

An evaluation of the stability of *Quercus lobata* and *Populus fremontii* on river levees assessed using static winching tests

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Tree stability is of great importance not only in forestry, but also in other contexts, such as dam and levee integrity. Extensive damage to New Orleans after levee failures during Hurricane Katrina in 2005 prompted widespread reevaluation of effects of trees and treefalls on the integrity of levees. We undertook a static winching study of western cottonwood (*Populus fremontii* Wats.) and valley oak (*Quercus lobata* Nee) trees on levees in the California Central Valley. We hypothesized that *Quercus* would be stronger; and that the size-stability relationship for both species would be non-linear. We further hypothesized that critical turning moments would decrease with greater soil moisture and with greater sheltering from neighbouring trees. As expected, the critical turning moments increased with tree size and that relationship was non-linear. Size-controlled critical turning moments of *Quercus* were much greater than *Populus*, but large inter-site variation made the difference non-significant. While the critical turning moments were not significantly influenced by differences in soil moisture, soil bulk density or soil texture for these sites, significant variation among sites suggest that history or unmeasured components of the environment can exert a strong influence on tree stability. Mirroring trends seen in natural wind disturbances of forests, larger trees were more likely to uproot, while smaller trees exhibited a more even mix of trunk breakage and uprooting. Pulled trees with greater abundance of very close neighbours showed no differences in critical turning moments compared with trees with no nearby (i.e. within 5 m) neighbours. The largest trees had critical turning moments exceeding 1 million newton-meters, demonstrating that large healthy trees in unrestrictive soil conditions can be extremely stable. While the maximum turning moments reported here are above those reported in the literature, when corrected for size, the trees of this study were in the upper range but not beyond turning moments previously reported, suggesting that open-grown trees may not have critical turning moments that greatly exceed those of forest and plantation trees.

Introduction

Tree stability or windfirmness has been extensively studied in the context of forestry, owing to concern over loss of growing stock and therefore revenue when production forests are blown down.^{1–3} Static winching tests,² mathematical modeling,⁴ and wind tunnel research with scale models^{5,6} have been employed to examine the critical turning moment or M_{crit} , each approach having advantages and disadvantages relative to the others. Static winching tests are perhaps the most widely used of the above approaches, and have been conducted on trees in production forests in the U.K. (reviewed in⁷), Finland,⁸ Canada,^{9,10} New Zealand,¹¹ France,¹² Japan¹³ and the U.S.¹⁴ In contrast, static winching studies are very rare in non-forestry contexts. While some winching studies have been conducted in street and residential areas¹⁵ the absence of winching studies in powerline corridors, on dams and levees, or other places where treefall is a major concern, is surprising, given the economic and societal importance of understanding tree stability in these non-forestry contexts.^{16–18}

The well-known damage to New Orleans from Hurricane Katrina in 2005 occurred in part because of the failure of several levees, prompting a resurgence of scrutiny of levees and any factors that might influence their integrity. In the U.S., there was increased discussion of whether or not trees had detrimental effects on levee integrity. In response to this concern, and because California has >2000 km of levees, more than any other state, the California Levee Vegetation Research Program (CLVRP) was formed in 2009, to coordinate and facilitate several related studies of the effect of woody vegetation on levees. One of several questions that the CLVRP sought to address was how likely it might be that winds typical of the Central Valley of California might cause levee trees to blow over and if so, the size of the root pit that might be created. These likelihoods could then be weighed against potential benefits of trees on levees (as, e.g. providers of riparian habitat, increasing resistance to erosion, etc.) to allow more informed management decisions on where and when existing trees might be pruned or removed. This study is one component of the CLVRP research effort.

Both observational and manipulative studies have shown that tree stability in forest contexts is influenced by a multitude of factors, but because many conditions on levees differ from those in forests, it remains unknown whether such factors have similar effects on levee tree stability. First, tree size is one of the most important influences, because strength of both the trunk and root system is closely related to tree size and because tree size simultaneously influences the force imposed on a tree by wind.³ In particular, bending stress is inversely proportional to the cube of diameter;³ if root strength follows a similar relationship to trunk diameter, then *theoretically* overall tree stability as estimated by M_{crit} should be a non-linear function of diameter. Yet, *empirically*, some studies show a strong relationship between M_{crit} and the square of diameter;⁸ numerous others have found that stem volume or tree mass best predict M_{crit} ^{4,14,19} and still others found that the simple linear relationship (dbh versus M_{crit}) best described the relationship.²⁰ Indeed, some empirical studies that have encompassed the largest size range⁹ found a linear relationship. Therefore, studies that sample trees across a very broad size range would be particularly informative about the shape of the size-stability relationship and which measures of tree size are most closely related to tree stability. Second, tree species differ in wood strength, crown and root architecture, rooting depth and numerous other factors that also influence stability.²¹ Such differences should be apparent in static winching studies, but only a few have winched two or more species in the same stands and results are inconsistent. Elie and Ruel¹⁰ found only slight differences in small size classes between jack pine (*Pinus banksiana*) and black spruce (*Picea mariana*); Meunier *et al.*²² and Achim *et al.*²³ found no differences between balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*); and Byrne and Mitchell⁹ found no differences between western red cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*). In contrast, and in the only such study to include angiosperms, Peltola *et al.*⁸ found that birch (*Betula* spp.) was consistently stronger than Scots pine (*Pinus sylvestris*) or Norway spruce (*Picea abies*), but their conclusions were based on a sample size of only 11 birch trees. In this study, it was expected that the stronger wood and deeper rooting of *Quercus* would lend it greater stability than *Populus*. Third, tree stability may vary with changes in soil characteristics such as saturation and bulk density. Although these soil factors have demonstrable and intuitive influences on forest trees, there has been no investigation of how stability varies with soil characteristics, on engineered soils of dams or levees. And fourth, the neighbourhood of a tree is expected to influence its stability, because trees with fewer neighbours experience more frequent sub-critical wind impacts during development and therefore adapt by allocating structural resources to increase stability.^{24,25} Levee trees generally grow in much more open surroundings than forest or plantation trees; so they may be expected to show greater stability than forest trees. Therefore, this research addressed the following questions:

- (1) How does tree stability vary with tree size (which size measures are the best predictors of M_{crit}), and between the two most common species in this area, *Quercus lobata* and *Populus fremontii*?
- (2) What is the influence on tree stability of variation in levee soils texture, bulk density and moisture?

- (3) What is the influence on tree stability of variation in neighbour density?
- (4) When levee trees uproot, what are the sizes and depths of root pits created?

Because of the use of heavy equipment to provide pulling force for the larger trees, this study reports M_{crit} values for trees far larger than any previous study and thus can address the above questions across a broad size range (diameter at breast height 13 cm–128 cm).

Materials and methods

Description of study site and winching experiment

Two of the most common tree species found on Central Valley levees (*S. Chainey*, personal communication) were chosen as the primary focus for this study: western cottonwood (*Populus fremontii* Wats.) and California valley oak (*Quercus lobata* Nee), henceforth referred to by their genus names. Numerous other native and introduced tree species are found on California levees, but are far less common. Locations of the static winching tests were chosen subject to availability of sites where winching was considered unlikely to present any danger of imminent levee failure. Five sites within the Central Valley of California were utilized, located in Stanislaus, Sutter and San Joaquin counties; however, because one site had only *Quercus* ($n=6$), analyses of covariance presented below will be based on the four sites with both species present (referred to as Bear, CC, Nel and SJR). All sites were at similar elevations (e.g. <30 m in all cases) and had similar wind climates²⁶ as well as similar precipitation levels.²⁶ The sites encompassed a variety of sandy, low-clay-content substrate materials that are common in California Central Valley levees. The findings reported here therefore are likely not representative of tree stability on levees with much higher clay contents.

Within the study area, trees that were selected for winching had to be in positions where the apparatus could operate and have straight trunks free of major visible defects. Winching was accomplished using procedures consistent with previous studies (Figure 1). A point of attachment was chosen as high as possible on the trunk, for attaching the apparatus. For trees <45 cm dbh, the following setup was used. A short (2 m) nylon 'collar' strap (7.5 cm width, two ply) was wrapped around the pulled tree and then linked to the longer pulling straps and cable via a 1" diameter steel tractor clevis hitch. Depending on distance to the anchor tree, 1 or more 10m nylon pulling straps (7.5 cm width, two ply; rated working load limit 30 000 lbs) were attached to the steel cable and hand winch (Tirfor model T532, rated to exert up to 8000 lbs of pull). For the smallest trees

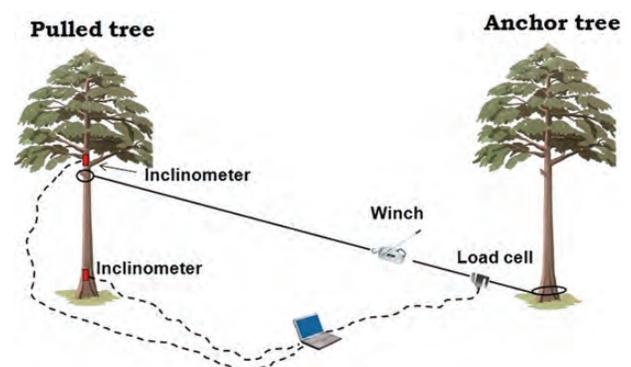


Figure 1 Schematic of the layout of static winching apparatus.

(< 20 cm dbh), the steel cable was pulled directly with the winch; for larger trees (20–45 cm dbh), a snatch block (pulley; working load limit 16 000 lbs) was attached to the end of the nylon strap furthest from the pulled tree and the steel cable doubled around the snatch block and attached to the front of the winch. This roughly doubled the pulling ability of the hand winch. The rear of the winch was attached to the load cell, which was in turn attached to the anchor tree with a 2 m nylon strap (7.5 cm width, two ply) around the base of the anchor tree. Thus the load cell measured all in-line force without being affected by doubling the steel cable around the snatch block. Two inclinometers (US Digital model A2) were attached to the pulled tree, one just below (within 10 cm) the point of ‘collar’ strap attachment and one at 1.5 m above the ground. Inclinometers measured departure from vertical at their respective locations and relayed by wire (wireless inclinometers were not available) the readings every 0.5 s during the winching to a laptop computer. The load cell (Straightpoint model Radiolink Plus, rated to loads of 20t) wirelessly transmitted strap tension every 0.5 s to the laptop computer. Readings from both inclinometers and the load cell were recorded in simple text files along with a time stamp and were later temporally aligned so that force and tilt were known for every 0.5 s of the winching process. Once this setup was established, tension was taken up from the strap and the tree winched until failure. Several trees were excluded from analyses: eight *Quercus* (most <20 cm dbh and all < 25 cm dbh) and one *Populus* (dbh 18.2 cm) bent sufficiently that the upper inclinometer exceeded 50° from vertical; computer or winching equipment failed on three trees (a 34.5 cm dbh *Populus*, a 47 cm *Quercus* and a 29.4 cm *Populus*). On two additional trees, low branching required attaching the strap rather low on the trunk (e.g. 4–5 m) and the hand winch (52.0 cm *Populus*) or bulldozer (71.0 cm *Quercus*) could not provide sufficient absolute force to topple the tree. All trees >45 cm dbh were pulled using either a bulldozer (Caterpillar D6 series) or excavator (Caterpillar 370 series) to provide the pulling force; consequently, this study reports findings from larger trees than have been previously utilized in static winching tests. The above apparatus was modified as follows: much larger-capacity nylon ‘collar’ straps (10 cm width, four ply) were used to wrap the point of attachment on the pulled tree; the strap linking the pulled tree to the bulldozer or excavator was 25 cm width and four ply (working load limit 78 000 lbs), and 30 m long. For these trees, the load cell was attached between the 30 m strap and the bulldozer/excavator; so it again measured all force exerted. An unknown small fraction of the force exerted by the hand winch or by the bulldozer/excavator undoubtedly went into stretching the nylon straps (it is assumed the stretching of the steel cable was negligible), thus the actual force against the pulled tree will be slightly less than that measured by the load cell. Plotting of critical turning moment versus trunk dbh for trees pulled by the different methods (Figure 2) revealed no systematic bias owing to the source of pull; so trees pulled by the different methods were pooled in analyses. In all cases, the distance and vertical difference in height of the point of attachment on the pulled tree and the winch or bulldozer/excavator, were measured prior to pulling. Once a tree failed (either in the trunk or root system), the fallen tree was measured for total height, height of the bottom of the crown and crown width at the widest point. Pulled trees were cut into 1 m sections and weighed, to determine the vertical distribution of mass and the center of mass of the tree. Trees were typically pulled across the slope of the levee. In a few cases, circumstances did not allow this and trees were pulled downslope; examination of the critical turning moments of those trees revealed no systematic differences from trees pulled across slope (data not shown) and therefore both groups of trees were pooled for subsequent analyses.

The effect of neighbouring tree density was quantified by measuring the size of any neighbours within a 5 m radius of the winched tree; neighbour basal area (cm²) was totaled, as well as distance-weighted basal area (basal area/distance in m) and all three neighbourhood variables

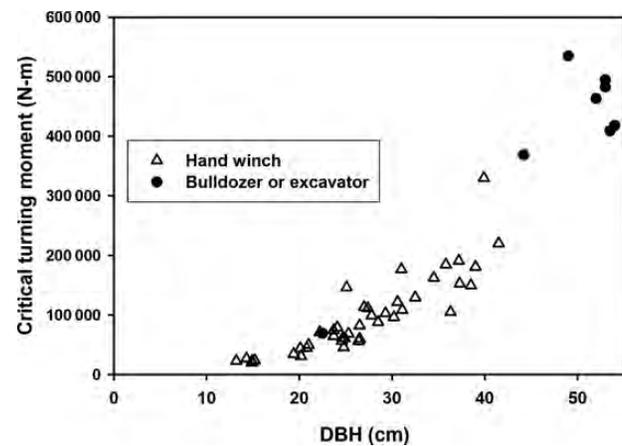


Figure 2 Critical turning moment versus trunk diameter at 1.3 m (dbh), for trees <55 cm, grouped by the source of pull (hand winch or bulldozer/excavator). In the interest of clarity among smaller sizes, trees > 55 cm have been excluded. Note that only one tree pulled by heavy equipment (22 cm dbh) overlaps the size range of those pulled by the hand winch.

were included as potential predictors of critical turning moment of the winched tree in statistical analyses described below.

This study appears to be one of only a few (see, e.g. the small sample of birch in Peltola⁸, also Kane and Clouston¹⁵) to present findings from winching tests with broadleaf trees. Because these trees often divide into several trunks in the upper part of the crown, it was seldom possible to attach the strap at the desired one-half of tree height. Consequently the attachment height was lower than in most studies of similar sized conifer trees.

Analyses of effects of soil characteristics on tree stability

Soil influences were examined by conducting measurements of soil moisture immediately after a successful winching and for a subset of trees, by excavation of 2–3 soil pits (1 m deep) around the base (2 m distant). Soil moisture of the upper soil horizon was measured in three locations roughly 1 m from the base of the tree using a Hydro-Sense time-domain reflectometer, which quantified volumetric water content in the upper 20 cm of soil. Because soils differed only modestly in particle size and structure, readings from the TDR are likely to be consistent among the study locations and therefore can be directly compared without extensive calibration. Soils were sampled at similar horizons at each site (40, 70 and 100 cm below surface; ~2 m from the base of the pulled tree) for in-situ bulk density, using the sand cone method (ASTM D 1556; www.astm.org; Certified Material Testing Products, Palm Bay, FL). Replicate soil pits were located equidistant around the tree or, in cases of space restrictions such as neighbouring trees, rocks or roadways, located perpendicular to the direction of the pull. Soil texture and bulk density data were averaged for whole profiles at each tree and also analyzed by horizon to evaluate the composite set of soil parameters indicative of the rooting environment of that tree. It should be noted that all trees reported here were growing on levee-impacted soils rather than native, undisturbed soils. These levee impacts include traffic compaction, additional sediment deposition, increased drainage adjacent to a deepened channel and displaced material from recent and historic levee construction.

Particle-size distribution analysis of soil samples from the excavated sand cone cavity was carried out using a Beckman–Coulter LS-230 laser-light diffraction particle-size analyzer²⁷ to obtain estimates of sand

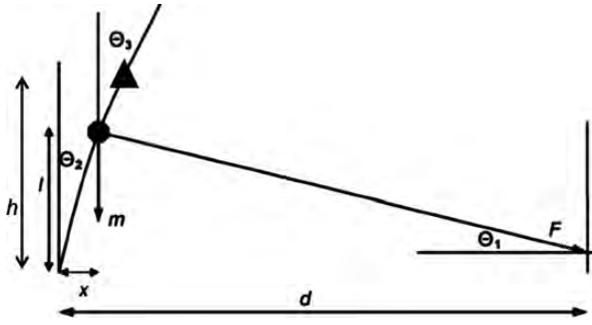


Figure 3 Explanation of measurements used in calculation of turning moment. Adapted from.⁷ Black triangle on pulled tree indicates center of mass. F = measured force in the winch + strap combination. D = distance between pulled tree and anchor tree. L = height of strap attachment on pulled tree. θ_1 = angle of strap with horizontal. θ_2 = stem deflection from vertical measured by lower inclinometer. θ_3 = stem deflection from vertical measured by upper inclinometer. h = height of center of mass. x = horizontal displacement at height of attachment and at moment of maximum force.

(200–50 μm), silt (50–2 μm) and clay (<2 μm) content. Field samples were dry-sieved to <2 mm and then subsampled by compositing multiple 0.2 g subsamples to obtain a one gram analytical sample. The analytical samples were placed in 25 mL glass vials; inundated with 20 mL of distilled, deionized water, sealed and placed on an orbital shaker table (at 12 revolutions per minute) for 24 h before analysis.

Analytical methods

The critical turning moment at the base of each pulled tree was calculated as in previous studies (Figure 3), summarized by Nicoll *et al.*⁷ The maximum force applied in the strap and the tilt of the tree from vertical at the moment of maximum force, was used in the following calculations. Total turning moment (M_{critical} , $\text{N} \cdot \text{m}$) is the sum of M_{applied} and M_{weight} , where M_{applied} represents the force resulting from pulling on the strap and M_{weight} represents the additional bending moment resulting from the mass of the tree itself once it has moved from vertical. M_{critical} is calculated when the maximum load is reached. M_{weight} is calculated as:

$$M_{\text{weight}} = mx \quad (1)$$

Where m is tree weight (N) and x is the horizontal displacement (m) of the tree at the time of maximum force. M_{applied} is calculated as:

$$M_{\text{applied}} = F \times \cos(\theta_1) \times h \quad (2)$$

Where F is the total force (N) applied by the winch and strap, θ_1 is the angle of the strap relative to horizontal and h is the height (m) of the center of mass of the tree at time of maximum load. Note that h becomes somewhat less than the height of strap attachment on the pulled tree, as the pulled tree deflects further from vertical. The values of x and h were calculated based on the inclinometer readings at the time of maximum load. Because trees under wind loads are not a straight beam rotating at the base and because bending increases with tree height, the best approximation of tree deflection from vertical was taken as the mean of the two inclinometer readings. While this could slightly over- or underestimate M_{critical} depending on trunk stiffness, the approach used here is consistent with previously published static winching studies.⁷

Statistical data analyses

The effects of study site, type of treefall (uprooting versus trunk break), tree species, tree mass, neighbour density (sum of neighbour basal area), soil moisture (volumetric water content), soil bulk density and proportions of sand, silt and clay on critical turning moment were tested using an analysis of covariance (ANCOVA), with site, type of treefall and species as categorical variables and the others as covariates. Because one of the original five sites had only *Quercus* ($n=6$), those trees were excluded from the ANCOVA to avoid confounding between site and species; major conclusions were not altered by this precaution. Tree mass was used as the measure of tree size for consistency with previous studies.⁷ Because the proportions of sand, silt and clay sum to unity, only the proportions of sand and clay were used in the ANCOVA. Subsequent to the ANCOVA, to test whether others measures of tree size better predict M_{crit} , simple linear regressions were run separately for *Populus* and *Quercus*, between M_{crit} and dbh , dbh^2 , dbh^3 , stem volume ($\text{dbh}^2 \times \text{total height}$), total tree height, stem taper (ht dbh^{-1}) and tree mass (kg).

For study trees that uprooted, dimensions of the pit were measured on two perpendicular axes incident and orthogonal to the direction of pull and these measurements used to calculate area, approximated as an ellipse. Pit depth was also measured (a single measurement of the deepest point in the pit), but rarely did the pit three-dimensional shape resemble any regular geometric solid (e.g. ellipsoid); so depths are presented separately and pit volume not calculated. The influence of tree, soil and neighbour characteristics on pit area and pit depth was tested with two analyses of covariance (ANCOVAs), with pit area and pit depth as the response variable, respectively; pulled tree species as the categorical main effect; and percent clay, percent sand, neighbour basal area, soil bulk density, soil moisture and tree mass as the covariates.

Results

Study trees encompassed an especially broad range of sizes, from 13 cm to 128 cm dbh and from 7 m–28 m tall; *Populus* reached the greatest diameter among the study trees, while the tallest were *Quercus*.

A total of 66 trees on levees were successfully winched: 21 *Populus* and 45 *Quercus*; of these 39 *Quercus* were used in analysis of covariance testing below. Thirty-five trees uprooted (11 *Populus*, 24 *Quercus*), while 31 trees experienced trunk breakage (10 *Populus*, 21 *Quercus*). The trees excluded owing to equipment failure or low branching were roughly evenly distributed between species and across sizes. Moreover, the fact that several small trees (e.g. < 20 cm dbh) had to be excluded because they deflected extensively without breakage or uprooting, suggests that small trees may avoid damage in high winds owing in part to their ability to deflect surprisingly far, in addition to lower wind velocities nearer the ground.

Winched trees generally had few nearby neighbours. The mean number of neighbours within 5 m of a winched tree was 0.6, with a range from 0 to 4; the mean sum of neighbour basal area was 317.2 cm^2 , with a range from 0 to 2285.1 cm^2 . The sum of distance-weighted neighbour basal area had a mean of 144.3 and a range of 0 to 1243.7. Thirty-seven of the winched trees had no neighbours within 5 m.

Effects of tree size and species on tree stability

Critical turning moment was significantly influenced by both tree size and study site, but not by type of tree failure, soil

characteristics or neighbour tree density (Table 1). Species differed substantially in critical turning moment, but the high inter-site variation led to the large interspecific differences being non-significant. Among the four study sites, critical turning moments adjusted for covariates were 185.5 ± 53.9 (SE) $\text{kN} \cdot \text{m}$ for Bear, 360.7 ± 78.0 $\text{kN} \cdot \text{m}$ for CC, 164.2 ± 48.4 $\text{kN} \cdot \text{m}$ for Nel and 231.3 ± 74.7 $\text{kN} \cdot \text{m}$ for SJR. Analysis of covariance revealed significant increase of critical turning moment with tree mass ($P < 0.0001$) (Table 1, Figure 4). When adjusted for the covariates, critical turning moments were 323.1 ± 28.6 (SE) $\text{kN} \cdot \text{m}$ for *Quercus* and 147.7 ± 61.3 $\text{kN} \cdot \text{m}$ for *Populus*. Type of treefall had no significant effect: least square means (adjusted for covariates) of critical turning moment were 260.8 ± 40.3 (SE) $\text{kN} \cdot \text{m}$ for trunk broken trees versus 275.5 ± 37.0 $\text{kN} \cdot \text{m}$ for uprooted trees. No significant effects were

found for soil bulk density, percent clay, percent sand, summed neighbor basal area or soil moisture level ($P > 0.1$ in all cases). All five measures of tree size were significant predictors of critical turning moment for both *Populus* and *Quercus* (Table 2). For *Populus*, regression R^2 values increased from dbh to dbh^2 to dbh^3 , while for *Quercus* the R^2 was similar for dbh, dbh^2 and slightly lower for dbh^3 ; both species exhibited the highest R^2 for stem volume or tree mass. Because of the large sizes included in this study and the steep increase in larger size classes, critical turning moments approached 1.5 million $\text{N} \cdot \text{m}$ for the largest *Populus* (128 cm dbh) and approached 1 million $\text{N} \cdot \text{m}$ for the largest *Quercus* (75 cm dbh).

Table 1. Analysis of covariance parameter estimates for M_{crit} , critical turning moment.

Source	Deg. free	Sum Sq.	Mean Sq.	F	P
Site	3	1315.5	438.50	7.29	0.001
Species	1	66.83	66.83	1.11	0.300
Fate	1	37.24	37.24	0.62	0.437
BulkDen	1	71.14	71.14	1.18	0.285
PctClay	1	125.53	125.53	2.09	0.159
PctSand	1	72.66	72.66	1.21	0.280
NbrBA	1	1.71	1.71	0.03	0.867
Soilmoist	1	5.45	5.45	0.09	0.765
Treemass	1	9690.20	9690.20	161.10	0.0001
Error	31	1864.90	60.16		
Total	42				
Covariate Summary					
Covariate	Coeff.	Std. Error	T	P	
Bulk	-10.500	9.651	-1.09	0.285	
PctClay	6.676	4.622	1.44	0.159	
PctSand	0.578	0.526	1.10	0.280	
NbrBA	-0.0004	0.002	-0.17	0.867	
Soilmoist	0.080	0.267	0.30	0.765	
Treemass	0.004	0.0003	12.69	0.0001	

Soil characteristics

Soil moisture had a mean of 24.8% ($\pm 13.8\%$, SD). These soils were far from saturated for most of the study trees, despite the research being conducted during California's rainy season (January and February). The soils supporting these trees had bulk densities averaging $1.58 \text{ g} \cdot \text{cm}^{-3}$ with a range from 1.26 to $1.98 \text{ g} \cdot \text{cm}^{-3}$. Particle size averaged 63.0% sand, 31.2% silt and 3.8% clay. The most common textural classification was sandy loam (43% of locations), with loamy sand (25% of locations), silt loam (22%) and sand (6%) textures also

Table 2. Summary of linear regressions of critical turning moment versus various measures of tree size, by species.

Size measure	<i>Quercus</i>		<i>Populus</i>	
	R^2	P	R^2	P
dbh	0.864	< 0.0001	0.831	< 0.0001
dbh^2	0.864	< 0.0001	0.886	< 0.0001
dbh^3	0.814	< 0.0001	0.900	< 0.0001
$\text{dbh}^2 \times \text{height}$	0.864	< 0.0001	0.947	< 0.0001
Taper ($\text{ht} \text{ dbh}^{-1}$)	0.428	< 0.0001	0.566	0.0001
Tree height	0.493	< 0.0001	0.658	< 0.0001
Tree mass	0.927	< 0.0001	0.930	< 0.0001

For *Quercus*, $n = 39$; for *Populus*, $n = 21$.

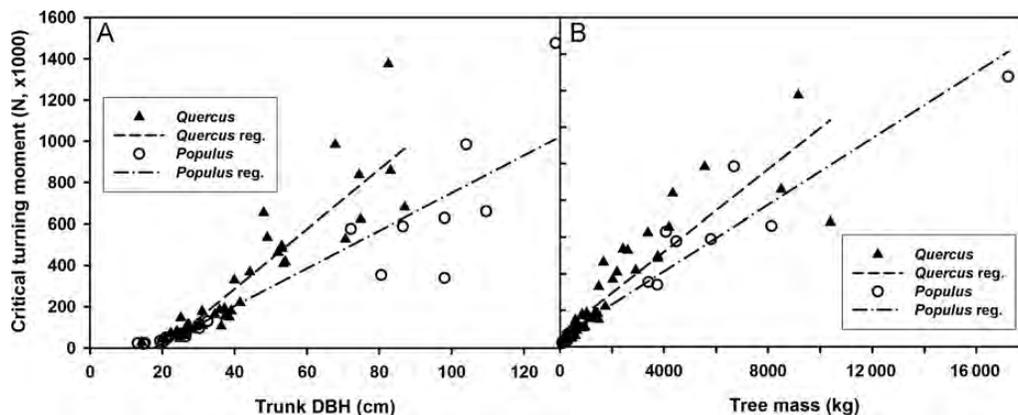


Figure 4 Critical turning moment versus trunk diameter (A) and tree mass (B), by species. Note that turning moment is given in $\text{N} \cdot \text{m} \times 1000$.

occurring. Using soil parameters pooled across depths, there was no significant relationship between turning moment and soil bulk density, soil moisture, or percent sand or percent clay ($P \gg 0.1$ in all cases). Similar analyses were also performed for the 70 cm depth data, because that depth appeared to have less surface variability and disturbance but frequently had the greatest root density (personal observations). As with the pooled depth analysis; however, turning moment had no significant relationship with soil parameters from the 70 cm depth. In addition, selected pairs or groups of trees with similar dbh values but different turning moments were also screened for differences in texture or bulk density, but none were significant ($P \gg 0.1$ in all cases).

Effects of tree size and species on root pits and type of treefall

Uprooted trees created root pits with a mean area of 4.11 m² (± 2.86 , SD) and root pit area increased with trunk diameter (Figure 5). Root pit area did not differ between tree species and was not significantly related to any soil characteristics or neighbour basal area (Table 3). However, pit area was significantly influenced (positively) by tree mass (Table 3). Root pit depth had a mean of 1.01 m (± 0.44 m, SD); the maximum was 1.50 m. Like pit area, pit depth was not significantly influenced by tree species or soil characteristics or neighbour basal area, but did vary significantly (positively) with tree mass (ANCOVA, $P > 0.2$ for all predictor variables except $P = 0.041$ for tree mass).

Finally, tree size (measured as dbh) significantly influenced the type of tree failure. Logistic regression of type of failure (uprooting versus trunk breakage, coded as 1 and 0, respectively) against tree dbh showed a significant relationship (Figure 6), with increasing probability of uprooting as dbh increased. Unexpectedly, type of tree failure may have been influenced by neighbours: trees that failed by uprooting were less likely to have neighbours within 5 m (5 trees with neighbours, out of 35), compared with trees that failed by trunk breakage (18 out of 31).

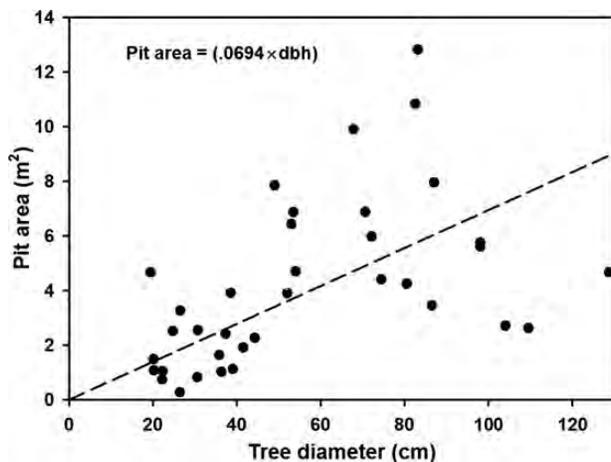


Figure 5 Root pit area (in m²) versus trunk diameter at 1.3 m (dbh), for trees that uprooted. Simple linear regression line and equation shown.

Table 3. Analysis of covariance parameter estimates for pit area.

Source	Deg. free.	Sum sq.	Mean sq.	F	P
Site	3	56.37	18.79	3.45	0.052
Species	1	0.301	0.301	0.06	0.818
PctClay	1	8.198	8.198	1.50	0.244
PctSand	1	8.965	8.965	1.65	0.224
NbrBA	1	4.329	4.329	0.79	0.390
BulkDen	1	0.227	0.227	0.04	0.842
Soilmoist	1	10.989	10.989	2.02	0.181
Treemass	1	17.844	17.844	3.28	0.095
Error	12	65.378	5.448		
Total	22				

Covariate Summary				
Covariate	Coeff.	Std. Error	T	P
PctClay	3.622	2.953	1.23	0.243
PctSand	0.367	0.286	1.28	0.224
NbrBA	-0.002	0.003	-0.89	0.390
BulkDen	-0.930	4.557	-0.20	0.842
Soilmoist	0.196	0.138	1.42	0.181
Treemass	0.0003	0.00001	1.81	0.095

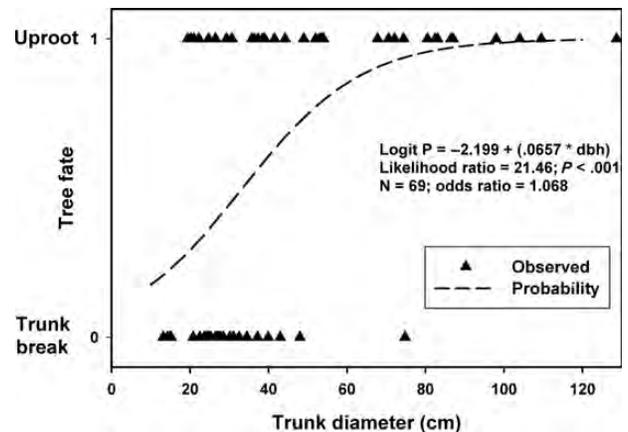


Figure 6 Distribution of fates of winched trees (uprooted versus trunk broken) versus trunk diameter at 1.3 m (dbh). Logistic regression results shown in text; dashed line shows back-transformation of logistic regression results to simple probability of uprooting.

Discussion

Broadly speaking, levee trees exhibited trends similar to those shown in static winching studies of forest trees.^{2,7} This simple observation increases confidence in the findings of this first study of trees on extensively engineered substrates. As seen in previous studies, critical turning moments increased with tree size, and species exhibited substantially but not significantly different (at similar size) critical turning moment.^{7,8} Not surprisingly, *Quercus* tended towards greater resistance than *Populus* (e.g. covariate-corrected means were nearly twice as large for *Quercus* as for *Populus*). This may be expected for a species with relatively stronger wood (modulus of rupture for *Quercus* = 60250 kPa, versus 34000 kPa for *Populus*²⁸; MOR

value estimated as mean of eight species in the white oak subgenus given in Table 5.3a of Kretschmann²⁸) and white oaks of western North America are generally considered to have deep and broad root systems.²⁹ However, the tendency for species to differ was nevertheless not significant owing to very large inter-site differences in critical turning moment.

The substantial variation among sites was unexpected, particularly in light of the lack of effects of the measured soil characteristics (soil moisture, bulk density and particle size distribution) or of neighbourhood. Several previous studies show variation among sites, but generally such variation has been readily explained by features that are obvious, such as the difference between well-drained and poorly-drained soils.^{20,30} The wind climate of these sites is very similar²⁶; so it seems unlikely that the history of wind exposure explains differences among sites in critical turning moments. More likely is that deeper rooting in some sites appears restricted to vertical cracks in deeper layers of the substrate (*V. Claassen*, personal observation), while other sites have less-constrained rooting. Such differences could explain inter-site variation but remain to be rigorously documented.

Several studies of root pit formation in forests^{31–33} (see review in Schaetzl *et al.*³⁴) report a general trend of increasing pit size with tree size. This study confirmed such a trend for levee trees, although pit depth was extremely variable and the shape of the divot did not allow volume calculations. Some of the largest diameter trees had pit areas rather less than expected and all of these trees were *Populus*, suggesting that the major roots of large *Populus* may cover less area than the roots of similarly-sized *Quercus*. If true, this trend would help explain the greater tendency of the largest trees to uproot rather than break.²¹

A unique aspect of this study is the range of sizes included among the winched trees; the larger trees substantially exceed the largest tree sizes used in previously published static winching studies.⁷ As a consequence, it is possible in this study to examine the size-stability relationship across a broader range of diameters than has previously been possible. Such an examination shows that for both species, tree mass is the best predictor of critical turning moment, confirming the non-linearity of the relationship. The result was extremely high critical turning moments for trees near or beyond 1 m dbh – the highest being 1476 kN * m (*Populus* 128 cm dbh), 984 kN * m (*Populus* 104 cm dbh), and 983 kN * m (*Quercus* 67.8 cm dbh). It remains unknown if other species of similar sizes would have similar critical turning moments when growing in these environments.

There is reason to expect that surroundings could strongly influence tree stability for large trees, because trees growing in dense stands (e.g. forests) will generally have had shelter and load-sharing with neighbouring trees³⁵ for much of their lives and thus may have grown into a much slenderer form than levee trees that have been mostly unsheltered throughout their lives. Similarly, trees growing in irregular stands showed greater resistance to uprooting than those in regular stands²⁴ and trees in windier locations are more windfirm than those growing in less windy situations.²⁵ However, this study did not reveal any impact of neighbour abundance on M_{crit} . The most parsimonious explanation is that the range of neighbour abundances represented by trees in this study was limited to low-values (i.e. most of the pulled trees had no neighbours within

5 m) and that therefore these trees were all in relatively open surroundings compared with forest and plantation trees. Moreover, in comparison with trees in previously published studies, when controlling for size, the trees in this study were in the upper range of critical turning moments but not beyond those previously reported. For example, Moore¹¹ reported maximal M_{crit} of 650–675 kN * m for trees roughly 65 cm dbh; and Lundström *et al.*¹⁹ reported 850 kN * m for trees roughly 70 cm dbh. These may be some of the largest reported in previous literature. In more commonly-reported size classes, Urata *et al.*³⁶ found a maximum M_{crit} of 29 kN * m for trees 18 cm dbh and Kamimura *et al.*²⁰ reported 72 kN * m for trees 21.6 cm dbh. All of the above are similar to values found in this study for similar-sized trees. Numerous other studies^{23,22,24,30} report M_{crit} that are somewhat to much less than the values found here for similar-sized trees. The implication of these findings is that while growing in more open surroundings may have contributed to somewhat greater stability of the levee trees, the levee trees are not outside the range of stability found in forest or plantation trees of similar size.²⁵

Nicoll *et al.*⁷ reported that rooting depth can significantly influence tree stability in forest contexts. The coarse sandy textured soils in this study did not appear to consistently limit root growth to less than 80 cm, which was the deepest category used by Blackwell *et al.*³⁷ However, several substrates did have sufficiently hard and massively structured substrates such that root growth was significantly constrained to vertical cracks. Other sites contained significant volumes of cobble up to 20 cm diameter, which confounded soil strength estimation based on fine (<2 mm) textural classification. While the effect of soil particle size distribution and bulk density on tree rooting strength and turning moment is not discounted in general, these study sites had relatively coarse-textured substrates. These conditions, in addition to other uncharacterized, levee-related features (e.g. subsurface vertical fractures, cobble and depositional lenses), created sufficient variation that the effect of differences in texture and bulk density within the study sites was obscured, and therefore was not significantly related to rooting strength as measured by critical turning moment.

Soil moisture is also a factor with potential to influence root anchorage and therefore tree stability^{30,38} Ecological studies have presented mixed results; while several report greater wind damage in stands with wet soils (see review in Everham and Brokaw³⁹), others^{40,41} explicitly report that areas with saturated soils did not suffer greater damage. A more focused and experimental study was recently published,²⁰ showing that Japanese hinoki (*Chamaecyparis obtuse*) had reduced root anchorage when soils were experimentally rapidly supplied with water in an attempt to mimic heavy rainfall events. In light of all of the above, it seems likely that the lack of a soil moisture influence on M_{crit} in this study may be simply because the highest levels of soil moisture were still well below saturation. The implication is that soil moisture levels may indeed influence tree stability, but in a complex fashion; for upland soils that are typically not saturated, soil moisture may have little discernible effect on tree stability until very high levels of soil moisture are reached.

This study revealed a very significant trend towards greater likelihood of uprooting in the largest size classes.²¹ As trees progress into large size classes, the increase in flexural strength of

the trunk with small increments of diameter becomes substantial, given that trunk resistance increases with the third power of diameter, while anchorage increases usually as $DBH^2 \times$ height.⁸ Indeed, expected trunk strength yielded very high values for the large trees, several of which exceeded two million N*M. This expectation can be calculated on the basis of diameter and modulus of rupture³:

$$m_{\text{break}} = \left[\frac{\pi}{32} \right] \times MOR \times dbh^3 \times \text{knot factor} \quad (3)$$

where *MOR* = modulus of rupture (N), *dbh* is in meters and *knot factor* is an adjustment to reduce expected trunk strength owing to knots and other wood defects (a value of 0.75 was used here for *knot factor*, based on;³ this value is for conifers because no analogous values are available for angiosperm trees). It may be that near the maximum of tree size, root system strength does not increase as rapidly as trunk strength, thereby shifting the dominant mode of tree failure to uprooting instead of trunk breakage. Obviously, extensive rot in the trunk would nullify such a trend, although it is notable that one of the *Populus* with unusually low critical turning moment (tree diameter = 98 cm and $m_{\text{critical}} = 341$ kNm) had substantial trunk rot, but nevertheless uprooted rather than snapped. This suggests that the influence of rotting on tree stability will depend strongly on the relative strength of the root system versus trunk (as previously noted by¹⁴), with the consequence that whether a tree breaks or uproots will be a result of whether trunk or root system has experienced greater decomposition.

Conclusions and practical applications

The very large critical turning moments of the larger trees used in this study imply that substantial winds would be necessary to overturn large healthy *Populus* and *Quercus* on these levees. Moreover, such stability should be robust across a range of surrounding neighbour densities and among differing soil characteristics, but inter-site variation in critical turning moments was large, showing that tree stability is a composite feature of not only tree characteristics, but site variables beyond the soil moisture and soil particle size that were measured here. Management of the risk of tree failure on levees can be guided by several of these inferences, e.g. that risk of tree failure is unlikely to increase as a result of modest amounts of precipitation if soils remain unsaturated. Conversely, the increase in tree stability that results from thinning in forest contexts is unlikely to have a similar benefit for levee trees. And when large levee trees fail, they are likely to uproot and remove a major fraction of coarse roots from the substrate, thus altering the potential for water seepage through root channels, as well as removing a source of cohesion within the levee substrate. However, these levee trees are at the upper limit of stability or beyond for a given tree size, compared with forest trees, suggesting that levee conditions and adaptive growth in a mostly-open setting result in strong anchorage compared to many forest trees.

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