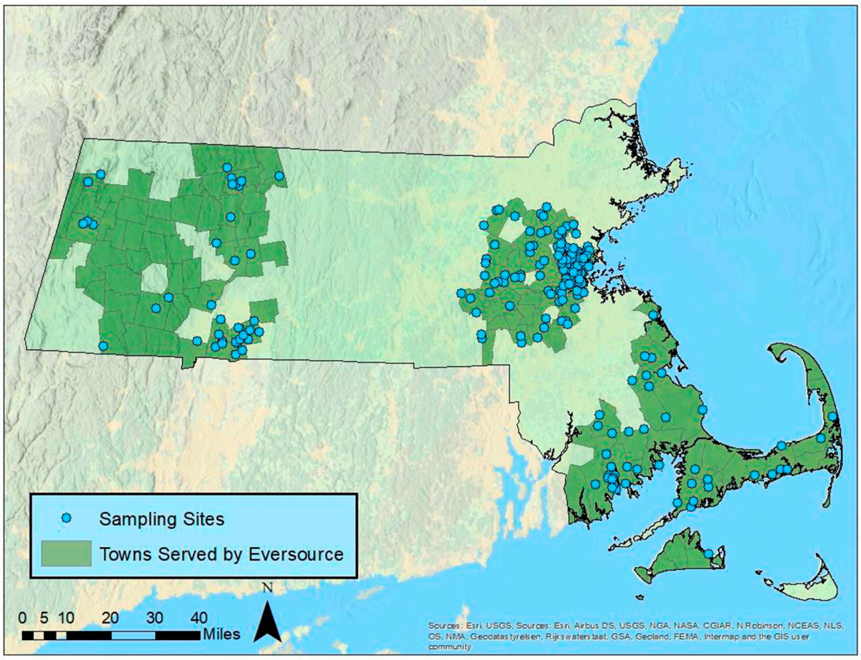

Figure 1. Distribution of sampling sites throughout Eversource Energy's service areas in Massachusetts, USA.

We collected data in May through September 2020, when leaves were fully expanded and before foliage changed color. For all trees greater than 2.5 cm in trunk diameter measured 1.4 m above ground (DBH), we measured DBH, tree height, height to crown base, crown width, percent crown missing, and percent crown dieback. We used a Forestry Pro Rangefinder/Hypsometer (Nikon USA, Melville, NY, USA) to measure tree height (H), height to crown base (C_B), and crown width in two perpendicular directions (C_{W_a}, C_{W_b}). We visually estimated the percent of crown missing, comparing the observed crown to a completely full crown, (C_M) and percent crown dieback in increments of five percent, following i-Tree protocol [32]. The i-Tree user's manual [32] includes examples of percent crown missing to assist in this measurement. We calculated crown length (C_L) as:

$$C_L = H - C_B \tag{1}$$

We calculated crown volume (C_V) as an ellipsoid, accounting for missing foliage:

$$C_V = (\pi/6)\,(C_L\, C_{W_a}\, C_{W_b})(1 - C_M) \tag{2}$$

We noted the presence of pruning cuts on trees. If cuts were present, we considered the tree pruned; if not, we considered the tree unpruned. Since the age of cuts could not be reasonably defined, we considered a tree pruned if there were any noticeable cuts that had not fully occluded. Due to time constraints, it was not possible to quantify pruning severity.

In accordance with Goodfellow's [7] level 1 inspection procedure, we assessed the likelihood of tree failure in a three-year timeframe. Likelihood of failure depends on expected loads on the tree within the timeframe and the tree's load-bearing capacity. The latter depends on diameter, intrinsic wood strength, and the presence and severity of observed structural defects such as decay, weak branch unions, cracks, or root damage [7,8]. We used i-Tree Eco v6 [33] to compute the ecosystem services delivered by each tree [carbon storage (kg), annual carbon sequestration (kg), annual runoff avoided (m^3), annual air pollution removed (g)], as well as the total value ($) of ecosystems services delivered and the tree's structural value ($). We collected all data with i-Tree Eco v6 mobile data collector.

We used generalized linear models to explore the effect of plot type, pruning status, and their interaction on tree size (DBH, height, and crown length and width—the latter calculated as (C_(W_a) C_(W_b))/2), percent crown missing, percent crown dieback, delivered ecosystem services and their annual value, and tree structural value. We used Tukey's Honestly Significant Difference test for multiple comparisons of significant ($p < 0.05$) interactions. To investigate the effect of plot type, pruning status, and their interaction on likelihood of tree failure, we used ordinal logistic regression, assigning values of 1, 2, 3, and 4 to the ratings "improbable", "possible", "probable", and "imminent", respectively, from Smiley et al. [8]. We included DBH and percent crown dieback as covariates in the ordinal logistic regression model because a preliminary analysis demonstrated that including them resulted in the lowest AICc value. We conducted all analyses in R statistical software [34]. We were not able to build an appropriate model for percent crown dieback despite trying different distributions and bins. As an alternative we used five tree condition classes based on the following ranges of percent crown dieback: "Excellent" was 0% dieback, "Good" was dieback of 5% or 10%, "Fair" was dieback between 15% and 55%, "Poor" was dieback between 60% and 95%, "Dead" was 100% dieback. We constructed a mosaic figure to illustrate the distribution of tree condition in each combination of plot type and pruning status.

3. Results

3.1. Tree Sample

The sample included 2361 individuals from 97 species. Figure 2 shows the distribution of trees by species; 37 individuals were only identified to genus. Only two species (*Acer platanoides* L. and *Quercus rubra* L.) made up more than 10% of the total sample. Figure 3 shows the distribution of trees by 10 cm DBH classes; 42% of individuals were greater than 30 cm DBH. There were nearly twice as many trees in utility plots as in control plots and a little more than twice as many pruned as unpruned trees (Table 1). The distribution of pruned and unpruned trees in control plots was similar, but there were almost three times as many pruned trees than unpruned trees in utility plots (Table 1). The proportional distribution of genera for each combination of the main effects (control and utility plots; pruned and unpruned trees) was similar (Table S1). Figure S1 includes the distributions of the main response variables for each combination of the main effects.

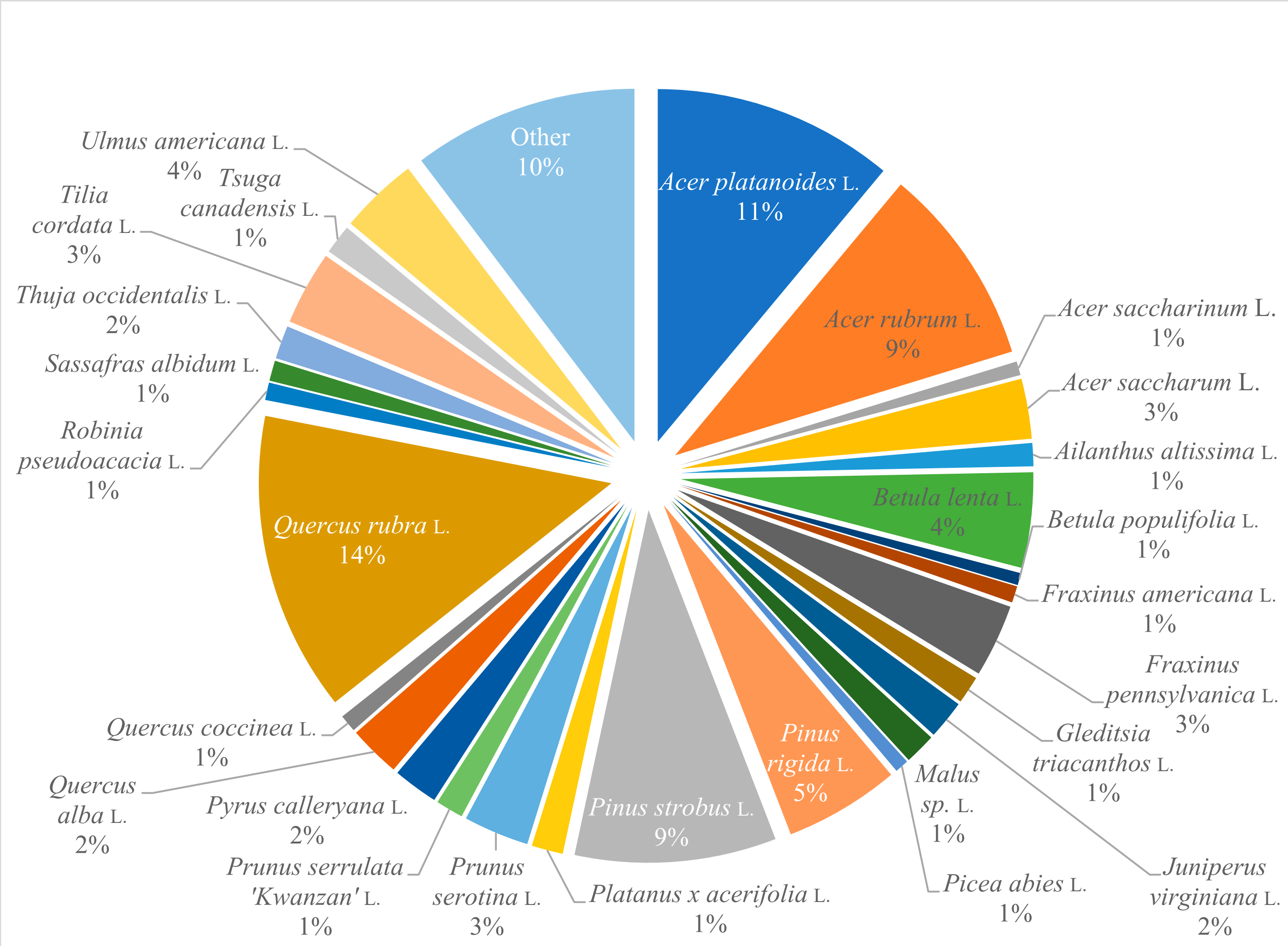

Figure 2. Species distribution of trees (n = 2361); "other" included 244 individuals of 66 species or, for individuals that could not be identified to species, 10 genera each of which comprised <1% of the total sample.

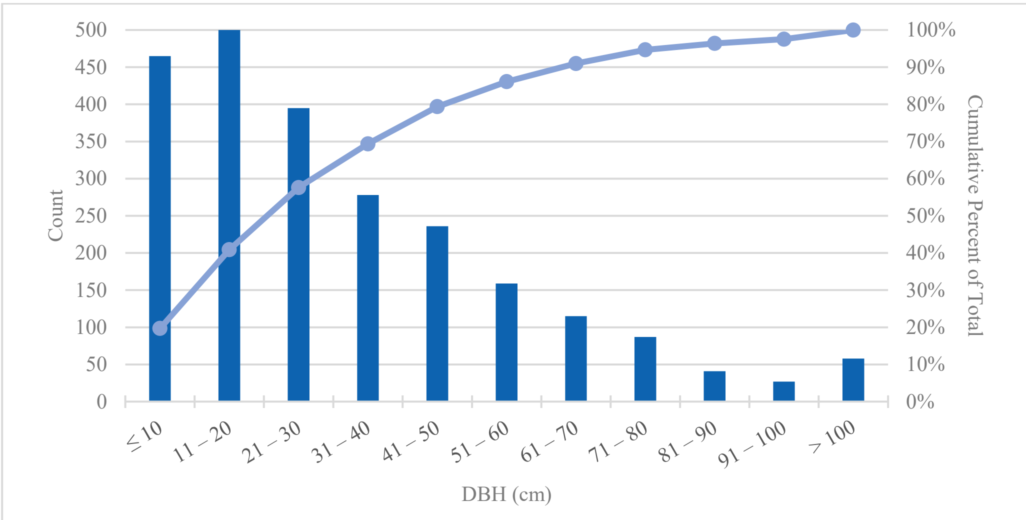

Figure 3. Distribution of trunk diameter 1.4 m above ground (DBH) of all trees (n = 2361).

Table 1. Means (followed by standard error in parentheses) of tree size and *p*-values for comparisons between plot types, pruning status, and their interaction; within each effect or their interaction, means followed by the same letter are not significantly different ($p > 0.05$) by Tukey's Honestly Significant Difference test. Crown volume was corrected for percent crown missing.

Parameter	Level	n	*p*-Value	DBH (cm)	*p*-Value	Height (m)	*p*-Value	Crown Width (m)	*p*-Value	Crown Length (m)	*p*-Value	Crown Volume (m^3)	*p*-Value	Percent Crown Missing
Plot type			<0.001		0.932		<0.001		<0.001		<0.001		<0.001	
	Control	792		35 (1.05) a		11.2 (0.22) a		7.7 (0.17) a		8.5 (0.13) a		355 (14.0) a		36.8 (1.05) a
	Utility	1569		31 (0.65) b		10.9 (0.16) a		6.9 (0.11) b		7.9 (0.19) b		241 (23.5) b		50.0 (0.75) b
Pruning status			<0.001		<0.001		<0.001		<0.001		<0.001		0.006	
	Pruned	1547		39 (0.71) a		12.7 (0.16) a		8.5 (0.11) a		9.4 (0.13) a		374 (17.1) a		50.0 (0.70) a
	Unpruned	758		18 (0.65) b		7.4 (0.18) b		4.6 (0.10) b		5.4 (0.14) b		84.2 (8.75) b		39.6 (1.20) b
Plot * Pruning			<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	
	Control Pruned	401		46 (1.58) a		12.8 (0.28) a		9.8 (0.24) a		9.9 (0.25) a		549 (39.2) a		34.6 (1.30) a
	Control Unpruned	371		23 (1.07) b		9.5 (0.32) b		5.4 (0.18) b		6.9 (0.25) b		139 (17.3) b		40.0 (1.70) b
	Utility Pruned	1146		37 (0.77) c		12.7 (0.19) a		8.0 (0.13) c		9.2 (0.15) c		311 (18.1) c		55.0 (0.80) c
	Utility Unpruned	387		13 (0.66) d		5.4 (0.11) c		3.8 (0.09) d		3.9 (0.11) d		32.6 (2.77) d		39.1 (1.70) ab

3.2. Tree Size

There were significant differences between plot type and pruning status for all morphologic measurements except tree height; the interaction of plot type and pruning status was also significantly different for all morphologic measurements (Table 1). Values of DBH and crown length, width, and volume followed the same pattern: they were greatest for pruned trees in control plots and significantly smaller, in descending order, for pruned trees in utility plots, unpruned trees in control plots, and unpruned trees in utility plots. Values of tree height followed the same pattern except that pruned trees in control and utility plots were statistically similar. The magnitude of difference between pruned and unpruned trees in utility plots was noticeably greater than in control plots. For example, DBH of pruned trees in control plots was twice as large as unpruned trees, but in utility plots, the DBH of pruned trees was nearly three times larger than unpruned trees. Similarly, crown volume of pruned trees in utility plots was nearly ten times greater than unpruned trees, but it was less than four times greater for pruned trees in control plots. Percent crown missing was greatest for pruned trees in utility plots; it was less for unpruned trees in control plots, and least for both pruned trees in control plots and unpruned trees in utility plots.

Figure 4 includes the distribution of five condition classes (excellent, good, fair, poor, dead) for each combination of plot type and pruning status. For all combinations, more than 79% of trees were in excellent or good condition and less than 10% of trees were dead or in poor condition.

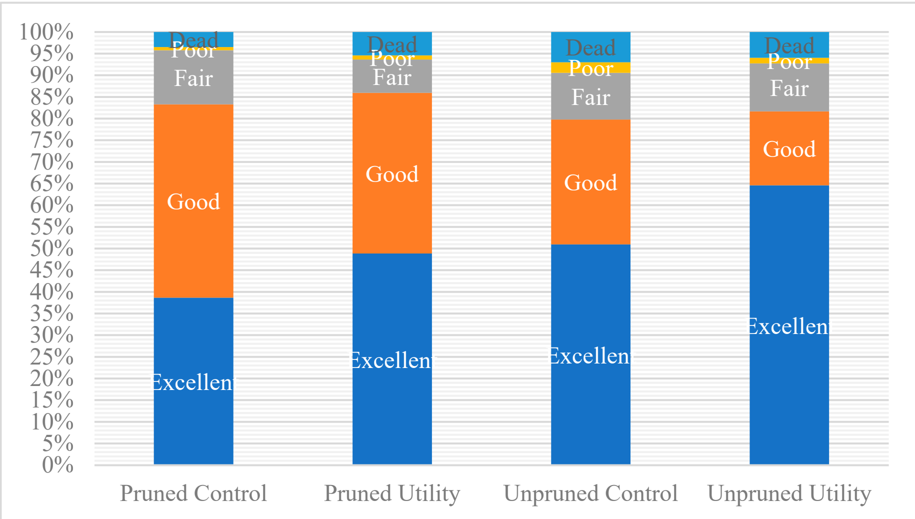

Figure 4. Distribution of tree condition for each combination of pruning status (pruned, unpruned) and plot type (control, utility); condition was based on 5% bins of percent crown dieback: "Excellent" was 0% dieback, "Good" was dieback of 5% or 10%, "Fair" was dieback between 15% and 55%, "Poor" was dieback between 60% and 95%, "Dead" was 100% dieback.

3.3. Ecosystem Services and Values from i-Tree Eco

The amounts of delivered ecosystem services (carbon storage, annual carbon sequestration, annual runoff avoided, annual air pollution removed) and their value were greater in control plots and for pruned trees; the same was true of the structural value of trees (Table 2). Evaluating the significant interaction of plot type and pruning status indicated that the means of carbon storage, annual carbon sequestration, and structural value were, in descending order, greatest for pruned trees in control plots, pruned trees in utility plots, unpruned trees in control plots, and unpruned trees in utility plots (Table 2). The interaction was not significant for annual runoff avoided, annual air pollution removed, and the value of ecosystem services.

Table 2. Means (followed by standard error in parentheses) of i-Tree Eco output and *p*-values for comparisons between plot types, pruning status, and their interaction; within each effect or their interaction, means followed by the same letter are not significantly different ($p > 0.05$) by Tukey's Honestly Significant Difference test.

Parameter	Level	*p*-Value	Carbon Storage (kg)	*p*-Value	Annual Carbon Sequestration (kg)	*p*-Value	Annual Runoff Avoided (m^3)	*p*-Value	Annual Air Pollution Removed (g)	*p*-Value	Value of Annual Ecosystem Services ($)	*p*-Value	Structural Value ($)
Plot type		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	
	Control		456 (31) a		12.8 (0.58) a		1.06 (0.05) a		136 (5.88) a		5.65 (0.28) a		1850.58 (90.92) a
	Utility		352 (17) b		10.8 (0.35) b		0.80 (0.03) b		103 (3.51) b		4.18 (0.15) b		1645.52 (53.44) b
Pruning status		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	
	Pruned		524 (21) a		14.9 (0.41) a		1.12 (0.03) a		142 (4.11) a		5.99 (0.19) a		2258.24 (63.04) a
	Unpruned		107 (11) b		4.43 (0.27) b		0.41 (0.03) b		57.2 (3.21) b		1.99 (0.12) b		603.88 (36.16) b
Plot * Pruning		<0.001		<0.001		0.061		0.129		0.205		<0.001	
	Control Pruned		707 (53) a		19.1 (0.91) a								2793.25 (148.85) a
	Control Unpruned		184 (22) b		5.96 (0.49) b								831.68 (67.47) b
	Utility Pruned		460 (21) c		13.5 (0.44) c								2071.03 (66.47) c
	Utility Unpruned		33.0 (4.7) d		2.97 (0.23) d								385.50 (24.23) d

3.4. Likelihood of Tree Failure

Pruning status, DBH, and percent crown dieback were all significant predictors of assessed likelihood of tree failure, as were the following interactions: pruning status with DBH and percent crown dieback with DBH (Table 3). There were no differences in assessed likelihood of failure between trees in control and utility plots; nor were any interactions between plot type and other model effects significant (Table 3). Odds ratios from the ordinal logistic regression model (Table 4) and a frequency plot (Figure 5) revealed trends in the likelihood of failure ratings. In the baseline ordinal logistic regression model, pruned trees have an odds ratio of one. Odds ratios greater than one for percent crown dieback and DBH indicated an increase in likelihood of failure rating as percent crown dieback or DBH increased. The odds ratio of unpruned trees was less than one, indicating that, compared to pruned trees, unpruned trees were less likely to have a greater likelihood of failure rating. However, since the interactions of DBH with both pruning status and percent crown dieback were significant (Table 4), it was necessary to examine the more detailed presentation of Figure 5.

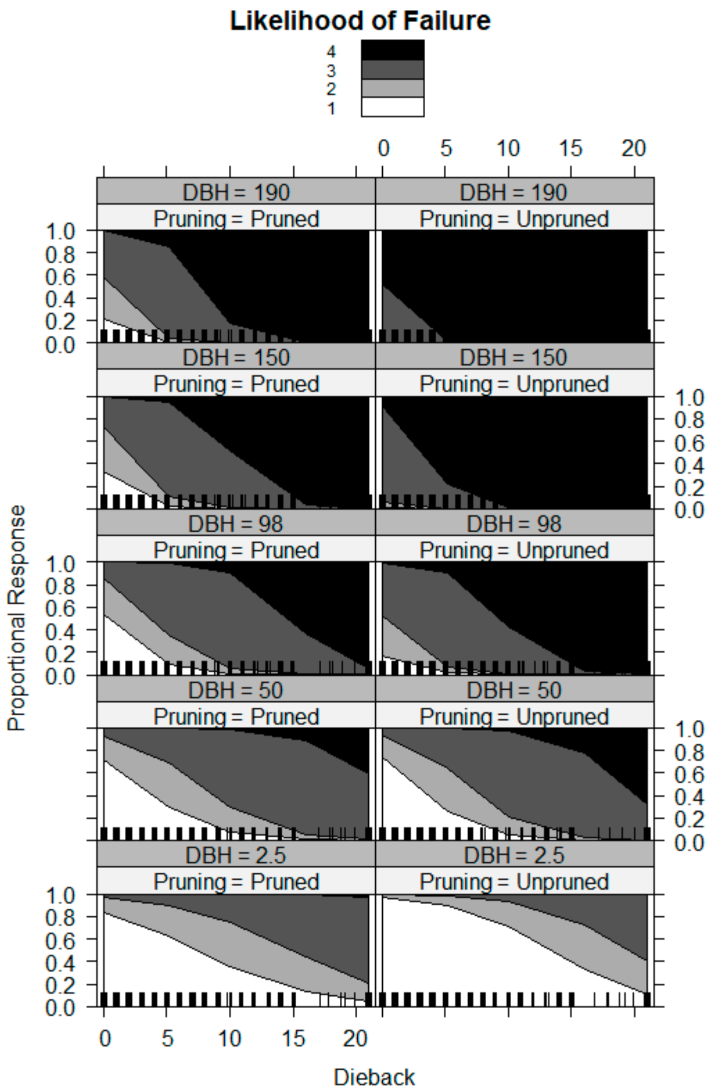

Figure 5. Visualization of the ordinal linear regression model to illustrate the effect of pruning status (pruned or unpruned), diameter 1.4 m above ground (DBH, cm), and percent crown dieback on the proportional response of assessed likelihood of failure. Numerical likelihood of failure values 1, 2, 3, 4, correspond to categories “improbable”, “possible”, “probable”, and “imminent,”, respectively, from Smiley et al. (2017). Note z below Table 3 describes percent crown dieback.

Table 3. Analysis of variance table for the ordinal logistic regression model (McFadden pseudo-r2 = 0.25) to predict assessed likelihood of failure from the effects of plot type (control, utility) pruning status (pruned, unpruned), trunk diameter 1.4 m above ground (DBH), percent crown dieback [z], and their interactions. Odds ratios in Table 4 were computed for the significant effects of pruning, DBH, crown dieback, and their interactions.

Effect	Likelihood Ratio χ^2	*p*-Value
Plot	0.345	0.5566
Pruning	23.5	<0.0001
DBH	6.12	0.0133
Dieback	9.50	0.0020
Dieback * DBH	5.11	0.0238
Plot * DBH	2.69	0.1010
Plot * Dieback	0.226	0.6344
Plot * Pruning	1.15	0.2839
Pruning * DBH	27.8	<0.0001
Pruning * Dieback	2.07	0.1501
Plot * Pruning * Dieback	0.287	0.5923
Plot * Pruning * DBH	3.00	0.0830
Plot * Dieback * DBH	1.16	0.2815
Pruning * Dieback * DBH	1.71	0.1913
Plot * Pruning * Dieback * DBH	0.143	0.7054

[z] Percent crown dieback is from i-Tree Eco v6 (https://www.itreetools.org/tools/i-tree-eco, accessed on 23 August 2022): 0 indicates 0% crown dieback, 1 indicates between 1% and 5% crown dieback, 2 indicates between 6% and 10% crown dieback, and so on until 20 indicates between 96% and 99% crown dieback, and 21 indicates 100% crown dieback—a completely dead standing tree.

Table 4. Odds ratios of significant effects (and their interactions with one another) in the ordinal logistic regression model to predict likelihood of failure (see Table 3). Coefficients (on the log scale) are relative to baseline model of pruning status = pruned which has an odds ratio of 1. Exponentiated from coefficients, odds ratios indicate the magnitude of the change in the odds of having a higher likelihood of failure rating (i) for unpruned compared to pruned trees or (ii) for a one unit increase in percent crown dieback or DBH. Odds ratios greater than one indicate an increase in the odds of having a higher likelihood of failure rating; odds ratios less than one indicate a decrease in the odds of having a higher likelihood of failure rating.

Effect	Coefficient (Std. Err.)	*p*-Value	Odds Ratio
Unpruned	−2.053 (0.260)	<0.001	0.13
Dieback [z]	0.216 (0.024)	<0.001	1.24
DBH [y]	0.016 (0.002)	<0.001	1.02
Unpruned * Dieback	0.046 (0.034)	0.182	1.05
Unpruned * DBH	0.038 (0.007)	<0.001	1.04
Dieback * DBH	0.002 (0.001)	0.001	1.00
Unpruned * Dieback * DBH	0.0003 (0.001)	0.831	1.00

[z] Note z below Table 3 describes percent crown dieback. [y] DBH (cm) is trunk diameter measured 1.4 m above ground.

Figure 5 shows the proportion of trees in each likelihood of failure category as a function of percent crown dieback for pruned and unpruned trees at five DBH values. The odds ratio greater than one for the effect of DBH in Table 4 is shown in Figure 5 as greater proportions of trees with higher likelihood of failure ratings within successively larger DBHs. The odds ratio greater than one for the effect of percent crown dieback in Table 4 is shown in each panel of Figure 5 as the increasing proportion of trees with higher likelihood of failure ratings as percent crown dieback increased. The significant interaction of DBH and pruning status in Table 4 is shown in Figure 5 as a greater proportion of trees with higher likelihood of failure ratings for larger (DBH $\geq$ 50 cm) unpruned trees compared to pruned trees but a greater proportion of trees with lower likelihood of failure ratings for smaller (DBH < 50 cm) unpruned trees compared to pruned trees. The significant interaction of DBH and percent crown dieback in Table 4 is shown in Figure 5 as greater proportions of trees with higher likelihood of failure ratings at smaller values of percent crown dieback for as DBH increased.

4. Discussion

The current study contributes to the growing body of research on utility arboriculture. Previous studies have considered the implications of converting previously topped crowns to directionally pruned V-shaped crowns [12,13], the effects of main stem reduction pruning on small stature trees in a nursery setting [26,27], and utility forest management on compatible right-of-way species richness [35], but the effect of utility pruning on larger trees in the landscape has not been thoroughly investigated.

We chose a mensurative approach for the study to ensure that we would sample a large number of individuals and sites throughout Massachusetts. Sites represented 5 USDA Hardiness Zones (5a, 5b, 6a, 6b, 7a) and the survey included broad ranges of genera and tree sizes. The mensurative approach also made it possible to measure trees in situ to explore the effects of utility pruning on young and old trees subject to stresses associated with growing in developed landscapes rather than in a nursery. However, the large sample size precluded more intensive measurements of factors such as pruning severity, which would be expected to influence growth. Consequently, we cannot empirically demonstrate the effects of pruning (whether utility or otherwise) on trees in control and utility plots. Despite this limitation, our results provide a baseline understanding of trees growing along distribution lines. The results are important because the vast network of above-ground electric distribution lines throughout the country affects many trees that are regularly pruned to maintain line clearance.

4.1. Tree Size and Delivery of Ecosystem Services

Measures of tree size followed a somewhat unexpected pattern: they were greater for pruned trees, despite many previous studies that showed a decrease in tree growth following pruning [36–39] especially when pruning was more severe [40,41]. The greater size of pruned trees presumably reflected the greater likelihood of larger trees being pruned to reduce risk (for trees in control plots) and provide clearance from utility infrastructure (for trees in utility plots). This would particularly apply to trees in utility plots because pruning would not be necessary to clear branches of smaller trees from interfering with powerlines since the typical height of the lines is roughly seven to nine meters above ground level [25]. This reasoning is supported by the findings that (i) nearly 75% of trees in utility plots were pruned, (ii) pruned trees in utility plots had the largest proportion of missing crown, and (iii) the disparity in tree size between pruned and unpruned trees was much greater in utility plots than in control plots.

More severe pruning of trees in utility plots, which was reflected in their smaller crown dimensions and greater percent crown missing, may have slowed diameter growth as previous studies have shown [36–41]. This was consistent with pruned trees in utility plots having smaller DBH and crown length, width, and volume than pruned trees in control plots. Unlike DBH and crown size, however, tree height was similar for pruned trees in control and utility plots despite more severe pruning of the latter. This counterintuitive result was not unexpected, however, because previous studies have shown a greater effect of pruning on trunk diameter than tree height [38,41], and increased terminal growth rates of unpruned remaining branches [36,42].

Compared to pruned trees in control plots, more severe pruning of trees in utility plots disproportionately reduced crown width over crown length, which makes sense given the nature of pruning to provide line clearance—only branches on the side of the crown adjacent to the powerlines need to be pruned. We also expected more severe pruning of trees in utility plots because Eversource prunes trees on a three-year cycle, which is similar to other utilities in the Northeast US. The pruning frequency in control plots was unknown, but Eversource's three-year pruning cycle is likely more intensive because most

US communities do not use scheduled pruning [43]. For those that do, the average pruning cycle was 6.6 years, 1.8 years behind the desired cycle of 4.8 years; in larger cities, pruning cycles were more than 2 years behind the desired pruning cycle [43].

As reflected in the greater percent of crown missing, more severe pruning of trees in utility plots, which reduced crown volume (see Equation (2)), did not reduce it enough to offset the larger DBH of pruned trees in utility plots compared to unpruned trees in control and utility plots. This is why differences in delivered ecosystem services from i-Tree Eco, which are based on tree size [44], aligned with differences in DBH and the length, width, and volume of tree crowns. Only means of carbon storage, annual carbon sequestration, and structural value were significantly different among the four combinations of pruning status and plot type, but numerical differences between combinations persisted for the other i-Tree Eco outputs (annual runoff avoided, annual air pollution removed, value of annual ecosystem services).

Mean values of i-Tree Eco outputs were for an individual tree in each combination of pruning status and plot type. Even though trees in utility plots were smaller, on average, than trees in control plots, because there were nearly twice as many trees in utility plots, their total value was greater. For example, the cumulative structural value of trees in utility plots was \$2.6 M or 1.8 times more value than for trees in control plots. This suggests that trees near powerlines may meaningfully contribute to ecosystem services in developed landscapes.

4.2. Likelihood of Failure

We expected higher likelihood of failure ratings as DBH increased: Many previous studies have shown that both perceived [45] and actual [45–48] likelihood of failure is greater for larger trees. We also expected higher likelihood of failure ratings as percent crown dieback increased because an increase in the latter reflects an increase in the number of dead branches, their size, or both. Professional guidance on tree risk assessment notes that trees with higher proportions of dead tissue may be assessed at higher likelihoods of failure due either to the dead portions failing themselves, or because they may indicate possible adverse root conditions or damage to roots that can compromise whole tree stability [7]. Empirical studies have also shown that trees with crown dieback [45] and dead branches [49] failed at a higher rate than trees without dieback.

Since failure of larger trees will likely lead to more severe consequences, pruning to reduce likelihood of failure is a common objective on larger trees [20] and some studies have suggested that it is effective [47,50]. Pruning larger dead branches to reduce risk, which would be more common on larger trees than smaller ones, is particularly important because the consequences of their failure and impact on a target will be more severe. This explains the greater proportion of higher likelihood of failure ratings for unpruned trees $\geq$50 cm DBH than pruned trees $\geq$50 cm DBH. Dead branches are only one of many defects that can increase the likelihood of tree failure; others include weakly attached branches, decay, cavities, cankers, and cracks [7]. Pruning is an effective way to mitigate the increased likelihood of failure by removing many types of defective branches or pruning to reduce the wind load on a tree [51,52]. Pruning of defective branches or stems that were not dead in trees $\geq$50 cm DBH, would explain the greater proportions of unpruned trees $\geq$50 cm DBH that had higher likelihood of failure ratings even at smaller values of percent crown dieback.

5. Conclusions

In general, trees pruned for overhead utility line clearance were smaller than other pruned trees and larger than unpruned trees (regardless of their proximity to powerlines), although tree height was an exception. While we could not analyze crown condition statistically, the overall proportions of trees in five condition classes did not appear to vary dramatically between pruned or unpruned trees in utility or control plots. The larger size of trees in control plots led to an overall trend that they delivered more ecosystem services than trees in utility plots, but this was true only on a per tree basis. Cumulatively, trees in utility plots had nearly twice as much structural value as those in control plots. Additionally, even though residents sometimes question the aesthetics of utility tree pruning [53], there were no differences in likelihood of failure ratings between trees in control and utility plots.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13101602/s1, Figure S1: Box and whisker plot showing distribution of selected measurements for each combination of main effects; Table S1: Supplementary table describing most common tree species in the sample.

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