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ORIGINAL ARTICLE

Effect of pruning type and severity on vibration properties and mass of Senegal mahogany (*Khaya senegalensis*) and rain tree (*Samanea saman*)

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Abstract

Key message **During pruning, shortening branches to decrease crown size significantly affected the vibration properties and mass of trees, but the progressive removal of lower branches only altered mass—not vibration properties.**

Abstract During pruning, arborists often intend to increase a tree's resistance to wind loading by selectively removing branches, but there are few studies examining the efficacy of these interventions, especially for large, open-grown trees. This study examined the vibration properties (frequency and damping ratio) and mass of Senegal mahogany (*Khaya senegalensis*) and rain tree (*Samanea saman*) before and after a series of pruning treatments: crowns were either raised or reduced at incremental severities between 0 and 80%. For both species, mass decreased faster on reduced than raised trees. The frequency and damping ratio of trees varied with the severity of pruning for reduced, but not raised, trees. The frequency of reduced trees generally increased with pruning severity. In contrast, damping ratio of reduced trees generally decreased with the severity of pruning, except for the unique increase in damping ratio on Senegal mahoganies reduced by 10–20%. Although the vibration properties and mass will change as trees grow after pruning, the results suggest that arborists can reduce trees to change their vibration properties and concomitant response to wind loads, but arborists should reduce trees by a small amount to avoid the adverse decrease in damping ratio.

Keywords Frequency · Damping ratio · Biomechanics · Pruning

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Introduction

Pruning is frequently used to, presumably, reduce the likelihood of tree failure by improving branch structure, reducing leaf area, or increasing crown porosity (Gilman and Lilly 2008). Physically, wind-induced drag will decrease if pruning reduces the size of tree parts exposed to the wind. A few studies demonstrated that pruning significantly reduced drag-induced bending moment (Smiley and Kane 2006; Pavlis et al. 2008) and trunk deflection (Gilman et al. 2008a, b) roughly in proportion with the mass of branches and foliage removed.

Pruning modifies the vibration properties (frequency and damping ratio) of trees (Kane 2018), and this may affect their ability to resist applied forces. Studies generally demonstrate that pruning increases a tree's natural frequency of vibration, f_n (Hz), and decreases its damping ratio, ζ (dimensionless), but pruning type and severity often interact uniquely with different species to produce distinct outcomes (Moore and Maguire 2005; Kane and James 2011). Previous work indicated that f_n did not increase until nearly, all branches were removed from excurrent conifers (Moore and Maguire 2005) and an open-grown decurrent tree (James 2014), but this appeared to be unique to the pruning type—progressively removing either lower branches (Moore and Maguire 2005) or individual, large branches (James 2014). Shortening branches and reducing tree height significantly increased f_n on small (Kane and James 2011) and large (Kane 2018) broadleaf trees. Although f_n is inversely proportional to mass, there are no existing reports on the change in mass caused by various pruning treatments.

The effect of pruning on ζ is not entirely clear. Following increasingly severe pruning treatments, Kane (2018) observed a marked reduction in ζ, but some authors observed a slight increase in ζ at lower pruning severities (Moore and Maguire 2005; Sellier and Fourcaud 2005). Sellier and Fourcaud (2005), for example, reported a modest increase in ζ after removing all tertiary axes on small maritime pine (*Pinus pinaster*) trees. These results suggest that pruning higher order branches, normalized by mass, may have an outsized influence on damping. Other studies reported that pruning did not affect ζ on small decurrent trees, independent of leaf condition (Kane and James 2011) or crown form (Miesbauer et al. 2014).

Many studies examining the mechanical consequences of pruning were conducted using relatively small, young trees (Sellier and Fourcaud 2005; Kane and James 2011; Miesbauer et al. 2014), and more work is needed to evaluate these effects on large trees. In addition to spatial gradients in wood material properties (Anten et al. 2011), age-associated changes to the size and mass of vegetative organs contribute meaningfully to both the loads that a tree experiences [e.g., drag is proportional to mass (Kane and Smiley 2006)], and its load-bearing capacity (e.g., the second moment of area for the trunk and branches increases as the fourth power of diameter). Most of these changes are influenced by the interaction between environmental stimuli and growth processes, and the distinctions between small and large trees have important mechanical implications that make it less appropriate to extrapolate results from small to large trees. The objective of this study was to determine the effect of arboricultural pruning treatments on the vibration properties and mass of large, open-grown tropical trees.

Methods

Site and trees

Twelve Senegal mahoganies [*Khaya senegalensis* (Meliaceae)] and 10 rain trees [*Samanea saman* (Fabaceae)] were selected from a managed urban woodland near Choa Chu Kang, Singapore (1°23′N, 103°45′E, elevation 10 m). These species are commonly planted as amenity trees in parks and urban landscapes throughout Southeast Asia, and they are often pruned to meet the unique objectives of a particular site, such as mitigating risk or maintaining unobstructed clearance. The trees were growing in a 5.5 ha even-aged homogeneous stand among 173 other large, mature trees (~ 31 trees ha^{-1}). The stand was composed almost entirely of Senegal mahogany and rain tree; the trees were not subjected to arboricultural maintenance after planting on an unknown date. Although it was not possible to accurately determine the age of the trees from wood anatomy or planting records, the size of trees and historical land use changes suggested that the trees were between 30 and 40 years old during the experiment. The mean height of Senegal mahoganies and rain trees in the stand was 26.6 and 22.2 m, respectively. Trees with similar size and shape were selected for the study. Prior to any measurements, crowns were pruned to remove dead, dying, diseased, damaged, or broken branches.

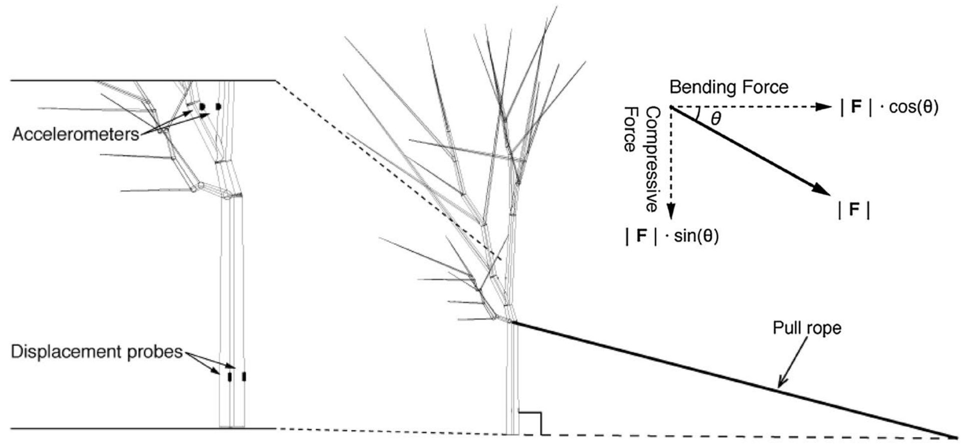
The following morphological measurements were made: trunk diameter at 1.37 m above the highest root, DBH (m); tree height, H (m), the vertical distance between the highest root and crown apex; crown width, W_{CROWN} (m), the mean of width measured in the North–South and East–West directions; and crown length, L_{CROWN} (m), the distance between the lowest branch and crown apex. All diameters were measured outside of the bark. Slenderness, λ (dimensionless), was calculated as the dimensionless ratio of H to DBH.

Instrumentation

To record axial trunk displacement during bending, two LVDT displacement probes (Solartron Metrology, VS/20/U, West Sussex, UK) were installed orthogonally on the trunk of each tree 1.37 m on-center above the highest root. Mounted on top of the bark using universal joints secured with hanger bolts, the probes measured up to 20 mm displacement over a linear distance of 226.9 mm with a measurement resolution of 10 µm and accuracy equivalent to 0.20% of output, yielding a strain resolution of 43 µm m^{-1}. They were oriented axially (i.e., parallel to wood grain) and positioned on the North (0°) and East (90°) aspects of the trunk (Fig. 1).

To record the sway motion of branches, two triaxial accelerometers (Freescale Semiconductor, MMA8452Q, Austin, TX, USA) were installed on a pair of large, similar-sized branches using mounting blocks secured with wood screws. They were positioned on the adaxial branch surface along the medial longitudinal plane bisecting the branch pair 1.5 m distal to the branch attachment. Accelerometers measured acceleration within a range of $\pm 2g$ with accuracy equivalent to 2.5% of output. The accelerometer's z-axis was positioned parallel to the local longitudinal axis of the branch to which it was attached (Fig. 1). One pair of accelerometers

Fig. 1 Schematic illustration of instrumentation (detail, left) and tree pulling layout



was installed on each Senegal mahogany included in the study, and three pairs of accelerometers were installed on one Senegal mahogany and three rain trees.

Mechanical property testing

Mechanical properties of each tree were determined by measuring its response to controlled loading conditions. The structural Young's modulus, E_{STRUCT} (MPa), was measured during static deflection, and trunk and branch frequencies, f_n (Hz), and damping ratios, ζ (dimensionless), were measured during free vibration tests. To measure E_{STRUCT}, a series of three or four loads was applied incrementally to each tree using a rope attached to the trunk. The measured compressive displacement (mm) induced by the static pull test was converted to strain, ε (%), using

$$\varepsilon = \Delta l / l, \tag{1}$$

where l is the length of the displacement probe before loading, and Δl is the difference in the length of the displacement probe before and after loading. Measured strain was compared to the sum of induced bending and axial stress, σ (MPa), calculated according to Kane (2014)

$$\sigma = {}^{F \sin \theta}/_{\pi ab} + {}^{F \cos \theta L b}/_{I}, \tag{2}$$

where F is the force (N) applied by the rope; θ is the angle (°) between the rope attachment point and a horizontal plane parallel to the ground; a and b are the trunk radii normal and parallel to the direction of bending, respectively; L is the distance (m) between the rope attachment point and the midpoint of the displacement probe; and I is the second moment of area (m^4) determined by considering each trunk cross section as approximately elliptical:

$$I = {}^{\pi}/_{4} ab^3. \tag{3}$$

E_{STRUCT} was determined as the slope of an ordinary least-squares regression line fit to model σ as a function of ε:

$$E_{STRUCT} = \sigma / \varepsilon. \tag{4}$$

Pull-and-release free vibration tests were performed on days without precipitation and when ambient wind speeds were < 3 m s^{-1}. Each tree was displaced from its resting position using a rope attached to the trunk incident to one of the displacement probes. The load was instantaneously released, allowing the tree to sway freely as it returned to its resting position. Crown collisions between experimental trees and their neighbors were prevented by selectively removing branches from nearby trees that would have inhibited free sway.

Trees were displaced using a rope attached to the trunk and aligned incident to one of the displacement probes (Fig. 1). A rope (16 mm Stable Braid or 13 mm AmSteel Blue, Samson Rope Technologies, Ferndale, WA, USA) extended from an anchor tree through an arborist block (RP055, International Safety Components, Gwynned, United Kingdom) attached to the trunk with a round sling (Super Techlon, Technotex Industrial Supply, Coevorden, The Netherlands) and returned parallel to itself. The working end of the rope was pulled using either a cable winch (Wire Rope Pulling Hoist, Toyu, Tianjin, China) or a capstan winch (GRCS, Good Rigging Control LLC, Hartland, WI, USA) to generate tension. The other end of the rope was connected to a digital dynamometer (EDXtreme-5T, Dillon, Fairmont, MN, USA) with 5000 kg capacity, 1 kg resolution, and ± 5 kg accuracy. This configuration made it easy to monitor rope tension during pull testing. During free vibration tests, the applied load was instantaneously released by cutting a sacrificial piece of rope with a pole saw. Rotation of the root-soil system was not monitored during pull testing.

Time histories of displacement, $\boldsymbol{x}$ (mm), and acceleration, $\boldsymbol{a}$ (m s^{-2}), from the free vibration tests were used to determine f_n and ζ. A scalar projection of each displacement or acceleration observation was made onto the resultant vector for each time history, decomposing recorded two- or three-dimensional movement into that along its primary axis. Initial displacements and accelerations recorded during free vibration tests, artefacts of the test method, were removed from time histories before analysis. Time histories were limited to 1024 observations, approximately 38 s. Since the data were sampled at uneven intervals, power spectral density (PSD) was computed using the Lomb-Scargle periodogram, and the absolute peak in PSD was used to identify the damped natural frequency, f_d (Hz).

ζ was determined by fitting the solution to the equation of motion for a freely vibrating single-degree-of-freedom (SDOF) mass-spring system, according to Bruchert and Gardiner (2006):

$$x(t) = A\mathrm{e}^{-\zeta\omega_n t}\sin\left(\omega_d t + \phi\right), \quad (5)$$

with $\omega_d = f_d \cdot 2\pi$ and the constants initial displacement, A (mm), and phase angle, ϕ (rad), set equal to $A = x(t_0)$ and $\phi = \pi/2$, respectively. In this treatment, the vibration is assumed to experience damping proportional to velocity (i.e., viscous damping), a common assumption confirmed by Jonsson et al. (2007) for Norway spruce (*Picea abies*). Natural frequency, f_n (Hz), of the measured tree part was determined using

$$f_n = f_d / \sqrt{1 - \zeta^2}. \quad (6)$$

All signal processing was performed using MATLAB (R2017a, MathWorks, Natick, MA, USA).

Pruning treatments

Trees were pruned using two methods commonly employed by practitioners in Singapore, broadly according to ANSI A300 (Part 1) (TCIA 2017). The crowns of one group of trees were raised to increase vertical space below the crown by progressively removing branches from the bottom of the crown upwards. The crowns of a second group of trees were reduced to decrease the overall height of each tree by shortening the length of the trunk and branches. During pruning, branches were progressively removed from horizontal slices of the crown (Fig. 2). For raised and reduced trees, the slices originated from the bottom and top of the crown, respectively. As pruning severity increased, the thickness of horizontal slices increased by a distance equal to pruning severity multiplied by L_{CROWN}. On reduced trees, all tree parts were removed from each horizontal slice, and pruning cuts were made at the intersection of each tree part with the lower limit of each slice. Most tree parts were shortened using a heading cut, but some were shortened using a reduction cut—TCIA (2017) describes pruning cuts. On raised trees, only branches with a diameter less than 60% of its subtending member were removed from each horizontal

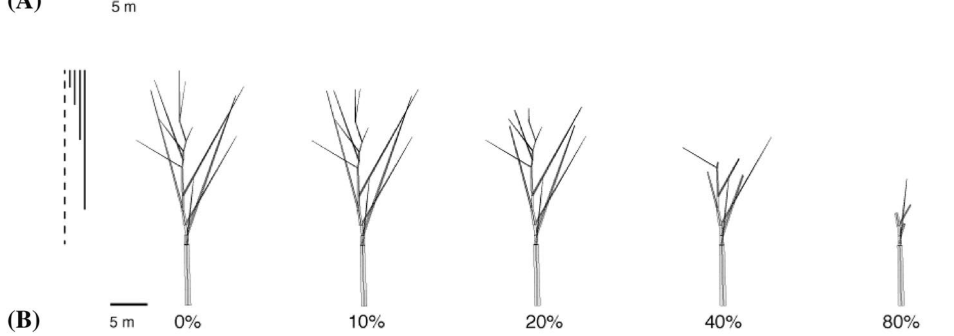


Fig. 2 Crown architecture models of (**a**) raised and (**b**) reduced Senegal mahoganies (*Khaya senegalensis*) at (L–R) 0%, 10%, 20%, 40%, and 80% pruning severity. Consisting of a series of joined truncated cones, digital models were reconstructed from manual measurements of the dimension, position, and topological order of branches. During pruning, branches were progressively removed from horizontal slices of the crown. For raised and reduced trees, slices originated from the bottom and top of the crown, respectively. At each severity, the thickness of horizontal slices increased by a distance equal to pruning severity multiplied by crown length, L_{CROWN} (m). For reference, solid vertical lines (left) show the increasing cumulative thickness of horizontal crown slices at each pruning severity relative to L_{CROWN} (dashed vertical line)

slice to preserve crown structure. This simplistic approach to pruning does not represent arboricultural practice, where the removal of branches depends on specific objectives, but it was needed for experimental consistency to induce similar changes to the crown dimensions of trees with different branch architectures.

Free vibration tests were conducted before pruning (i.e., 0% pruning severity), and the trees were subsequently subjected to pruning severities between 10% and 80%. Senegal mahoganies were pruned to remove the specified tree parts from horizontal crown slices with thickness equal to 10, 20, 40, and 80% of L_{CROWN}. Rain trees were similarly pruned, except that the 10% pruning severity was excluded. Pruning treatments were applied under the supervision of a single person to maintain consistency.

For Senegal mahoganies, free vibration tests were conducted immediately after each pruning treatment, but the severity of pruning was progressively increased at 45-day intervals to measure wind-induced tree movement between pruning treatments for a separate experiment. In contrast, the severity of pruning was increased immediately after free vibration tests for rain trees without the 45-day interval. The iterative process of pruning and testing was repeated on pairs of rain trees (one of each pruning type) until 80% severity. The post-pruning growth response of Senegal mahoganies was not measured, but it was possible to qualitatively assess whether post-pruning growth of Senegal mahoganies confounded the pruning treatments, since rain trees were pruned immediately after free vibration tests.

The total fresh mass (kg) of all tree parts removed during each pruning severity was recorded in the field using the EDXtreme-5T dynamometer. Leaves were removed from each pruned tree part to determine the fresh mass of wood, m_{WOOD} (kg), and leaves, m_{LEAF} (kg). After the final pruning treatment, the trees were felled to determine the mass of the remaining tree parts, and m_{TREE} was recorded as the total mass of each tree. The percent decrease in m_{TREE} and m_{LEAF} at each pruning severity was determined as the cumulative proportion of excised mass.

Basic wood density, ρ (g cm^{-3}), and moisture content, MC (%), were determined using core samples extracted at 1 m intervals from the trunk and primary branches with an increment borer (Haglof Increment Borer, Langsele, Sweden). After extraction, the wood core samples were cut into regular 3 cm sections consisting entirely of peripheral sapwood and stored in sealed plastic bags for processing within 48 h. Fresh volume was determined by measuring the mass of water displaced by cores on a precision balance (Setra Systems EL-410S, Boxborough, MA, USA), and the mass of core samples was recorded using the same precision balance before and after drying in a forced convection oven (Binder BIN-FD115, Tuttlingen, Germany) at 103 °C to practical equilibrium. Afterwards, ρ was determined as oven-dry mass divided by fresh volume (ASTM 2014), and MC was determined as follows (Glass and Zelinka 2010):

$$\mathrm{MC} = \left(m_{\mathrm{wet}} - m_{\mathrm{dry}}/m_{\mathrm{dry}}\right) \times 100, \tag{7}$$

where m_{wet} and m_{dry} are wet and dry mass (g), respectively.

Experimental design and data analysis

Data were collected in two separate experiments independently addressing each tree species. The Senegal mahogany experiment was designed as a one-way repeated measures analysis of variance (ANOVA) with one between-subject factor with two levels (pruning type: raise and reduce) and one within-subject factor with five levels (pruning severity: 0%, 10%, 20%, 40%, and 80%). To minimize initial variability, trees were randomly assigned to pruning type after accounting for morphology. The rain tree experiment, conducted separately, was designed similarly to the Senegal mahogany experiment, except without the (i) 10% pruning severity and (ii) 45-day interval between pruning severities.

One individual of each species was removed from the data set prior to analysis, because it was not possible to induce sufficient movement during free vibration testing. During free vibration testing, insufficient branch movement on raised rain trees prevented a comparison of the effect of pruning type on branch f_n and ζ. Linear mixed effects models for repeated measures ANOVA were fit to the percent decrease in m_{TREE}, percent decrease in m_{LEAF}, f_n, and ζ using proc mixed in SAS 9.4 (SAS Institute, Inc., Cary, NC, USA). For each combination of pruning type and severity, the mean of three f_n or ζ observations was analyzed. Fixed effects for the model included pruning type, pruning severity, and their interaction. The random effect of tree, nested within pruning type, was also included in the model. For the rain tree experiment, an additional random replication effect was included to account for the iterative application of experimental treatments to pairs of trees. Significant interactions were separated to determine the effect of pruning severity within each pruning type. Regression was used to separate means associated with specific levels of pruning severity (a continuous variable); total sums of squares were partitioned into single-degree-of-freedom orthogonal polynomial comparisons to assess the significance of individual polynomial terms. Based on these results, least-squares regression was used to determine the associated polynomial coefficients. An F test was used to evaluate the mean difference between pruning types before pruning (i.e., 0% severity).

Results

Tree and wood attributes

When subjected to a static bending moment, mean E_{STRUCT} was 6.26 GPa ($n=11$; SD 2.20×10^9) for Senegal mahogany and 6.14 ($n=9$; SD 2.22×10^9) for rain tree. Mean ρ of sapwood core samples was 0.62 g cm^{-3} ($n=762$; SD 0.09) and 0.55 g cm^{-3} ($n=377$; SD 0.06) for Senegal mahogany and rain tree, respectively. Mean MC of sapwood core samples was 67% ($n=762$; SD 26) and 75% ($n=377$; SD 25) for Senegal mahogany and rain tree, respectively.

Post-pruning changes in tree attributes

Since trees were selected to minimize initial variability in size, there was modest variation in tree morphology among individuals within each species before pruning, but pruning treatments changed the size of residual tree parts according to the deliberate removal of branches from raised and reduced trees (Table 1). For raised rain trees, mean L_{CROWN} did not change, because the lowest branch was not removed from any of the trees, since the ratio of branch to trunk diameter consistently exceeded 0.6 (see "Methods"). Mean H and λ did not change on raised Senegal mahoganies or rain trees, but the two attributes decreased on reduced trees according to the planned changes in L_{CROWN}.

Pruning treatments affected the percent decrease in m_{TREE} and m_{LEAF} similarly for both species. The percent decrease in m_{TREE} and m_{LEAF} was significantly greater for reduced than raised trees. Although the percent decrease in m_{TREE} and m_{LEAF} increased significantly with pruning severity, pruning type and severity interacted significantly, because the rate of change in the percent decrease in m_{TREE} and m_{LEAF} was greater for reduced than raised trees (Tables 2, 3). While the percent decrease in m_{TREE} increased linearly up to 24% and 22% for raised Senegal mahoganies and rain trees, respectively, the percent decrease in m_{TREE} increased curvilinearly and linearly up to 61% and 65% for reduced Senegal mahoganies and rain trees, respectively (Fig. 3a). For reduced rain trees, the percent decrease in m_{LEAF} was exceptionally large at 20% severity, indicating the thorough removal of leaves concentrated near branch tips (Table 3). For most pruning treatments, the percent decrease in m_{LEAF} was greater for rain trees than Senegal mahoganies. For raised Senegal mahoganies and rain trees, the percent decrease in m_{LEAF} increased linearly up to 55% and 82%, respectively; and the percent decrease in m_{LEAF} increased curvilinearly up to 96% and 100% for reduced Senegal mahoganies and rain trees, respectively (Fig. 3b). At 80% severity, pruning treatments caused total defoliation to two and five reduced Senegal mahoganies and rain trees, respectively; none of the raised trees was completely defoliated for either species.

Natural frequency

A single peak in PSD was observed in most free vibration tests with trunk and branch motion reasonably approximated by a simple harmonic function (Fig. 4). On Senegal mahoganies, trunk and branch f_n varied between pruning types and severities, but pruning type interacted significantly with severity to affect both trunk and branch f_n (Table 4). Mean trunk and branch f_n for the reduced trees were significantly greater than the raised trees. The interaction of pruning type and severity was significant, because trunk and branch f_n increased curvilinearly as severity increased for reduced, but not raised, trees (Table 4).

Table 1 Mean (SD) tree height, H (m); crown length, L_{CROWN} (m); slenderness, λ (dimensionless); total mass, m_{TREE} (kg); and leaf mass, m_{LEAF} (kg) for Senegal mahogany (*Khaya senegalensis*, $n=11$) and rain tree (*Samanea saman*, $n=9$) modified by pruning type and severity

Severity	H		L_{CROWN}		λ		m_{TREE}		m_{LEAF}	
	Raise	Reduce	Raise	Reduce	Raise	Reduce	Raise	Reduce	Raise	Reduce
(a) Senegal mahogany (%)										
0	25.8 (2.2)	28.9 (1.8)	21.5 (2.8)	22.3 (1.8)	36.0 (4.4)	40.1 (1.1)	10,583 (2982)	11,420 (992)	391 (135)	454 (79)
10	25.8 (2.2)	24.5 (1.1)	18.8 (2.9)	17.8 (1.7)	36.0 (4.4)	34.0 (0.9)	10,013 (2764)	10,735 (939)	343 (116)	308 (90)
20	25.8 (2.2)	22.2 (1.2)	18.4 (2.9)	15.5 (1.6)	36.0 (4.4)	30.8 (0.6)	9749 (2614)	9802 (891)	328 (108)	186 (89)
40	25.8 (2.2)	16.9 (1.6)	17.5 (4.4)	10.3 (1.1)	36.0 (4.4)	23.4 (1.4)	9105 (2578)	7344 (1041)	277 (105)	58 (48)
80	25.8 (2.2)	11.0 (1.7)	17.3 (4.7)	4.4 (0.8)	36.0 (4.4)	15.3 (2.1)	8021 (2148)	4525 (752)	178 (98)	23 (21)
(b) Rain tree (%)										
0	23.0 (0.8)	21.6 (0.6)	20.1 (1.2)	18.9 (0.8)	23.7 (0.6)	24.8 (1.2)	16,083 (1850)	12,960 (1852)	200 (14)	139 (23)
20	23.0 (0.8)	18.4 (0.8)	20.1 (1.2)	15.6 (0.7)	23.7 (0.6)	21.1 (2.1)	14,716 (1434)	11,326 (1711)	195 (50)	36 (31)
40	23.0 (0.8)	14.4 (0.7)	20.1 (1.2)	11.6 (0.5)	23.7 (0.6)	16.5 (1.6)	13,432 (1497)	9207 (1172)	154 (42)	4 (10)
80	23.0 (0.8)	6.7 (0.8)	20.1 (1.2)	4.0 (0.7)	23.7 (0.6)	7.7 (1.2)	12,116 (1487)	4686 (735)	80 (28)	0 (0)

Wood mass, m_{WOOD} (kg), is the difference between m_{TREE} and m_{LEAF}

Table 2 Analysis of variance of the percent decrease in total mass, m_{TREE}, (%) for (A) Senegal mahogany (*Khaya senegalensis*) and (B) rain tree (*Samanea saman*)

Effect	*df*	*F*	*p*	Level	LS mean (SE)
(A) Senegal mahogany m_{TREE}					
Type	1, 9.78	74.78	<0.001	Raise	12.7 (1.3)a
				Reduce	28.8 (1.4)b
Severity	3, 26.2	199.09	<0.001		
Type × severity	3, 26.2	47.84	<0.001		
Severity: $type_1$ (raise)	3, 26.2	28.88	<0.001	10%	5.3 (1.7)
				20%	7.7 (1.7)
				40%	14.0 (1.7)
				80%	23.9 (1.7)
Severity: $type_2$ (reduce)	3, 26.2	202.28	<0.001	10%	5.4 (1.8)
				20%	14.0 (1.8)
				40%	35.4 (1.8)
				80%	60.5 (1.8)
(B) Rain tree m_{TREE}					
Type	1, 7	37.45	<0.001	Raise	14.1 (2.5)a
				Reduce	35.0 (2.3)b
Severity	2, 14	363.53	<0.001		
Type × severity	2, 14	108.77	<0.001		
Severity: $type_1$ (raise)	2, 14	35.24	<0.001	20%	6.2 (2.8)
				40%	13.9 (2.8)
				80%	22.2 (2.8)
Severity: $type_2$ (reduce)	2, 14	487.29	<0.001	20%	12.7 (2.5)
				40%	28.0 (2.5)
				80%	64.5 (2.5)

Fixed effects include pruning type: raise, reduce; severity: 10, 20, 40, 80% (10% omitted from rain tree experiment); and their interaction: type × severity. Percent decrease in m_{TREE} was measured repeatedly on six raised and five reduced Senegal mahoganies and four raised and five reduced rain trees. Least squares (LS) means followed by the same letter are not significantly different at the $\alpha = 0.05$ level

For reduced Senegal mahoganies, orthogonal polynomial comparisons revealed a quadratic response of trunk and branch f_n to pruning severity (Online Resource 1). Least-squares regression revealed a highly significant, positive relationship between trunk and branch f_n and the severity of reduction pruning (Fig. 5). At 0% severity, the mean f_n of trunks ($F = 0.01$; $df = 1, 36$; $p = 0.930$) and branches ($F = 0.70$; $df = 1, 24$; $p = 0.410$) did not differ between pruning types. Although statistical comparisons were not made, branch f_n was approximately one-half trunk f_n at all treatment combinations, roughly consistent with the average ratio of branch to trunk diameter (0.56) for all instrumented branches. Regressed against the percent decrease in m_{TREE}, trunk, and branch f_n of reduced trees revealed similar positive, highly significant quadratic relationships (Fig. 6). For raised trees, pruning severity did not affect trunk or branch f_n (Table 4).

There were highly significant differences in rain tree trunk f_n between pruning types and severities, but pruning type and severity interacted significantly to affect trunk f_n (Table 5). Mean trunk f_n for reduced trees was significantly greater than raised trees. The interaction between pruning type and severity was significant, because trunk f_n increased curvilinearly with pruning severity on reduced, but not raised, trees (Table 5). Similarly, the mean branch f_n on reduced trees increased curvilinearly with pruning severity (Table 5).

For reduced rain trees, orthogonal polynomial comparisons revealed a cubic response of trunk and branch f_n to pruning severity (Online Resource 1). Least-squares regression revealed a significant, positive relationship between trunk and branch f_n and reduction pruning severity (Fig. 5). At 0% severity, the mean trunk f_n of trees in each pruning type was not significantly different ($F = 0.06$; $df = 1, 3.42$; $p = 0.823$). Although statistical comparisons were not made, branch f_n was approximately two-fifths of trunk f_n on trees reduced by 0, 20, and 40%, and branch f_n subsequently increased, on a relative basis, to approximately three-fifths of trunk f_n on trees reduced by 80% (Table 5). Regressed against the percent decrease in m_{TREE}, trunk and branch f_n of reduced trees revealed similar positive, highly significant cubic relationships (Fig. 6). For raised trees, pruning severity did not affect trunk f_n (Table 5).

Table 3 Analysis of variance of the percent decrease in leaf mass, m_{LEAF}, (%) for (A) Senegal mahogany (*Khaya senegalensis*) and (B) rain tree (*Samanea saman*)

Effect	*df*	*F*	*p*	Level	LS mean (SE)
(A) Senegal mahogany m_{LEAF}					
Type	1, 9.96	46.18	< 0.001	Raise	28.3 (4.1)a
				Reduce	69.2 (4.4)b
Severity	3, 26.9	61.70	< 0.001		
Type × severity	3, 26.9	13.99	< 0.001		
Severity: type$_1$ (raise)	3, 26.9	26.02	< 0.001	10%	11.8 (4.8)
				20%	15.8 (4.8)
				40%	30.4 (4.8)
				80%	55.0 (4.8)
Severity: type$_2$ (reduce)	3, 26.9	47.70	< 0.001	10%	30.3 (5.3)
				20%	60.6 (5.3)
				40%	89.4 (5.3)
				80%	96.3 (5.3)
(B) Rain tree m_{LEAF}					
Type	1, 12.9	54.67	< 0.001	Raise	45.3 (4.7)a
				Reduce	92.1 (4.2)b
Severity	2, 14	51.72	< 0.001		
Type × severity	2, 14	16.49	< 0.001		
Severity: type$_1$ (raise)	2, 14	54.64	< 0.001	20%	15.2 (7.0)
				40%	38.9 (7.6)
				80%	81.7 (1.4)
Severity: type$_2$ (reduce)	2, 14	8.44	0.004	20%	78.5 (6.2)
				40%	97.9 (6.8)
				80%	100.0 (1.2)

Fixed effects include pruning type: raise, reduce; severity: 10, 20, 40, 80% (10% omitted from rain tree experiment); and their interaction: type × severity. Percent decrease in m_{LEAF} was measured repeatedly on six raised and five reduced Senegal mahoganies and four raised and five reduced rain trees. Least squares (LS) means followed by the same letter are not significantly different at the $\alpha = 0.05$ level

Damping ratio

At 0% pruning severity, for Senegal mahoganies, the mean difference in trunk ($F = 2.10$; $df = 1, 36$; $p = 0.156$) and branch ($F = 0.92$; $df = 1, 110$; $p = 0.339$) ζ between pruning types was not significant. Mean Senegal mahogany trunk ζ did not vary between the two pruning types, but there were significant differences in mean branch ζ between pruning types (Table 6). Mean branch ζ for reduced trees was significantly less than for raised trees. Both trunk and branch ζ varied significantly among levels of pruning severity, but pruning type and severity interacted significantly to affect trunk and branch ζ. Mean trunk and branch ζ decreased as pruning severity increased for reduced, but not raised, trees (Table 6).

On reduced Senegal mahoganies, cubic functions described the response of trunk and branch ζ to pruning severity (Online Resource 1). Least-squares regression confirmed a highly significant, negative curvilinear relationship between pruning severity and ζ measured on the trunks and branches of reduced trees (Fig. 7). Although statistical comparisons were not made, mean branch ζ was higher than mean trunk ζ at 10% and 20% pruning severity before converging to similar values at 40% and 80% pruning severity. Regressed against the percent decrease in m_{LEAF}, trunk and branch ζ of reduced trees revealed similar highly significant cubic relationships; ζ generally increased on trunks and branches until a 63% and 52% decrease in m_{LEAF}, respectively, before subsequently declining, as more leaves were removed (Fig. 8a).

For rain trees, the mean difference in trunk ζ between pruning types at 0% severity was not significant ($F = 2.77$; $df = 1, 6.71$; $p = 0.142$). Mean trunk ζ did not vary between pruning types, but it varied significantly among pruning severities. However, pruning type and severity interacted significantly to affect trunk ζ, which varied among pruning severities only for reduced trees (Table 7). Orthogonal polynomial comparisons revealed a quadratic response of trunk ζ to the severity of reduction (Online Resource 1). Least-squares regression confirmed the highly significant quadratic relationship between trunk ζ and reduction pruning severity (Fig. 9). Regressed against the percent decrease in m_{LEAF}, however, the significant decrease in trunk ζ was linear, not quadratic, for reduced rain trees (Fig. 8b).

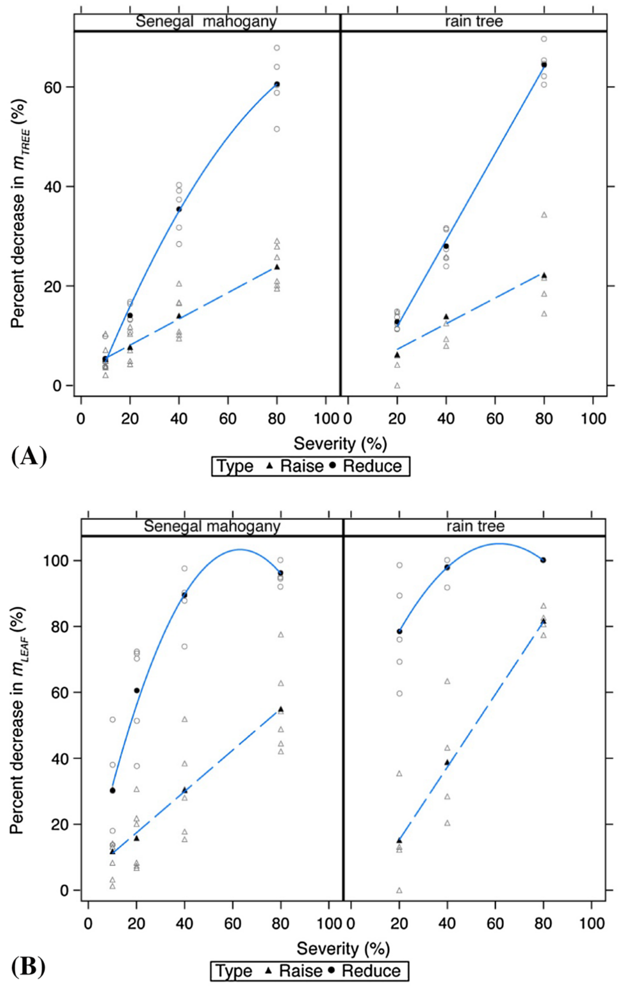


Fig. 3 Regression of mean percent decrease in (**a**) total mass, m_{TREE}, and (**b**) leaf mass, m_{LEAF}, against pruning severity for raised (filled triangles) and reduced (filled circles) rain tree (*Samanea saman*) and Senegal mahogany (*Khaya senegalensis*). Percent decrease in mass was measured repeatedly on six raised and five reduced Senegal mahoganies and four raised and five reduced rain trees. For Senegal mahogany, least-squares regression equations are $y=0.26\ x+2.82$ [$r^2=0.99$] and $y=(-5.32\times10^{-3})\ x^2+1.28\ x-7.49$ [$R^2=0.99$] for the percent decrease in m_{TREE} on raised and reduced trees, respectively, and $y=0.63\ x+4.91$ [$r^2=0.99$] and $y=(-2.55\times10^{-2})\ x^2+3.21\ x+2.12$ [$R^2=0.99$] for the percent decrease in m_{LEAF} on raised and reduced trees, respectively. For rain tree, least-squares regression equations are $y=0.26\ x+2.08$ [$r^2=0.97$] and $y=0.87\ x-5.53$ [$r^2=0.99$] for the percent decrease in m_{TREE} on raised and reduced trees, respectively, and $y=1.10\ x-6.80$ [$r^2=0.99$] and $y=(-1.53\times10^{-2})\ x^2+1.89\ x+46.86$ [$R^2=0.99$] for the percent decrease in m_{LEAF} on raised and reduced trees, respectively. For reference, empty gray symbols show all observations of individual trees

Although statistical comparisons were not made, branch and trunk ζ were similar at 0% pruning severity. On reduced rain trees, mean branch ζ also varied significantly among pruning severities (Table 7). However, orthogonal polynomial comparisons indicated a linear rather than a quadratic response of branch ζ to pruning severity (Online Resource 1). Least-squares regression confirmed a highly significant, negative relationship between branch ζ and pruning severity on these trees (Fig. 9). Regressed against the percent decrease in m_{LEAF}, there was a similar, highly significant linear decrease in branch ζ for reduced rain trees (Fig. 8b).

Discussion

Especially, for large, open-grown broadleaf trees, this study clearly demonstrates a consistent and practically meaningful difference between pruning types over a wide range of severities. Quantifying changes to vibration properties and mass provided novel insights into the effect of increasingly severe pruning, which has previously only been documented for a single pruning type on plantation-grown conifers of excurrent form (Moore and Maguire 2005). In previous work on broadleaf trees, observations were limited to smaller (Kane and James 2011; Miesbauer et al. 2014) or forest-grown (Kane 2018) trees, often pruned at a single severity (Kane and James 2011; Miesbauer et al. 2014).

Senegal mahogany and rain tree E_{STRUCT} was the same order of magnitude as values reported for plantation-grown excurrent conifers (Milne and Blackburn 1989; Milne 1991; Bruchert et al. 2000; Peltola et al. 2000) and open-grown decurrent trees (Kane 2014). Senegal mahogany E_{STRUCT} was similar to values reported for green-milled specimens obtained from congeneric African mahoganies measured in three-point bending (Kretschmann 2010). In existing attempts to determine E_{STRUCT} on standing trees subjected to static bending, authors reported similar variability in estimates for multiple trees of the same species (Milne and Blackburn 1989; Peltola et al. 2000; Kane 2014). However, the use of outer bark diameters may have caused a small underestimation of E_{STRUCT} (Cannell and Morgan 1987; Lundstrom et al. 2008); a uniform bark thickness of 1 cm, for example, would have caused an error of approximately 5% in E_{STRUCT} for the trees used in this study from the overestimate of a, b, and I in Eq. 2.

For Senegal mahogany and rain tree, mean sapwood ρ was similar to the average of measurements reported globally for each species (Chave et al. 2009), and mean sapwood MC fit the expected range of values for most species (Glass and Zelinka 2010). Although MC varies with seasonal environmental conditions, the MC measurements provide important context for other properties measured in this study, since MC influences the mechanical behavior of wood in trees. In the future, these measurements should be used to facilitate comparisons with similar studies of other species.

The greater percent decrease in m_{TREE} on reduced trees was expected, because this pruning type removed all tree parts from a portion of L_{CROWN}, while only higher order branches were removed from raised trees to retain the

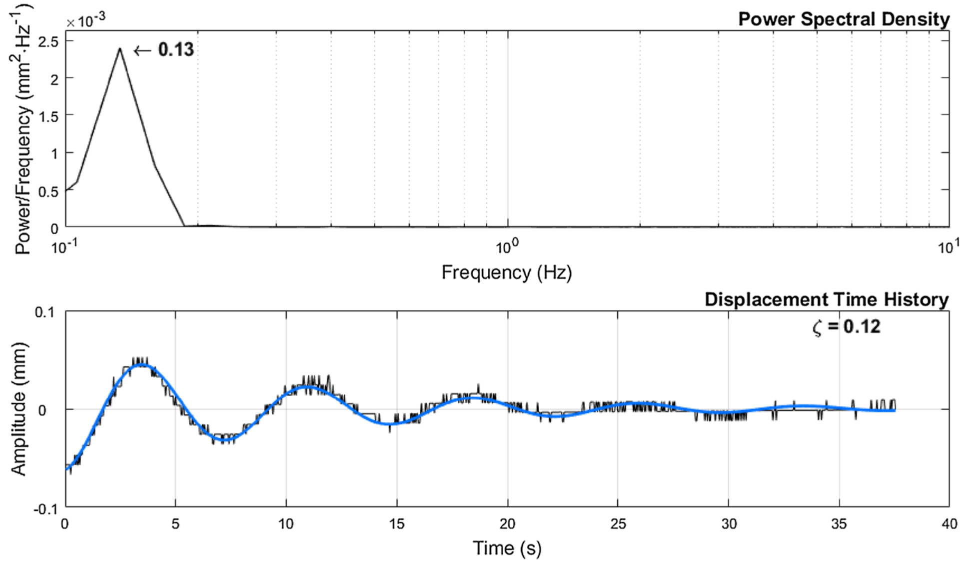


Fig. 4 Pre-treatment time history of trunk displacement measured during free vibration on Senegal mahogany (*Khaya senegalensis*) tree number 16 (KS16), including the equation of motion for a damped harmonic oscillator (solid blue line) fit to recorded observations (bottom); and power spectral density plot with annotation showing peak frequency (top)

Table 4 Analysis of variance of natural frequency, f_n (Hz), measured on the (A) trunks and (B) branches of Senegal mahogany (*Khaya senegalensis*)

Effect	*df*	*F*	*p*	Level	LS mean (SE)
(A) Trunk f_n					
Type	1, 9	84.47	< 0.001	Raise	0.16 (0.04)a
				Reduce	0.65 (0.04)b
Severity	4, 36	91.72	< 0.001		
Type × severity	4, 36	83.27	< 0.001		
Severity: $type_1$ (raise)	4, 36	0.20	0.938		
Severity: $type_2$ (reduce)	4, 36	160.24	< 0.001	0%	0.15 (0.01)
				10%	0.20 (0.01)
				20%	0.27 (0.03)
				40%	0.66 (0.02)
				80%	1.99 (0.18)
(B) Branch f_n					
Type	1, 44.9	1038.85	< 0.001	Raise	0.08 (0.01)a
				Reduce	0.28 (0.01)b
Severity	4, 47.3	1083.58	< 0.001		
Type × severity	4, 47.3	1034.24	< 0.001		
Severity: $type_1$ (raise)	4, 48.5	1.59	0.191		
Severity: $type_2$ (reduce)	4, 46.6	1716.01	< 0.001	0%	0.08 (0.01)
				10%	0.09 (0.01)
				20%	0.15 (0.01)
				40%	0.31 (0.02)
				80%	0.75 (0.01)

Fixed effects include pruning type: raise, reduce; severity: 0, 10, 20, 40, 80%; and their interaction: type × severity. Trunk f_n was measured repeatedly on six raised and five reduced Senegal mahoganies; branch f_n was simultaneously measured on 12 and 14 branches, respectively, distributed among these raised and reduced trees. Least squares (LS) means followed by the same letter are not significantly different at the $\alpha = 0.05$ level

trunk and large primary branches. A distal concentration of leaves on the branches of both species resulted in a faster rate of decrease in m_{LEAF} for reduced trees, and this was especially true for rain tree. The distinct form of polynomial regression functions fit to the percent decrease in m_{LEAF} on reduced trees, especially the large negative quadratic term, depicted the unique defoliation of these trees. This finding suggests that, especially for rain trees, arborists must use

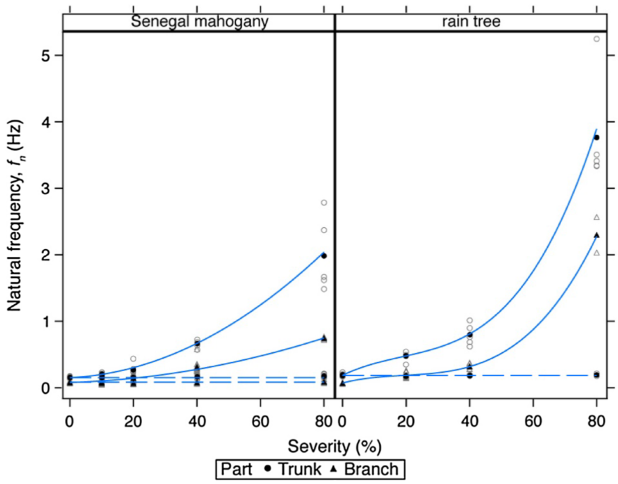


Fig. 5 Regression of mean Senegal mahogany (*Khaya senegalensis*) and rain tree (*Samanea saman*) natural frequency, f_n (Hz), against pruning severity for reduced trees (solid line) with data obtained from trunk displacement (filled circle) and branch acceleration (filled triangle) time histories of free vibration tests. Trunk f_n was measured repeatedly on six raised and five reduced Senegal mahoganies and four raised and five reduced rain trees; branch f_n was simultaneously measured on 12 and 14 branches, respectively, distributed among the raised and reduced Senegal mahoganies and six branches in one reduced rain tree. For Senegal mahogany, least-squares regression equations are $y=(2.68\times10^{-4})\ x^2+(2.16\times10^{-3})\ x+0.15\ [R^2=0.99]$ and $y=(8.60\times10^{-5})\ x^2+(1.47\times10^{-3})\ x+0.08\ [R^2=0.99]$ for trunk and branch f_n, respectively. For rain tree, least-squares regression equations are $y=(1.20\times10^{-5})\ x^3-(6.70\times10^{-4})\ x^2+(2.31\times10^{-2})\ x+0.19\ [R^2=0.99]$ and $y=(8.63\times10^{-6})\ x^3-(5.00\times10^{-4})\ x^2+(1.23\times10^{-2})\ x+0.07\ [R^2=0.99]$ for trunk and branch f_n, respectively. Dashed horizontal lines depict the mean f_n for similar trunk and branch observations on raised trees, for which f_n remained constant across the range of tested pruning severities. For reference, empty gray symbols show all observations of individual trees

good judgment when prescribing the severity of reduction pruning to avoid defoliation. It should be noted, however, that the polynomials fit to the percent decrease in m_{LEAF} are not well-suited for prediction, because the functions unrealistically exceed 100% over part of their range. The polynomial regression models used to separate means should be regarded as describing trends in measurements over the range of tested pruning severities, rather than predictive models. Pruning severity is often estimated visually as the percentage of foliage removed, but the accuracy of these subjective visual estimates is questionable (Pavlis et al. 2008). Since the mass of trees and leaves correlates strongly with vibration properties (Bruchert and Gardiner 2006) and drag (Vollsinger et al. 2005; Kane et al. 2008), more work is needed to examine and facilitate the use of mass as a measure of pruning severity by practitioners.

Overall, similar trends in the vibration properties of pruned trees for both species did not suggest that post-pruning growth confounded the analysis of Senegal mahogany

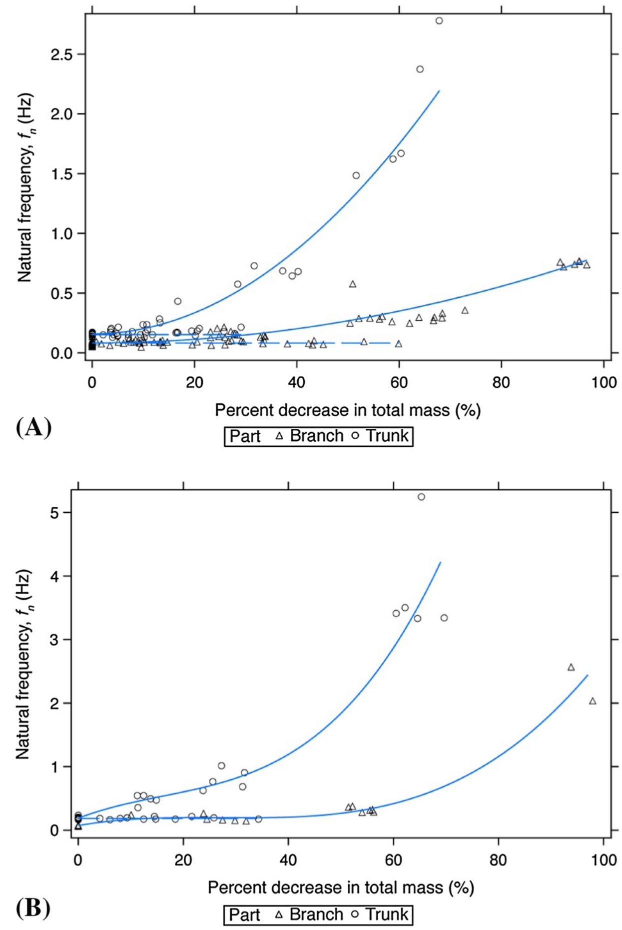


Fig. 6 Regression of (**a**) Senegal mahogany (*Khaya senegalensis*) and (**b**) rain tree (*Samanea saman*) natural frequency, f_n (Hz), on percent decrease in total mass, m_{TREE}, of the relevant tree part for reduced trees (solid line) with data obtained from trunk displacement (circle) and branch acceleration (triangle) time histories of free vibration tests. Trunk f_n was measured repeatedly on six raised and five reduced Senegal mahoganies and four raised and five reduced rain trees; branch f_n was simultaneously measured on 12 and 14 branches, respectively, distributed among the raised and reduced Senegal mahoganies and six branches in one reduced rain tree. For Senegal mahogany, least-squares regression equations are $y=(4.42\times10^{-4})\ x^2+(2.42\times10^{-3})\ x+0.16\ [R^2=0.97]$ and $y=(7.40\times10^{-5})\ x^2+(6.70\times10^{-5})\ x+0.08\ [R^2=0.91]$ for trunk and branch f_n, respectively. For rain tree, least-squares regression equations are $y=(1.90\times10^{-5})\ x^3-(9.20\times10^{-4})\ x^2+(3.15\times10^{-2})\ x+0.19\ [R^2=0.92]$ and $y=(6.72\times10^{-6})\ x^3-(5.50\times10^{-4})\ x^2+(1.46\times10^{-2})\ x+0.07\ [R^2=0.95]$ for trunk and branch f_n, respectively. Dashed horizontal lines depict the mean f_n for analogous trunk and branch observations on raised trees, for which f_n remained constant across the range of tested pruning severities

vibration properties. For both species tested in this study, trunk and branch f_n increased continually with pruning severity only for reduced trees, consistent with existing reports of small (Kane and James 2011; Miesbauer et al. 2014) and large (Kane 2018) trees. In contrast, trunk and branch f_n remained constant on raised trees of both species

Table 5 Analysis of variance of natural frequency, f_n (Hz) measured on the (A) trunks and (B) branches of rain tree (*Samanea saman*)

Effect	*df*	*F*	*p*	Level	LS mean (SE)
(A) Trunk f_n					
Type	1, 8.37	98.91	< 0.001	Raise	0.18 (0.08)a
				Reduce	1.31 (0.08)b
Severity	3, 8.62	37.89	< 0.001		
Type × severity	3, 8.62	39.74	< 0.001		
Severity: $type_1$ (raise)	3, 8.62	0.05	0.986		
Severity: $type_2$ (reduce)	3, 8.62	87.28	< 0.001	0%	0.19 (0.01)
				20%	0.48 (0.03)
				40%	0.80 (0.05)
				80%	3.76 (0.28)
(B) Branch f_n					
Severity	3, 11	110.40	< 0.001	0%	0.07 (0.01)
				20%	0.19 (0.02)
				40%	0.32 (0.02)
				80%	2.30 (0.27)

Note: for trunk f_n, fixed effects include pruning type: raise, reduce; severity: 0, 20, 40, 80%; and their interaction: type × severity. For branch f_n, insufficient observations of branch acceleration on raised trees resulted in a single fixed effect: pruning severity for reduced trees. Trunk f_n was measured repeatedly on four raised and five reduced rain trees; branch f_n was simultaneously measured on six branches in one reduced rain tree. Least squares (LS) means followed by the same letter are not significantly different at the $\alpha = 0.05$ level

Table 6 Analysis of variance of damping ratio, ζ (dimensionless), measured on the (A) trunks and (B) branches of Senegal mahogany (*Khaya senegalensis*)

Effect	*df*	*F*	*p*	Level	LS mean (SE)
(A) Trunk ζ					
Type	1, 9	0.55	0.479		
Severity	4, 36	4.29	0.006		
Type × severity	4, 36	2.78	0.041		
Severity: $type_1$ (raise)	4, 36	0.43	0.789		
Severity: $type_2$ (reduce)	4, 36	6.12	0.001	0%	0.11 (0.02)
				10%	0.14 (0.04)
				20%	0.23 (0.05)
				40%	0.05 (0.02)
				80%	0.03 (0.01)
(B) Branch ζ					
Type	1, 110	66.84	< 0.001	Raise	0.19 (0.01)a
				Reduce	0.13 (0.01)b
Severity	4, 110	17.25	< 0.001		
Type × severity	4, 110	16.74	< 0.001		
Severity: $type_1$ (raise)	4, 110	1.58	0.183		
Severity: $type_2$ (reduce)	4, 110	31.80	< 0.001	0%	0.17 (0.01)
				10%	0.19 (0.01)
				20%	0.18 (0.01)
				40%	0.07 (0.01)
				80%	0.04 (0.02)

Fixed effects include pruning type: raise, reduce; severity: 0, 10, 20, 40, 80%; and their interaction: type × severity. Trunk ζ was measured repeatedly on six raised and five reduced Senegal mahoganies; branch ζ was simultaneously measured on 12 and 14 branches, respectively, distributed among these raised and reduced trees. Least squares (LS) means followed by the same letter are not significantly different at the $\alpha = 0.05$ level

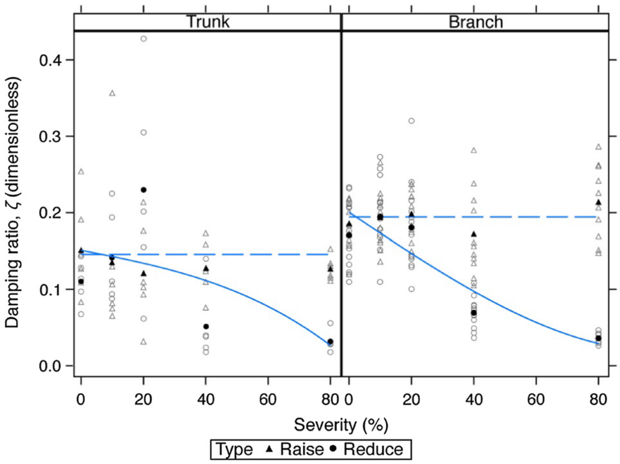
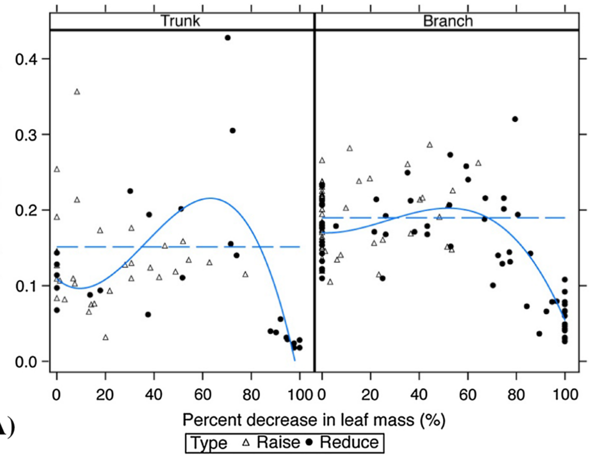
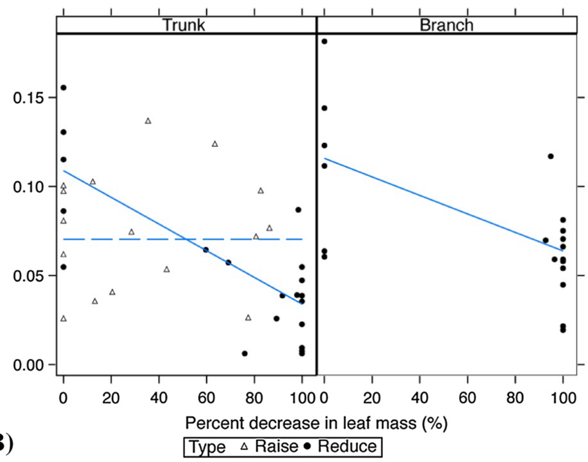


Fig. 7 Regression of mean Senegal mahogany (*Khaya senegalensis*) damping ratio, ζ (dimensionless), on pruning severity for reduced trees (filled circle marker, solid line) with data obtained from trunk displacement (left panel) and branch acceleration (right panel) time histories of free vibration tests. Trunk ζ was measured repeatedly on six raised and five reduced Senegal mahoganies; branch ζ was simultaneously measured on 12 and 14 branches, respectively, distributed among these raised and reduced trees. Least-squares regression equations are $y=(-1.18\times10^{-7})\ x^3-(8.00\times10^{-4})\ x+0.15$ [$R^2=0.42$] and $y=(9.04\times10^{-8})\ x^3-(2.72\times10^{-3})\ x+0.20$ [$R^2=0.85$] for trunk and branch ζ, respectively. Dashed horizontal lines depict the mean ζ for similar trunk and branch observations on raised trees (filled triangle marker), for which ζ remained constant across the range of tested pruning severities. For reference, empty gray symbols show all observations of individual trees



(A)



(B)

Fig. 8 Regression of (**a**) Senegal mahogany (*Khaya senegalensis*) and (**b**) rain tree (*Samanea saman*) damping ratio, ζ (dimensionless), on percent decrease in leaf mass, m_{LEAF}, of the relevant tree part for reduced trees (solid line) with data obtained from trunk displacement and branch acceleration time histories of free vibration tests. Trunk ζ was measured repeatedly on six raised (empty triangle) and five reduced (filled circle) Senegal mahoganies and four raised and five reduced rain trees; branch ζ was simultaneously measured on 12 and 14 branches, respectively, distributed among the raised and reduced Senegal mahoganies and six branches in one reduced rain tree. For Senegal mahogany, least-squares regression equations are $y=(-1.54\times10^{-6})\ x^3+(1.68\times10^{-4})\ x^2-(2.78\times10^{-3})\ x+0.11$ [$R^2=0.53$] and $y=(-5.21\times10^{-7})\ x^3+(4.20\times10^{-5})\ x^2-(1.50\times10^{-4})\ x+0.17$ [$R^2=0.63$] for trunk and branch ζ, respectively. For rain tree, least-squares regression equations are $y=(-7.50\times10^{-4})\ x+0.11$ [$r^2=0.59$] and $y=(-5.20\times10^{-4})\ x+0.12$ [$r^2=0.40$] for trunk and branch ζ, respectively. Dashed horizontal lines depict the mean ζ for analogous trunk and branch observations on raised trees, for which ζ remained constant across the range of tested pruning severities

over all pruning severities tested in this study. Previous studies have similarly documented the minimal effect of raising on f_n (Kane and James 2011) unless a substantial proportion of crown mass was removed (Moore and Maguire 2005). These findings are physically intuitive, since f_n of a cantilever beam is inversely proportional to the square of its length, but only to the square root of its mass (Niklas 1992); tree parts were shortened only on reduced trees, and m_{TREE} decreased much faster on reduced compared to raised trees. On raised Douglas-firs (*Pseudotsuga menziesii*), Moore and Maguire (2005) did not observe an increase in f_n until more than 80% of crown mass was removed. For Senegal mahogany and rain tree, m_{TREE} decreased on raised trees, at most, by only 24%, and it would have been practically challenging to further decrease m_{TREE} without removing very large branches. Such severe pruning is unlikely in most arboricultural settings.

Although trunk and branch f_n increased curvilinearly on reduced trees for both species, the unit difference in the degree of polynomials indicated that post-pruning f_n increased faster on rain tree than Senegal mahogany, and this was likely caused by the smaller λ for rain tree originating from the larger basal diameter of most tree parts and shorter tree height. In addition, the absence of the 10% pruning severity from the rain tree experiment may have contributed to a difference in the modeled trend for the two species; a difference in the concavity of the two functions existed only between 0 and 19% pruning severity. Still, the general pattern of the two functions was similar over the entire range of tested pruning severities. For both species, the absence of a difference in f_n and ζ between pruning types at 0% severity

Table 7 Analysis of variance of damping ratio, ζ (dimensionless), measured on the (A) trunks and (B) branches of rain tree (*Samanea saman*)

Effect	*df*	*F*	*p*	Level	LS mean (SE)
(A) Trunk ζ					
Type	1, 6.96	1.88	0.213		
Severity	3, 12.1	4.13	0.031		
Type × severity	3, 12.1	5.33	0.014		
Severity: $type_1$ (raise)	3, 12.1	0.87	0.483		
Severity: $type_2$ (reduce)	3, 12.1	9.56	0.002	0%	0.11 (0.02)
				20%	0.05 (0.02)
				40%	0.02 (0.02)
				80%	0.04 (0.01)
(B) Branch ζ					
Severity	3, 7.21	31.98	< 0.001	0%	0.11 (0.02)
				20%	0.07 (0.01)
				40%	0.06 (0.01)
				80%	0.02 (0.01)

For trunk ζ, fixed effects include pruning type: raise, reduce; severity: 0, 20, 40, 80%; and their interaction: type × severity. For branch ζ, insufficient observations of branch acceleration on raised trees resulted in a single fixed effect: pruning severity for reduced trees. Trunk ζ was measured repeatedly on four raised and five reduced rain trees; branch ζ was simultaneously measured on six branches in one reduced rain tree

suggests that it was not necessary to include a covariate to account for the initial condition of trees in statistical models.

The accelerated rate of leaf loss on reduced trees likely explained the decline in ζ only on reduced trees. This distinction affirms the effect of leaves on damping in existing reports from smaller trees (Sellier and Fourcaud 2005; Kane and James 2011). Distal tree parts also experience larger wind-induced displacements, undergo extended periods of motion, and usually interact with faster moving air, because the horizontal wind speed increases nonlinearly above ground (Oliver 1971). Since drag is proportional to the square of wind velocity, ignoring reconfiguration, the outsized contribution of leaves at the top of the crown to total damping was expected. Despite an average 61% decrease in m_{LEAF} for raised trees, the preservation of distal branches and leaves on these trees offers one explanation for the observed difference between pruning types.

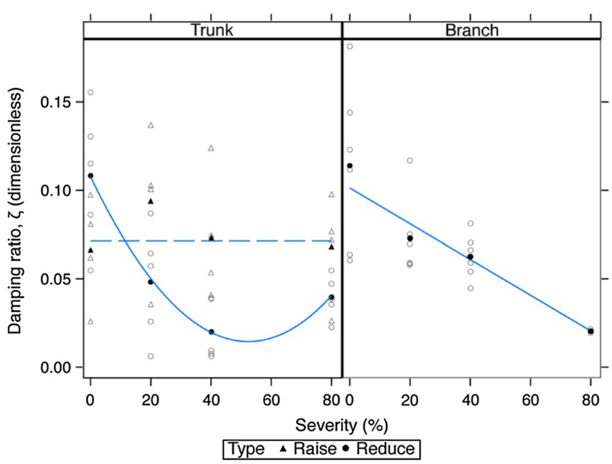


Fig. 9 Regression of mean rain tree (*Samanea saman*) damping ratio, ζ (dimensionless), on pruning severity for reduced trees (filled circle marker, solid line) with data obtained from trunk displacement (left panel) and branch acceleration (right panel) time histories of free vibration tests. Trunk ζ was measured repeatedly on four raised and five reduced rain trees; branch ζ was simultaneously measured on six branches in one reduced rain tree. Least-squares regression equations are $y = (3.40 \times 10^{-5})\ x^2 - (3.56 \times 10^{-3})\ x + 0.11$ $[R^2 = 0.99]$ and $y = (-1.01 \times 10^{-3})\ x + 0.10$ $[r^2 = 0.96]$ for trunk and branch ζ, respectively. Dashed horizontal line depicts the mean ζ for similar trunk observations on raised trees (filled triangle marker), for which ζ remained constant across the range of tested pruning severities. For reference, empty gray symbols show all observations of individual trees

Although ζ generally decreased with pruning severity on reduced trees, the change was, except for rain tree branch ζ, not constant. For reduced Senegal mahogany, mean trunk and branch ζ increased between 0 and 20% pruning severity before decreasing to similar values, and this explains the lack of an overall difference in trunk ζ between pruning types. The local increase in trunk ζ for some Senegal mahoganies reduced by 20% was unexpected, but similar to selected observations of raised Douglas-firs (Moore and Maguire 2005) and reduced maritime pines (Sellier and Fourcaud 2005). For the maritime pines, ζ increased by 15–25% after the removal of tertiary branches that comprised less than 1% of each sapling's biomass, and the authors suggested that the flexibility and topological position of these tertiary branches might have explained their negative influence on ζ (Sellier and Fourcaud 2005). However, this effect is not always observed after shortening tree parts by different methods; Kane (2018) reported a large decrease in ζ after all primary branches were shortened by one-third on a single red oak.

The increase in ζ, observed on multiple reduced trees in this experiment, was likely caused by a shift in the relative contribution from various damping sources. On reduced trees, greater leaf area per unit mass was removed at low pruning severity, decreasing contributions from aerodynamic drag on damping. Recalling that inter-crown collisions were restricted in this study, the remaining sources of damping that could have contributed to this post-pruning increase in ζ include internal wood friction, root-soil friction, intra-crown collisions, and structural damping (Spatz et al. 2007). Among these sources, an increase in structural damping is plausible, since m_{WOOD} decreased and the root-soil system was not modified on any trees. A post-pruning increase in intra-crown collisions was not visually observed or detected as shocks in acceleration time histories during free vibration testing. Practically, the increase in ζ on some Senegal mahoganies reduced by 20% was practically significant, because it should attenuate tree movement under external loading, and it should be a priority to attempt to replicate and examine these conditions in future studies.

However, the relationship between ζ and pruning severity was clarified by regressing ζ against the percent decrease in m_{LEAF} rather than percent decrease in L_{CROWN} (i.e., pruning severity). One distinction was apparent between the observations for each species: ζ increased on selected trees until a majority of m_{LEAF} was removed from reduced Senegal mahoganies, but ζ decreased linearly between observations mostly constrained near 0% and 100% decrease in m_{LEAF} on reduced rain trees, since leaves were removed quickly from these trees. Although the source and mechanism of increased damping on reduced Senegal mahoganies remains unclear, it uniquely occurred on reduced trees that retained most of their leaves. In future studies, researchers should reduce trees to progressively remove leaves over a series of small increments when examining pruning-induced changes to ζ. Such investigations could lead to an improved mechanistic understanding of energy dissipation in trees.

There was considerable variability in ζ among trees subjected to the same pruning treatment, and these results demonstrate a complicated response pattern for ζ on the reduced trees of each species. Under certain conditions, the kinematics of reduced branches undergoing free vibration likely created greater interference from out-of-phase movement that dissipated total kinetic energy. In addition to a smaller initial value, the data suggest that rain tree ζ is more sensitive to reduction than Senegal mahogany, a distinction that can be similarly attributed to its relatively sparse crown. Practically, rain tree should be reduced carefully to avoid a large decrease in damping; preservation of ζ is important, since trees are generally underdamped ($\zeta < 1$) structures (Moore and Maguire 2004). Senegal mahoganies reduced by $\leq 20\%$, on the other hand, may benefit from the increased post-pruning trunk and branch ζ by better dissipating motion energy compared to their unmodified counterparts.

Conclusion

Vibration properties and mass of trees were more affected by pruning on reduced than raised trees. Vibration properties (i.e., f_{n} and ζ) affect a tree's response to wind loads, and these properties only changed on reduced trees. Considering this difference, any post-pruning change in a tree's response to wind loads is likely to be greater on reduced than raised trees. For reduced trees, the results suggest that the mechanical benefits of pruning are realized at low severities ($\leq 20\%$). In addition to the increased f_{n}, the adverse decrease to ζ was minimized after trees were reduced by relatively small amounts, and ζ usefully increased for many reduced Senegal mahoganies up to 20% severity. However, trees with sparse foliage situated near the crown apex, such as the rain trees used in this study, should be reduced carefully by smaller amounts to prevent a large decrease in ζ. This important distinction suggests that pruning treatments should take into account the unique branch and leaf attributes of each species, but there is a need for additional studies on pruning-induced changes to the vibration properties of other species.

It is important to recall that pruning affects other aspects of wind-tree interaction. Per unit mass removed, existing studies of smaller trees reported that drag-induced bending moments decreased more on reduced than raised trees (Smiley and Kane 2006; Pavlis et al. 2008). These observations, combined with the increase in frequency observed in this study, indicate that the likelihood of failure should decrease more for reduced than raised trees at a given severity of pruning, but it remains unclear whether pruning actually reduces the likelihood of failure in major wind events (Kane 2008). Our ongoing work to quantify the effect of pruning on wind-induced tree movement aims to address this important issue.

The long-term effects of pruning on the mechanical properties of trees were not studied in this project. In future work, it will be important to examine post-pruning changes to mechanical properties as trees grow over longer periods to determine the duration of the effects caused by pruning. This will inform the intervals over which tree pruning should be repeated. It is also important to remove branches in a way that minimizes infection of pruning wounds by wood decay fungi. More work is needed to examine the effect of pruning on tree health and vitality, and future studies should evaluate methods to maximize the mechanical and biological benefits of tree pruning.

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Compliance with ethical standards

Conflict of interest statement The authors declare that they have no conflict of interest.

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