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ORIGINAL ARTICLE

The effect of simulated trunk splits, pruning, and cabling on sways of *quercus rubra* L.

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Abstract

Key message **Cabling co-dominant stems at different heights and tensions altered neither frequency nor damping ratio, but the location and proportion of pruned crown mass significantly influenced both frequency and damping ratio.**

Abstract Amenity trees provide many benefits, but can damage property and injure persons. Arboricultural treatments like pruning and cabling intend to reduce the likelihood of tree failure, but the effect of such treatments on tree sways is not well known. We measured the sway response (frequency and damping ratio) of seven *Quercus rubra* L. before and after consecutive arboricultural treatments, including the addition a climber swaying freely or secured rigidly to the tree. We also quantified crown architecture and tree mass. Cabling two co-dominant stems did not influence sway response, but pruning increased frequency and decreased damping ratio. The effect of pruning depended on the proportion and location of pruned crown mass. Adding a climber predictably affected frequency and damping ratio in accordance with physical principles. This work adds novel insights to the understanding of tree sways, since previous studies have been limited by single trees, pruning types, or pruning severities.

Keywords Pruning · Cabling · Frequency · Damping ratio

Introduction

Amenity trees—those growing in towns and cities—provide many benefits [see, for example, Sect. 1 in Ferrini et al. (2017)], but can damage property and injure persons (Schmidlin 2009), sometimes involving costly litigation (Mortimer and Kane 2004). While all trees can fail if external loads like those induced by wind or ice are sufficiently large, those with structural defects like decay or axial splits ("cracks") have less load-bearing capacity. For the same amplitude of force, a structurally deficient tree has a greater likelihood of failure than one without defects. Defects in the trunk may also alter the sway motion of a tree, possibly increasing the likelihood of failure, but this effect has not been previously measured. Assessing the likelihood of failure of a structurally deficient tree is an important part of tree risk assessment (Smiley et al. 2011), as is mitigating risk, which arborists undertake by pruning or cabling trees.

Studies have shown that pruning can reduce drag and drag-induced bending moment (Smiley and Kane 2006; Pavlis et al. 2008) and trunk deflection (Gilman et al. 2008a, b, 2015), which reduces the likelihood of failure. Pruning can also change the sway frequency and damping ratio of a tree, but the effect differs among different pruning types and severities. De-branching small (Spatz et al. 2007) or large (Milne 1991) conifers with a single pruning increased frequency and decreased damping ratio, but repeated partial pruning of large conifers (Moore and Maguire 2005) or a single, large decurrent tree (James 2014) revealed that the effect on frequency was negligible until more than 80% of crown mass was pruned. These results are explained in part by the effect of leaves since removing all the needles on small conifers (Sellier and Fourcaud 2005) or comparing pruning types for broadleaf trees in- and out-of-leaf (Kane and James 2011) have shown a strong effect of leaves on frequency and damping ratio. Of these studies, however, only

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Kane and James (2011) compared the effects of different arboricultural pruning treatments, but that study was limited to smaller trees and a single pruning severity.

Very little work has investigated the effect of cabling trees on their sway motion. Arborists typically install a cable to reduce the likelihood of failure of a weakly attached branch or co-dominant stem, but the effect on sway motion is not well known. Reiland et al. (2015) investigated the effect of cabling co-dominant stems on frequency and damping ratio of *Quercus rubra* L., but only considered cables installed at the height and tension recommended in a relevant arboricultural standard (Anonymous 2013). Few experimental data support the standard, and in practice, arborists rarely measure the height and tension at which a cable is installed, warranting further study of the effects of cable tension and height on tree sways.

Given the sparse empirical data and importance of mitigating the likelihood of failure of amenity trees, our objective was to investigate further the effects of simulated cracks, cabling, and pruning on the sway characteristics of large, broadleaf trees. We hypothesized that (1) a simulated crack in the trunk would change its sway frequency, (2) increased cable tension and height would alter sway characteristics, because the co-dominant stems would not sway independently of one another, and (3) pruning branches from different crown locations would affect sway characteristics differently because of the relative proportion of leaves removed and changes to the relative spatial distribution of mass. To explore in detail the effect of the spatial distribution of mass on sway characteristics, we added the mass of a climber at different locations in one tree after it had been partially pruned.

Methodology

Site

We tested *Q. rubra* growing in a forested stand in Pelham, MA (42.374551, −72.424184, USDA hardiness zone 5b). The site had been cleared of saplings and pole-sized trees in 2005, and 35 over-story trees were removed in 2010 and 2011, creating a park-like setting in an area of approximately 0.4 ha. Soil is a well-drained Gloucester gravelly fine sandy loam and extremely stony; mean annual precipitation is between 81 and 127 cm (USDA NRCS). The growth rate of *Q. rubra* averaged less than 2.0 mm per year between 1996 and 2011 (Kane and Autio 2014).

Trees

We selected seven trees—relevant morphology described in Table 1—with a single stem that bifurcated into a pair of co-dominant stems between 38 and 55% of tree height. We refer to the more massive co-dominant stem as "co-dominant 1" and the less massive co-dominant stem as "co-dominant 2". We refer to "primary" and "secondary" branches with respect to each co-dominant stem: first-order branches arising from co-dominant stems—including the distal, leafy portion—are primary branches and second-order branches arising from primary branches are secondary branches. We measured the mass, diameter, and length of the main stem, each co-dominant stem, all primary branches, and any secondary branches greater than 5 cm in diameter. Unless otherwise noted, when we refer to primary branch mass, it includes the mass of secondary branches arising from it. We also measured the angle above horizontal, azimuth, and height above ground of each primary branch, and the distal diameter of the main stem (below the union of co-dominant stems) and co-dominant stems (below the distal, leafy portion).

Testing

Prior to pruning treatments, we tested trees 52, 53, 55, and 58 to establish a baseline frequency and damping ratio. Since cables had been previously installed in trees 57, 59, and 61 (Reiland et al. 2015), the initial trials were of cabled trees (described in the following sub-section). We attached two tri-axial accelerometers (G-Link, Lord Microstrain, Williston, VT, USA) to two or three locations on each tree for repeated trials. Table 2 presents the specific locations of accelerometers on each tree. Except for trees 55 and 57, we measured accelerations at each location for each pruning or cabling treatment, which are described in the following sub-section. On tree 55, we measured accelerations before pruning on each co-dominant stem and the main stem, but for the remaining pruning treatments, we only measured accelerations on co-dominant 1 and the main stem. On tree 57, we only measured accelerations on the main stem 1.8 m below the co-dominant union when the tree was leafless and not cabled.

We only tested trees on calm days, with ambient wind speed less than 2 m/s. We swayed trees by installing a rope near the union of co-dominant stems. One person cyclically pulled on the rope to sway the tree; after several induced sways, the person released the rope and a second person triggered the accelerometers, which recorded oscillations at 128 Hz for 31 s.

Treatments

During the summers (July through September) of 2015 and 2016, when trees were fully in-leaf and maximum daily temperature varied between 20 and 30 °C, we tested seven trees. We also re-tested tree 57 in April 2017 when it was leafless

Table 1 Morphology of measured parts of each tree (and the overall mean and standard deviation for all trees), including proximal diameter[a], total length[b], slenderness[c], the number of primary branches (NPB), the ratio of diameter of the main stem to tree height squared (D/H^2), the total diameter of primary branches ($\sum_d$), and relative mean height of branch mass[d] (R_b)

	Tree							Mean	Std. dev.
	52	53	55	57	58	59	61		
NPB	16	10	10	14	10	12	14	12	2.43
$\sum_d$ (cm)	106	69	101	141	83	116	119	105	23.9
D/H^2 (cm/m^2)	0.05	0.05	0.06	0.07	0.06	0.07	0.08	0.06	0.01
R_b	0.71	0.80	0.79	0.70	0.92	0.75	0.54	0.74	0.12
Diameter (cm)									
Main stem	48	46	50	55	39	52	41	47	5.77
Co-dominant 1	29	25	29	38	18	30	26	28	6.04
Co-dominant 2	23	23	22	35	19	26	19	24	5.49
Mean primary branches	6.2	6.7	11.3	10.4	7.5	8.4	8.5	8.5	1.68
Total length (m)									
Main stem	30	29	28	28	25	27	23	27	2.41
Co-dominant 1	16	19	13	20	10	18	10	15	4.18
Co-dominant 2	16	16	12	20	10	21	11	15	4.34
Mean primary branches	4.5	4.5	7.1	6.4	5.5	6.0	5.4	5.6	0.96
Slenderness (m/cm)									
Main stem	62	64	56	51	63	52	44	56	7.46
Co-dominant 1	54	75	44	41	55	58	40	52	12.3
Co-dominant 2	69	73	55	46	52	79	54	61	12.4
Mean primary branches	77	66	72	64	76	73	64	70	5.56

[a] Measured above the root flare or distal to the branch collar

[b] Measured from the location of diameter measurement to the distal tip of the axis

[c] Calculated as total length/proximal diameter

[d] See Eq. 4

Table 2 Location of accelerometers used to calculate frequency and damping ratio on each tree and, for pruned trees, dimensions of the axial split cut in the main stem; direction of the axial split is relative to the plane that bifurcates the union of co-dominant stems

Tree	Co-dominant 1[a]	Co-dominant 2[a]	Main stem[a]	Axial split cut in main stem		
				Length	Height	Direction
52	0.4	0.5	–	0.4	0.5	Parallel
53	0.5	0.5	–	0.3	0.5	Perpendicular
55	0.9	0.9	0.7	0.4	0.8	Perpendicular
57	4.0	4.0	0.3, 0.6, 1.8			
58	0.3	–	0.3	0.1	0.5	Perpendicular
59	1.8	1.9	0.2			
61	0.7, 4.7, 5.2	0.8, 4.7, 5.2	0.7			

All measurements are in meters; locations are either above (for co-dominant stems) or below (for the main stem) the co-dominant union

– indicates that no measurements were taken at that location

[a] Multiple values separated by commas indicate multiple measurement heights

and the temperature was 18 °C. Table 3 describes consecutive pruning and cabling treatments. Table 2 describes the axial splits cut into the main stem of each tree. Following treatment 3 of tree 52, we pruned the distal, leafy portion of each co-dominant stem, and the climber who performed the work (mass 86 kg) remained in the tree. We repeated the sway tests 18 times: 3 trials each of 6 treatments during which the climber positioned himself differently in the crown. In chronological order: (1) the climber secured himself with a rope to co-dominant 1 16.1 m above ground; as the test commenced, he allowed himself to sway freely and opposite the sway motion of the tree; (2) the climber secured himself with a rope to co-dominant 1 19.3 m above ground; as the test commenced, he allowed himself to sway freely and opposite the sway motion of the tree; (3) the climber secured himself with a rope to both co-dominant stems 16.1 m above ground; as the test commenced, he remained rigidly secured to co-dominant 2, rather than

Table 3 Consecutive treatments for pruned (52, 53, 55, 58) and cabled (57, 59, 61) trees; treatments in italics indicate that pruning had removed all primary branches or leaves from the crown

Tree	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5	Treatment 6
52[a]	Before pruning	Prune secondary branches from primary branches, leaving distal, leafy portion	Prune primary branches (leaving distal, leafy portion) from each co-dominant stem	*Reduce length of co-dominant stems by one-half*	Cut axial split in main stem above root flare	–
53	Before pruning	Reduce length of primary branches by approximately one-third	Prune all secondary branches	*Prune all primary branches*	Prune co-dominant 1	Cut axial split in main stem above root flare
55	Before pruning	Prune co-dominant 2	Cut axial split in main stem above root flare	Prune large primary branch from co-dominant 1	*Prune co-dominant 1*	–
57	Cable tension: proper cable height: proper (9.3 m above co-dominant union)	Cable tension: proper cable height: proper Leafless	Cable tension: tight Cable height: proper Leafless	No cable Leafless	–	–
58	Before pruning	Prune primary branches from co-dominant 2 (leaving distal, leafy portion)	Prune co-dominant 2	Prune primary branches from co-dominant 1 (leaving distal, leafy portion)	*Prune co-dominant 1*	Cut axial split in main stem above root flare
59	Cable tension: proper cable height: proper (18.1 m above co-dominant union)	Cable tension: proper cable height: low (3.2 m above co-dominant union)	Cable tension: very tight Cable height: low	No cable	Cable tension: tight Cable height: proper	Cable tension: very tight Cable height: proper
61	Cable tension: proper cable height: proper (14.7 m above co-dominant union)	Cable tension: tight Cable height: proper	Cable tension: proper cable height: low (1.7 m above co-dominant union)	Cable tension: tight Cable height: low	No cable	–

[a] Treatments do not include those with a climber in the tree, which followed treatment 3 and are described in the text

swaying freely; (4) the climber secured himself with a rope to both co-dominant stems 19.3 m above ground; as the test commenced, he remained rigidly secured to co-dominant 2, rather than swaying freely; (5) the climber secured himself to co-dominant 1 16.1 m above ground; as the test commenced, he remained rigidly secured to co-dominant 1, rather than swaying freely; and (6) the climber secured himself to co-dominant 1 19.3 m above ground; as the test commenced, he remained rigidly secured to co-dominant 1, rather than swaying freely. Table 3 does not include treatments involving the climber in tree 52.

In 2012, we had installed single steel cables between the co-dominant stems of trees 57, 59, and 61 (Reiland et al. 2015) in accordance with Part 3 of the ANSI A300 arboricultural standard (Anonymous 2013). Prior to changing cable height and tension, we first tested trees 57, 59, and 61 with a properly installed cable. Then, we re-tested trees 57, 59, and 61 after adjusting the height and tension of the cable (Table 3). We could not measure cable tension (Reiland et al. 2015).

Analyses

We used spectral analysis of each time history of acceleration [the p-Welch method in MatLab (Mathworks, Inc., Natick, MA)] to determine the fundamental frequency, first applying a smoothing function to reduce signal noise. We calculated damping ratio (ζ) from Eq. 1:

$$\zeta = \delta / \sqrt{4\pi^2 + \delta^2}, \tag{1}$$

where δ is the dimensionless logarithmic decrement:

$$\delta = \frac{1}{n} \ln \left({}^{u_i}\!/_{u_{i+n}} \right), \tag{2}$$

where u_i is the amplitude of acceleration of the first cycle of free sway, and u_{i+n} is the amplitude of acceleration of the nth cycle of free sway. For each pruning or cabling treatment and each re-positioning of the accelerometers, we swayed trees at least three times and calculated a mean frequency and damping ratio from three time histories of acceleration for each accelerometer. In a few cases, however, only two time histories were usable. In nearly every acceleration time history, accelerations incident and orthogonal to the direction of initial displacement were the same or nearly so; this was untrue for some time histories with very weak accelerations in the orthogonal direction, and we did not analyze those time histories. Prior to analysis, we averaged frequency and damping ratio determined from incident and orthogonal accelerations.

Since measurement location and treatment were different for all trees, we analyzed their effect on the frequency and damping ratio of each tree separately. We used a two-way analysis of variance to determine whether frequency and damping ratio differed among measurement locations or treatments. To compare frequency and damping ratio before and after pruning, we normalized the values within each tree as described by Moore and Maguire (2005) and plotted normalized values by the proportion of pruned crown mass. We also used least squares regression to investigate whether morphological characteristics were correlated with frequency and damping ratio of *Q. rubra* before pruning and without a cable (except tree 57 which was only measured in-leaf when it was properly cabled). We explored correlations with the following morphological characteristics, which previous studies have shown can influence frequency: proximal diameter of main stem/square of tree height (Moore and Maguire 2004), the total diameter of primary branches (Kane et al. 2014), slenderness (length/proximal diameter) of the main stem and primary branches (Sellier and Fourcaud 2009), and tree center of mass (Fournier et al. 2013). For the latter, we calculated the relative mean height of branch mass (R_b) as the sum of the mass-weighted height ($m \times h$) of each branch (i) divided by the product of total branch mass and tree height (H) (MacFarlane and Kane 2017):

$$R_b = \frac{\sum_{i=1}^{z} m_i h_i}{H \sum_{i=1}^{z} m_i}. \tag{3}$$

Since many branches were oriented well above horizontal, we assumed the height (h) of each branch at its estimated center of mass, rather than its attachment height (h_b):

$$h_i = h_{ib} + 0.4 l_i \sin \theta_i, \tag{4}$$

where l and θ are the length and angle above horizontal, respectively, of a branch. We measured θ to the visually estimated midpoint of the branch, and multiplied l by 0.4 based on our experience weighing whole branches by balancing them from a rope tied at the center of mass. Although we did not quantify the distance to the center of branch mass, it was typically between one-third and one-half of branch length.

To compare crown architecture among trees, we plotted the relative diameter of co-dominant stems and primary branches (diameter/main stem diameter) against their relative height (height/tree height).

Results

Tree morphology

Figure 1 shows the mass distribution of each tree. Even leafless, tree 57 was the most massive, exceeding the mass of the next largest tree (55) by 43% and the smallest tree (58) by 210%. However, unlike trees 55 and 58, the main stem of tree 57 represented only one-third of tree mass, while the

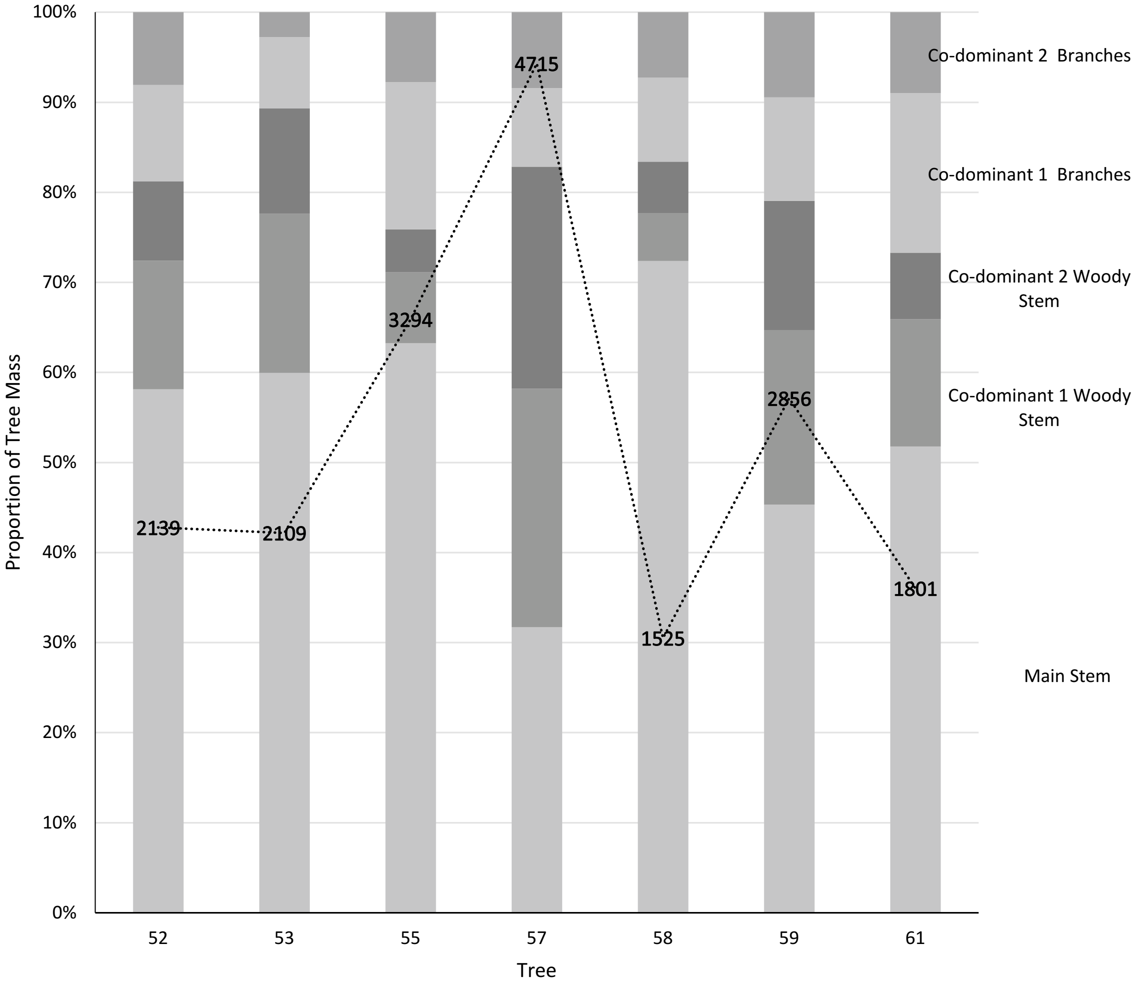

Fig. 1 Tree mass (numbers, in kg, connected by dotted black line) and its distribution among parts (main stem and the woody stem and branches of each co-dominant stem) of each tree. Tree 57 was measured when it was leafless

woody parts of the co-dominant stems represented about half of tree mass. Trees 55 (24%) and 61 (27%) had the greatest proportion of branch mass, and tree 53 the least (11%). Proximal diameter of each tree part predicted its length and mass, and power relationships ($y=\alpha x^{\beta}$) described each (Fig. 2). Trees 55 and 57 had, on average, larger branches (greater diameter and length) than other trees, especially compared to trees 52 and 53 (Table 1). Main and co-dominant stems were generally less slender than primary branches, but this was not true of tree 53, which had the most slender co-dominant stems (Table 1). Trees had between 10 and 16 primary branches (Table 1).

For all trees combined, the relative diameter of branches and co-dominant stems decreased logarithmically with relative height, but there were differences that became obvious when examining plots for individual trees (Fig. 3). The pair of co-dominant stems is clearly visible as the two largest relative diameters on all trees except 55. On tree 55, there was a very large branch on co-dominant 1, just above the co-dominant union. There was also a single large branch nearly the size of co-dominant 2 on tree 61. On trees 53, 57, and 59, primary branches were noticeably higher than the co-dominant union, but this was not true for trees 52, 55, 58, and 61. On some trees (52, 53, 57, 61), there were relatively small branches lower in the crown (less than 50% of tree height), but on others (55, 58, 59), the smaller branches were mostly, if not entirely, higher in the crown (above 60% of tree height).

Frequency

Correlations

Figure 4 shows a typical time history of accelerations and the resulting power spectral density output. The sway motion of all trees reasonably approximated that of a freely swaying, single-degree-of-freedom mass-spring system:

$$x(t) = Ae^{-\zeta\omega_n t}\sin(\omega_d t + \phi), \tag{5}$$

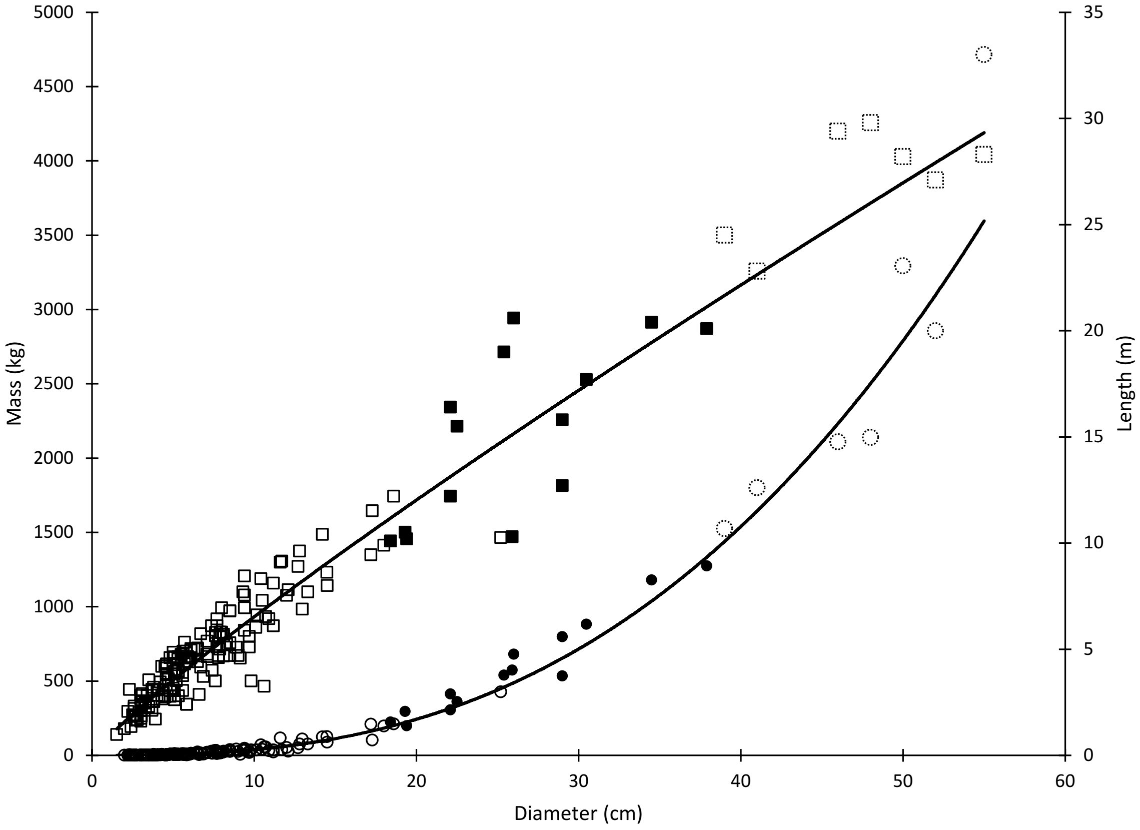

Fig. 2 Mass (m, circles) and length (l, squares) of branches (open), co-dominant stems (filled), and whole trees (dotted outline) plotted against proximal diameter (d); power functions describe each relationship: $l = 0.8584d^{0.8812}$ (solid line, $r^2 = 0.91$); $m = 0.0833d^{2.6634}$ (solid line, $r^2 = 0.96$)

where A is the initial amplitude, ϕ is the phase angle, and ω_d is the damped circular frequency. Although none of the predictors explained more than 64% of the variance in frequency, the p value of the slope associated with two of them (relative mean height of branch mass and mean slenderness of primary branches) indicated that there was only a 3.3% chance that the non-zero slope was not a real effect. Frequency was inversely proportional to both predictors (Table 4). Frequency was directly proportional to the ratio of main stem diameter to the square of tree height, but that predictor explained less than one-half of the variance in frequency, and there was a 7.8% chance that the non-zero slope was not a real effect. There was no effect of the total diameter of primary branches on frequency.

Pruning

Table 5 includes pruning-induced changes in frequency measured at each location in trees 52, 53, 55, and 58. Two consistent trends among pruned trees are evident: (1) for each combination of tree and pruning treatment, frequency was the same or nearly so regardless of the measurement location (co-dominant 1, co-dominant 2, or the main stem); (2) for all trees, frequency increased with consecutive pruning treatments that pruned increasingly greater proportions of crown mass. Some of the latter differences were not statistically significant, however.

Plotting the mean of normalized frequency measured at two locations on each tree against the pruned proportion of crown mass did not reveal a clear pattern for all trees, aside from (1) the lowest normalized frequency consistently occurred before pruning and (2) the highest normalized frequency consistently occurred after pruning more than 60% of crown mass (Fig. 5). Examining the pattern of individual trees clarified that pruning different parts of a tree increased normalized frequency differently (Fig. 5). In particular, the largest relative increase in normalized frequency for each tree occurred after pruning nearly all of the primary branches (see Table 3). Large relative increases in normalized frequency also followed pruning that shortened the tree or branches. This was evident after reducing the length of branches on tree 53 (treatment 2), reducing by half the length of co-dominant stems on tree 52 (treatment 3), and removing co-dominant 1 after previously removing co-dominant 2 on trees 55 and 58 (treatment 5). On trees 52, 53, and 58, the highest normalized frequency occurred following

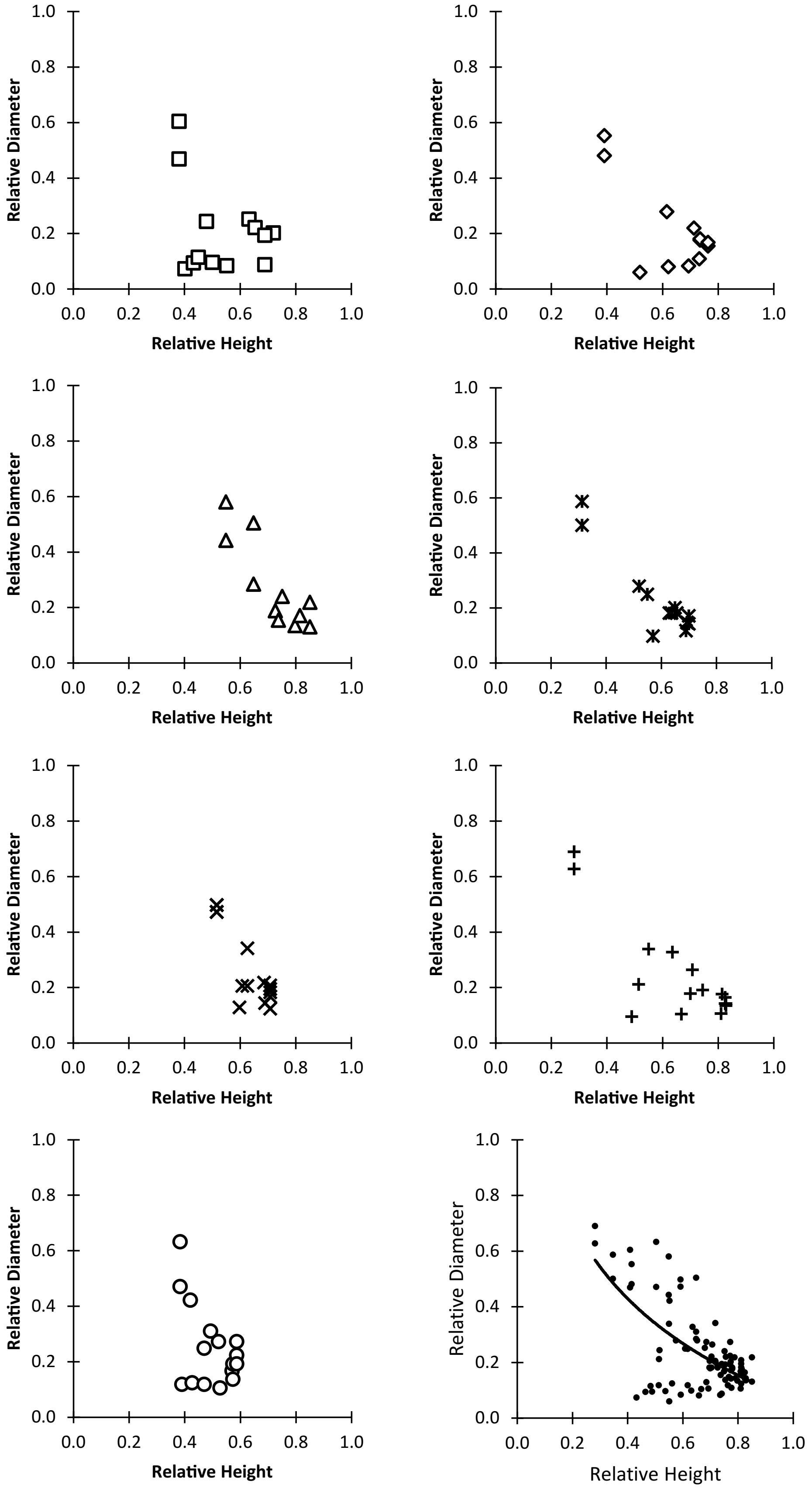

Fig. 3 Relative diameter (R_d = diameter/main stem diameter) plotted against the relative height (R_h = height/tree height) for all primary branches and both co-dominant stems of trees 52 (square), 53 (diamond), 55 (triangle), 57 (plus sign), 58 (cross), 59 (star), 61 (open circle), and all trees (filled circle). The relationship for all trees (dashed line) was: $R_d = -0.397 \ln(R_h) + 0.065$ ($r^2 = 0.42$)

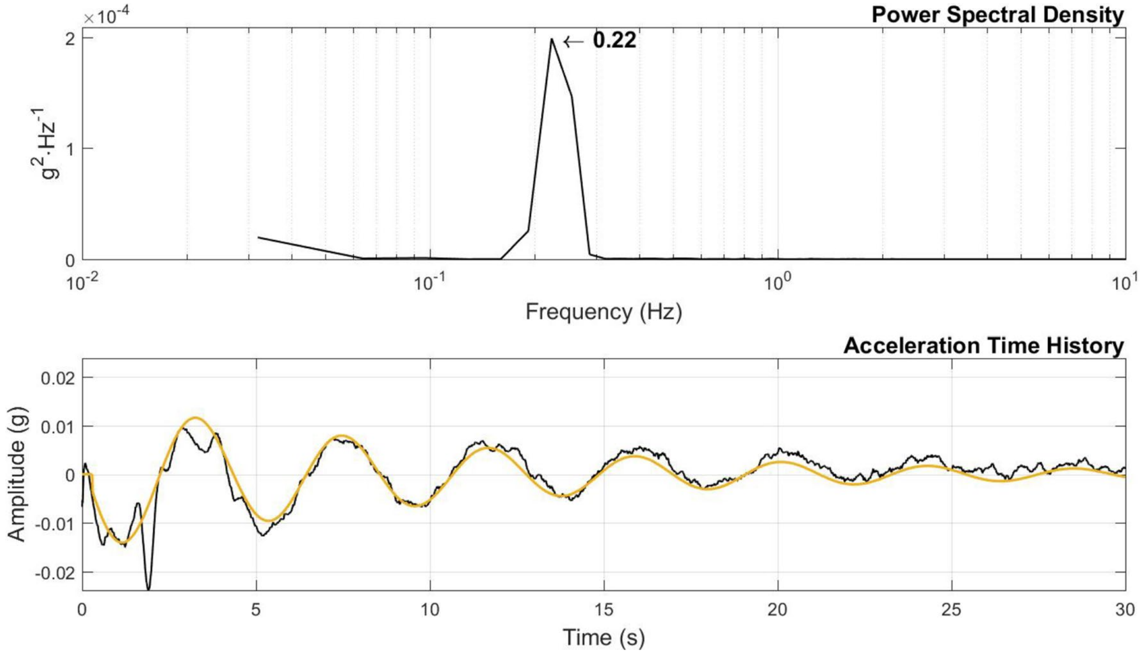

Fig. 4 Power spectral density output and the first mode frequency (top) from a typical acceleration time history (bottom). In the acceleration time history, the black line indicates the raw data and the yellow line indicates a fit of the equation of motion for a freely swaying single-degree-of-freedom mass-spring system: $x(t) = Ae^{-\zeta\omega_n t}\sin(\omega_d t + \phi)$, where A is the initial amplitude, ζ is the damping ratio, ϕ is the phase angle, and ω_d is the damped circular frequency

Table 4 Coefficient of determination (r^2), slope (β), intercept (B), and their respective standard errors (SE) and p values of least squares regression lines predicting frequency—calculated as the mean of values from two or more measurement locations (see Table 2)—of trees before pruning or without a cable (except tree 57, which was properly cabled)

Predictor	β	SE_β	p_β	B	SE_B	p_B	r^2
Main stem diameter/(tree height)^2 (cm/m^2)	1.278	0.578	0.078	0.118	0.038	0.026	0.494
Relative mean height of branch mass[a]	−0.113	0.038	0.033	0.285	0.029	0.000	0.631
Mean slenderness of primary branches (m/cm)	−0.002	0.001	0.033	0.368	0.057	0.001	0.630
Total diameter of primary branches (cm)	0.000	0.000	0.127	0.155	0.026	0.002	0.401

[a] See Eq. 4 for calculation

the penultimate treatment; cutting an axial split into the main stem—the final treatment—very slightly lowered normalized frequency (Fig. 5). In contrast, cutting an axial split in the main stem on tree 55 (treatment 3) had no effect on normalized frequency. After the final treatment, trees 55 and 58 had no crown mass while trees 52 and 53 retained 39 and 29% of crown mass, respectively.

Figure 6 shows tree 52 after pruning primary branches and the distal leafy portion of each co-dominant stem and with the climber tied to co-dominant 1 and rigidly secured to co-dominant 2 19.3 m above ground. Figure 7 shows mean normalized frequency measured on co-dominant stems of tree 52 for each pruning treatment, including with a climber in the tree. Including treatments with the climber positioned in the tree in different ways, the greatest changes in normalized frequency still occurred after pruning (1) primary branches (leaving the distal, leafy portion) from each co-dominant stem and (2) half of the length of the co-dominant stems. However, the location and relative motion of the climber clearly affected frequency.

Figure 7 shows that the freely swaying climber 16.1 m above ground lowered normalized frequency (treatment 4), but increased it when swaying freely 19.3 m above ground (treatment 5). Rigidly securing himself to co-dominant 2 while tied in to co-dominant 1 produced nearly the same effect on normalized frequency as rigidly securing himself only to co-dominant 1. This was true when the climber was tied in 16.1 m (treatments 6 and 7) and 19.3 m (treatments 8 and 9) above ground. Normalized frequency was higher than when the climber swayed freely during the test (regardless

Table 5 Frequency and damping ratio (mean of values measured incident and orthogonal to the direction of displacement to initiate tree sways) measured at different locations on each tree for each treatment

Tree	Measurement location	Frequency						Damping ratio					
		Treatment						Treatment					
		1	2	3	4	5	6	1	2	3	4	5	6
52	Co-dominant 1	0.19	0.22	0.50	0.64	0.64	–	0.06	0.05	0.06	0.01	0.01	–
	Co-dominant 2	0.18	0.21	0.51	0.63	0.62	–	0.06	0.05	0.05	0.0.01	0.01	–
	Mean	0.19a	0.22a	0.51b	0.64c	0.63c	–	0.06a	0.05a	0.06a	0.0.01b	0.01b	–
53	Co-dominant 1	0.19	0.26	0.29	0.38	0.48	0.48	0.05	0.03	0.01	0.01	0.01	0.01
	Co-dominant 2	0.19	0.26	0.30	0.37	0.49	0.46	0.06	0.04	0.01	0.01	0.01	0.01
	Mean	0.19a	0.26b	0.30b	0.38c	0.49d	0.47d	0.06a	0.04b	0.01c	0.01c	0.01c	0.010c
55	Co-dominant 1	0.21	0.26	0.26	0.64	0.74	–	0.07	0.04	0.04	0.03	0.01	–
	Main stem[a]	0.20	0.24	0.24	0.63	0.74	–	0.05	0.04	0.05	0.03	0.00	–
	Co-dominant 2	0.20	–	–	–	–	–	0.06	–	–	–	–	–
	Mean	0.20a	0.25b	0.25b	0.64c	0.74d	–	0.06a	0.04a	0.05a	0.03ab	0.01b	–
57	Co-dominant 1	0.22	0.27	0.27	0.28	–	–	0.06	0.02	0.03	0.03	–	–
	Co-dominant 2	0.22	0.28	0.28	0.28	–	–	0.07	0.03	0.02	0.02	–	–
	Main stem[a]	0.21	0.28	0.28	0.29	–	–	0.06	0.03	0.02	0.03	–	–
	Main stem[b]	–	–	–	0.27	–	–	–	–	–	0.04	–	–
	Mean	0.22a	0.28b	0.28b	0.28b	–	–	0.07a	0.03b	0.02b	0.03b	–	–
58	Co-dominant 1	0.20	0.22	0.24	0.56	0.71	0.71	0.10	0.08	0.08	0.04	0.01	0.01
	Main Stem[a]	0.19	0.22	0.24	0.56	0.72	0.70	0.09	0.09	0.06	0.03	0.01	0.01
	Mean	0.20a	0.22ab	0.24b	0.56c	0.72d	0.71d	0.10a	0.09a	0.07a	0.04b	0.01b	0.01b
59	Co-dominant 1	0.19	0.19	0.19	0.19	0.19	0.18	0.08	0.07	0.09	0.08	0.08	0.09
	Co-dominant 2	0.18	0.18	0.19	0.18	0.18	0.19	0.07	0.06	0.08	0.07	0.07	0.09
	Main Stem[a]	0.18	0.18	0.18	0.18	0.18	0.18	0.08	0.10	0.08	0.07	0.08	0.08
	Mean	0.18a	0.18a	0.19a	0.18a	0.18a	0.18a	0.08a	0.08a	0.08a	0.07a	0.08a	0.09a
61	Co-dominant 1 above union	0.22	0.24	0.22	0.23	0.21	–	0.06	0.07	0.07	0.09	0.06	–
	Co-dominant 1 below cable	0.23	0.24	0.23	0.23	0.22	–	0.07	0.06	0.09	0.09	0.05	–
	Co-dominant 1 above cable	0.23	0.23	0.23	0.24	0.24	–	0.07	0.09	0.08	0.07	0.06	–
	Co-dominant 2 above union	0.23	0.24	0.23	0.23	0.23	–	0.06	0.07	0.06	0.08	0.04	–
	Co-dominant 2 below cable	0.23	0.23	0.23	0.23	0.23	–	0.07	0.06	0.09	0.09	0.05	–
	Co-dominant 2 above cable	0.23	0.24	0.23	0.24	0.22	–	0.08	0.06	0.08	0.07	0.05	–
	Main stem[a]	0.22	0.23	0.23	0.23	0.23	–	0.05	0.07	0.07	0.07	0.05	–
	Mean	0.23a	0.24a	0.23a	0.23a	0.23a	–	0.07a	0.07ab	0.08a	0.08a	0.05b	–

Descriptions of each measurement location and treatment are in Tables 2 and 3, respectively. Rows labeled “mean” refer to the mean of all measurement locations for each treatment within a tree. Read across a row, means of frequency or damping ratio followed by the same letter are not significantly different ($p > 0.01$) by Tukey’s honestly significant difference test

[a] Within 0.7 m of the union of co-dominant stems

[b] 1.8 m below the union of co-dominant stems, 5.8 m above ground

of his height above ground); it was also higher when the climber was rigidly secured 16.1 m above ground compared to 19.3 m above ground (regardless of whether the climber was secured to co-dominant 1 or 2).

Cabling

Consistent with pruned trees, frequency measured at different locations on cabled trees was similar (Table 5). This was true for a wide variety of measurement locations, including different heights on the main stem, and on each co-dominant stem at different heights above the co-dominant union (Table 2). Neither did the presence of a cable, its tension, nor its height above the co-dominant union meaningfully alter frequency, with one exception: it was higher at all measurement locations when tree 57 was leafless (Table 5).

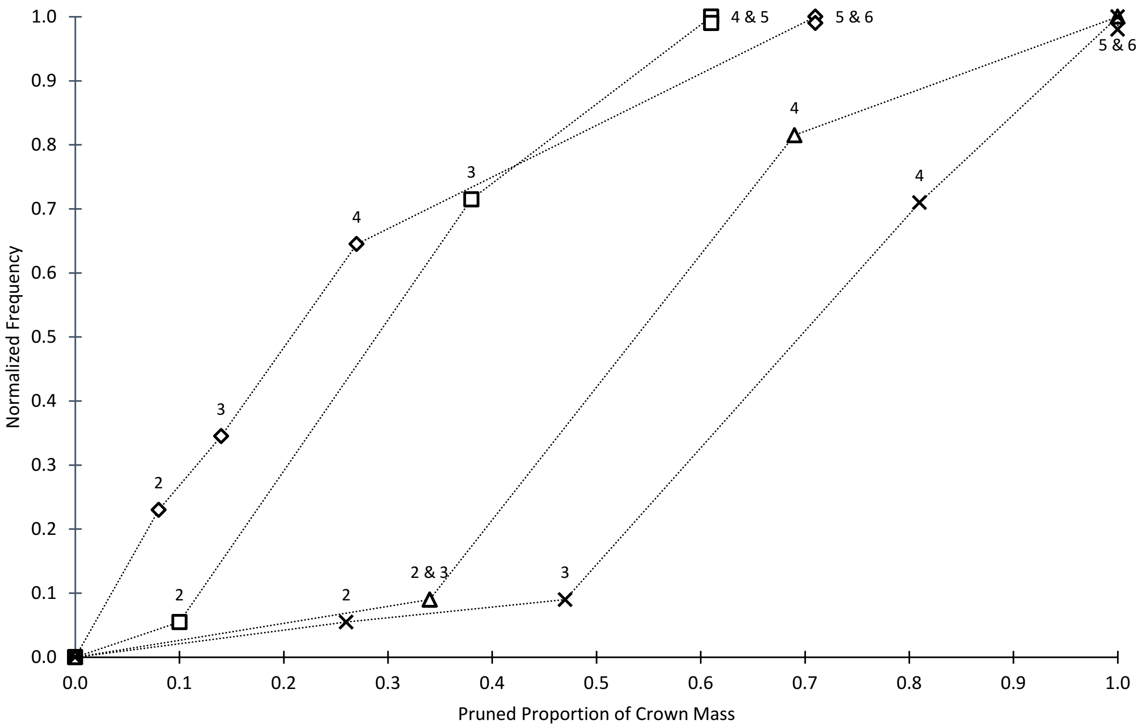

Fig. 5 Normalized frequency plotted against the pruned proportion of crown mass for trees 52 (square), 53 (diamond), 55 (triangle), and 58 (cross). Numbers above or next to each datum correspond to pruning treatments listed in Table 3. Each datum represents the mean of measurements from two locations (Table 2) on each tree

Damping ratio

Correlations

None of the selected morphological characteristics (relative mean height of branch mass, mean slenderness of primary branches, ratio of main stem diameter to the square of tree height, and total diameter of primary branches) predicted damping ratio of trees before pruning and without a cable. The highest correlation coefficient was 0.39, which described the correlation between damping ratio and the relative mean height of branch mass, but the p value of the slope of the least squares regression line was 0.14.

Pruning

Within each tree, damping ratio was similar for different measurement locations, and it generally decreased with pruning, but not all differences were statistically significant (Table 5). Relative to the pruned proportion of crown mass, pruning influenced normalized damping ratio differently (Fig. 8). On all trees, maximal normalized damping ratio occurred before pruning, and minimal normalized damping ratio occurred following pruning that left a tree leafless and with shortened primary branches (tree 53) or without any leaves and primary branches (trees 52, 55, 58). After the first pruning, normalized damping ratio decreased for all trees, and the effect was most severe after shortening primary branches (tree 53) and removing co-dominant 2 (tree 55). However, the latter removed a fourfold greater proportion of crown mass than the former. Pruning all primary branches except the distal, leafy portion of each co-dominant stem on tree 52 (treatment 3) did not change normalized damping ratio. Adding an axial split on the main stem above the root flare (treatment 3) increased normalized damping ratio on tree 55, but doing the same treatment had no effect for the other trees (treatment 5 or 6). Normalized damping ratio consistently decreased following the systematic removal of primary branches and co-dominant stems on tree 58.

Relative to the pruned proportion of crown mass, pruning all secondary branches (tree 52) induced a greater decrease in normalized damping ratio than pruning co-dominant 2 (tree 55) or pruning all primary branches from co-dominant 2 (tree 58). Normalized damping ratio of tree 53 remained at the minimal value for subsequent treatments, and it continued to decrease on tree 58. Cutting an axial split in the main stem near the ground on tree 55 increased normalized damping ratio compared to the previous treatment, but we did not observe a similar increase after cutting an axial split in the main stem of trees 52, 53, and 58. Normalized damping ratio remained the same as the previous treatment after pruning

Fig. 6 Tree 52 following the removal of primary branches and the distal, leafy portion of each co-dominant stem with a climber (mass 86 kg) tied in to co-dominant 1 19.3 m above ground and rigidly secured (i.e., not swaying freely) to co-dominant 2; right-hand image is a close-up of the climber

primary branches from each co-dominant stem (leaving the distal, leafy portion) on tree 52.

Figure 7 shows the mean normalized damping ratio measured on both co-dominant stems of tree 52 for all pruning treatments, and including the climber in the crown after treatment 3 in Table 3. Normalized damping ratio followed a similar pattern when treatments with the climber in the tree were included with pruning treatments. Maximal normalized damping ratio occurred before pruning and there was a substantial decrease after pruning leaves from the crown (treatment 4). However, the swaying climber 16.1 or 19.3 m above ground (treatments 4 and 5) provided damping that did not exist when the climber was rigidly secured to one or both co-dominant stems 16.1 or 19.3 m above ground (treatments 6–9).

Cabling

Consistent with pruned trees, damping ratio measured at different locations on trees subjected to cabling treatments (57, 59, 61) was similar (Table 5), despite the wide range of measurement locations. Neither did the presence of a cable, its tension, nor its height above the co-dominant union meaningfully alter damping ratio, with one exception: it was lower at all measurement locations when tree 57 was leafless (Table 5).

Discussion

Tree morphology

Very few studies have investigated the effect of arboricultural treatments on the sway response of broadleaf trees. Existing studies are limited by (1) consideration of only smaller individuals pruned once (Kane and James 2011), (2) not quantifying the reduction in mass following repeated pruning of a single individual (James 2014), or (3) considering only a single cabling treatment (Reiland et al. 2015). Although the current results pertain to a small sample of a single species, they represent the effect of arboricultural treatments on large trees—those of interest to arborists and urban foresters who must assess tree risk. Tree 58, the smallest tree we tested, was 300 kg more massive than the largest tree in a previous study on the effect of pruning on sway characteristics (Moore and Maguire 2005). Results from smaller trees may not apply to larger trees, since many relevant mechanical parameters (e.g., second moment of area and deflection) scale non-linearly with size, and since tree morphology, the relative proportion of woody and non-woody mass, and wood properties all change as trees mature.

Q. rubra in the current study grew in a relatively open forest stand—growth of smaller primary branches lower on the crown was presumably related to an earlier stand thinning—but their crown form more closely resembled that of a forest-grown tree than one that was open-grown. The relative height and diameter of *Q. rubra* branches were consistently higher and smaller, respectively, than those on large, open-grown, decurrent trees (Kane et al. 2014). In general, *Q. rubra* also had many fewer branches, and less than half the total primary branch diameter and ratio of main stem diameter to tree height squared than open-grown decurrent trees (Kane et al. 2014). Branches were also more slender than the mean of open-grown individuals of four species (MacFarlane and Kane 2017), and the scalar (β) in the power function relating length to diameter (0.8812) was closer to geometric ($\beta = 1$) than elastic ($\beta = 0.67$) self-similarity (McMahon and Kronauer 1976).

Frequency and damping ratio

Morphological similarity to forest-grown trees explains why frequency of *Q. rubra* was correlated with the relative mean height of branch mass and the ratio of main stem diameter to tree height squared. Previous work has similarly demonstrated these correlations on forest- and plantation-grown conifers (Sugden 1962; Moore and Maguire 2004), but not

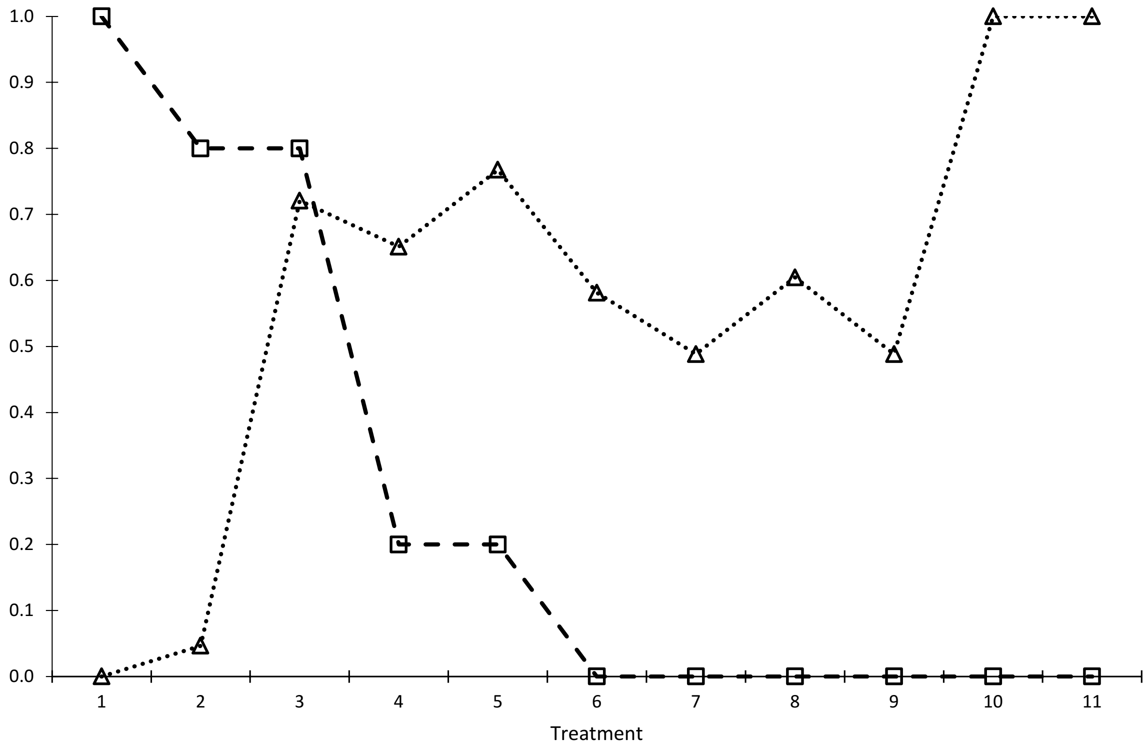

Fig. 7 Normalized frequency (triangle) and damping ratio (square) (*y*-axis) plotted against consecutive treatments (*x*-axis) applied to tree 52. In chronological order, treatments were: (1) before pruning, (2) pruning all secondary branches except the distal leafy portion of primary branches, (3) pruning all primary branches except the distal, leafy portion of each co-dominant stem, (4) pruning the distal, leafy portion of each co-dominant stem and a climber (mass 86 kg) tying in to the more massive co-dominant stem (co-dominant 1) 16.1 m above ground and freely swaying during the test, (5) the climber tying in to co-dominant 1 19.3 m above ground and freely swaying during the test, (6) the climber tying in to co-dominant 1 and rigidly securing himself to co-dominant 2 16.1 m above ground rather than freely swaying during the test, (7) the climber tying in to co-dominant 1 and rigidly securing himself to co-dominant 2 19.3 m above ground rather than freely swaying during the test, (8) the climber rigidly securing himself to co-dominant 1 16.1 m above ground rather than freely swaying during the test, (9) the climber rigidly securing himself to co-dominant 1 19.3 m above ground rather than freely swaying during the test, (10) without a climber in the tree, the length of each co-dominant stem was reduced by one-half, and (11) an axial crack was cut into the main stem near the ground. Table 3 does not include treatments involving the climber (4–9 in this figure); treatments 10 and 11 in the figure correspond to treatments 5 and 6 in Table 3

open-grown trees of decurrent form (Baker 1997; Kane and James 2011; Kane et al. 2014). Miesbauer et al. (2014) highlighted the effect of the vertical distribution of branch mass on frequency, demonstrating that trees of excurrent form had higher frequency than those of decurrent form.

Applying a point load to the main stem induced a sway response dominated by the main stem, consonant with previous work on large (Moore and Maguire 2005) and small (Sellier and Fourcaud 2005) conifers. We expected this result because the more massive parts of a tree dominate its sway response (Sellier and Fourcaud 2005; Ciftci et al. 2013), and the main stem accounted for more than 50% of tree mass in all *Q. rubra* except trees 57 and 59. For the latter two trees, however, we applied the point load to the co-dominant stems themselves. This explained why frequency and damping ratio did not vary among measurement locations.

Reiland et al. (2015) tested the same *Q. rubra* (except tree 57), but induced sways with a single pull and release, rather than repeatedly swaying them as in the current study. Frequency values in Reiland et al. (2015) were largely similar (tree 61 was an exception), suggesting that the different methods to induce sways did not substantially influence frequency. Sellier and Fourcaud (2005) also found similar fundamental frequencies of saplings using two methods to induce sways, with one exception: they only observed a short-lived, second mode frequency when inducing sways with a single pull and release. We did not observe a second mode frequency on *Q. rubra*. The different methods appeared to affect damping ratio, however: values presented here were less than those presented by Reiland et al. (2015). We expected this since the acceleration time histories were generally longer when we induced sways by repeatedly swaying trees prior to measuring free sways.

Pruning *Q. rubra* induced a noticeable increase in normalized frequency even at relatively small pruned proportions of crown mass, which previous work on large trees

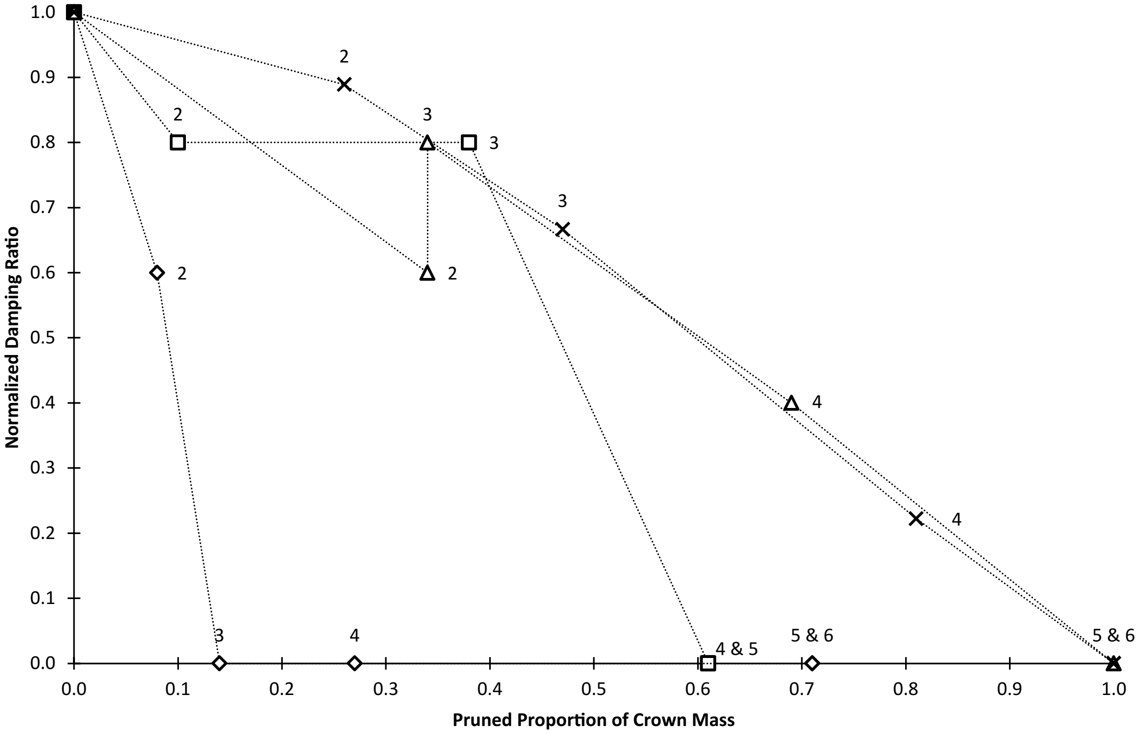

Fig. 8 Normalized damping ratio plotted against the pruned proportion of crown mass for trees 52 (square), 53 (diamond), 55 (triangle), and 58 (cross). Numbers above or next to each datum correspond to pruning treatments listed in Table 3. Each datum represents the mean of measurements from two locations (Table 2) on each tree

has not shown. The effect was most pronounced when pruning shortened primary branches on tree 53, but normalized frequency also increased for the other trees. We attribute the difference to pruning type and crown form. We expected shortening primary branches on tree 53 to increase frequency because of the inverse correlations between frequency and both relative mean height of branch mass and the square of tree height. The finding was also consistent with experimental (Kane and James 2011) and modeling (Sellier and Fourcaud 2009) studies. In contrast, Moore and Maguire (2005) decreased crown length by consecutively pruning the lowest branches in the crown, leaving the distal portion intact until the final pruning. Presumably, the effect of the higher center of mass that results from this type of pruning (Pavlis et al. 2008), which would decrease frequency (Sugden 1962; Miesbauer et al. 2014), offsets the reduction in mass, which would increase frequency. We observed this effect when the climber rigidly secured himself to either co-dominant 1 or 2 on tree 52. Adding the rigidly secured mass of the climber lowered normalized frequency after the initial increase following pruning, and the effect was more pronounced when the climber was secured higher to either co-dominant stem. Pruning lower branches on decurrent trees similarly had a minimal effect on frequency (Kane and James 2011). James (2014) consecutively pruned individual co-dominant stems from a large *Acer saccharinum* L. without increasing frequency until nearly all foliage and branches were removed. However, pruning single co-dominant stems on trees 55 and 58 increased normalized frequency, perhaps because doing so removed a greater proportion of primary branches. The greatest increases in normalized frequency followed pruning that removed all or nearly all primary branches, which aligns with the previous work showing the effects of (1) de-branching conifers of excurrent form (Milne 1991; Moore and Maguire 2005; Spatz et al. 2007) and (2) foliage on lowering frequency (Sellier and Fourcaud 2005; Kane and James 2011).

Although cabling only increased frequency on leafless *Q. rubra* (Reiland et al. 2015), we expected that increasing cable height and tension would affect frequency by restricting independent sway motion of the co-dominant stems. However, this was not true for any cabling treatment on trees 59 and 61. Both trees were tested in-leaf, so the effect of leaves again superseded the effect of adding a cable. It was unclear why cabling had no effect on frequency of tree 57 when it was leafless, and Reiland et al. (2015) did not measure it, so there was no basis for comparison. Since the first sway mode was induced by the test, it may be that the co-dominant stems did not move independently of the trunk, negating the cable's effect.

Leaves exerted the greatest effect on damping ratio: the minimal value of normalized damping ratio always occurred following pruning that removed all foliage. This finding aligned with previous studies (Sellier and Fourcaud 2005; Kane and James 2011; Reiland et al. 2015) and is due to both aerodynamic drag itself and the sway motion of branches that drag induces. The effect was obvious on pruned trees as well as in the difference between the damping ratios of tree 57 with and without leaves (while no other cabling treatment meaningfully altered damping ratio). The location of foliage was also important, because distal foliage has a greater relative velocity than proximal foliage and drag is proportional to the square of velocity. The presence of distal foliage explained why normalized damping ratio was greater on tree 52 following the pruning of proximal secondary branches compared to tree 53 after pruning the distal portion of each primary branch, even though the proportion of pruned crown mass was similar. It also explained why normalized damping ratio of (1) tree 52 did not change after pruning all primary branches except the distal, leafy portion of each co-dominant stem; (2) trees 55 and 58 were not minimal, even though pruning had removed most primary branches (tree 55) and all but the distal, leafy portion of co-dominant 1 (tree 58); and (3) tree 53 was minimal after removing leaves, even though shortened primary branches were still present. The effect on tree 53 may have been more pronounced, because it had the smallest proportion of branch mass before pruning.

Adding a freely swaying climber to tree 52 after pruning all primary branches and the distal, leafy portion of each co-dominant stem mimicked the effect of swaying branches and partially compensated for their loss because normalized damping ratio was not minimal when the climber was freely swaying, even though all primary branches and leaves had been pruned. Video indicated that the freely swaying climber assumed the same frequency as the swaying tree, but 180° out of phase with it. In contrast, when the climber was rigidly secured to either co-dominant stem at either height above ground, the effect disappeared and normalized damping ratio was minimal (and remained so after the climber left the tree for the final treatments).

We expected tight and very tight cables to affect damping ratio, even though Reiland et al. (2015) did not observe an effect, because we expected that they would restrict the motion of co-dominant stems more than cables installed at the proper tension. The absence of an effect of cabling co-dominant stems, especially when the cable tension was tight or very tight, was not inconsistent with the concept of damping by branching, because effective damping ratio is maximized when the angle between branches is closer to 90° (Theckes et al. 2011). In addition, consistent with Reiland et al. (2015), the presence of leaves influenced damping ratio more than cable installation.

Arboricultural implications

Increasing sway frequency generally means that less wind energy can be transferred to the tree (Baker 1995), which would reduce the likelihood of tree failure assuming other factors remain constant. However, damping ratio generally decreased as frequency increased, which we expected since damping ratio reflects the proportion of dissipated energy per sway cycle and, therefore, depends on frequency (Sellier and Fourcaud 2009). Less damping means that a tree does not efficiently dissipate energy, perhaps predisposing it to greater dynamic amplification. The presence of primary branches and leaves influenced frequency and damping ratio, and would also influence drag and drag-induced bending moment (Kane and Smiley 2006; Kane et al. 2008). Understanding the interaction of pruning-induced changes to these factors is critical to refine models to predict tree failure, but modeling their effects (which sometimes counteract one another) presents a challenge (Ciftci et al. 2014a). Despite this limitation, there appears to be a real benefit to shortening branches because of the increased frequency and decreased drag-induced bending moment. However, the long-term effects of pruning on decay formation must also be considered, since decay reduces load-bearing capacity (Ciftci et al. 2014b).

Although conventional arboricultural wisdom generally discourages pruning a large proportion of the crown in a single event, pruning larger proportions of the crown (e.g., pruning co-dominant 2 from tree 55) sometimes occurs—for example, to create clearance near a structure. Our results indicate that removing a substantial proportion of crown mass has less of an effect on frequency and damping ratio when sufficient primary branches remained.

Cutting an axial split into the main stem above the root flare was intended to simulate the effect of an important structural defect of trees that has not been previously studied: cracks. The axial split slightly decreased normalized frequency, but the effect was only noticeable after pruning all primary branches (compare tree 55, which retained 60% of crown mass, to trees 52, 53, and 58). The opposite was true regarding the effect of the axial split on normalized damping ratio, which increased on tree 55, but not on the other trees, which retained much less crown mass when the axial split was cut. These preliminary insights clearly indicate that additional studies are needed to investigate the effect of an axial split, including, obviously, testing a greater range of lengths. Anecdotally, cracks in the main stem of trees tend to be longer than those simulated in the experiment. Longer cracks may cause the trunk to behave mechanically as two separate beams of semi-circular cross section.

The lack of meaningful changes to frequency and damping ratio for the variety of cabling treatments supports previous findings (Reiland et al. 2015). More work on the effects of cabling on the likelihood of failure is necessary. In particular, studies that consider the effect of cabling co-dominant stems on open-grown trees would be useful, as would examinations of the effects of multiple cables attached to multiple stems (e.g., a triangular cabling system). Numerical modeling of these (and the pruning) treatments would greatly enhance the ability to generalize results. Data from this and other studies could be used to develop such models.

Author contribution statement BK collected and analyzed data and wrote the manuscript.

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Compliance with ethical standards

Conflict of interest The author declares that he has no conflict of interest.

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