BLOWING IN THE WIND: STORM-RESISTING FEATURES OF THE DESIGN OF TREES

by Steven Vogel

Abstract. Many of the features of trees represent arrangements that minimize the chance that they will uproot when exposed to high winds. At least four schemes, singly or in combination, keep the bases of trees from rotating in the face of the turning moment imposed by the drag of their leaves. Trunks and petioles are relatively more resistant to bending than to twisting, giving good support but permitting drag-reducing reconfiguration in high winds. Leaves curl and cluster in a variety of ways, all of which greatly reduce the drag they incur relative to the values for ordinary thin and flexible objects such as flags. However, information derived from measurement and experimentation about such mechanical matters is still quite limited.

Wind is caused by the trees waving their branches.
—Ogden Nash

Quite often, the mechanical failure of a tree is a result of wind and thus of a sideways force rather than the downward action of gravity. Since such a lateral force comes mainly from the drag of the leaves, the center of force must be well above ground level. As a result, the lower portions of a tree will face a substantial turning moment that may cause it to snap or uproot. That turning moment is the product of its drag, centered in the crown, and the moment arm of that force, very nearly proportional to its height. (Gravitational loading, by contrast, should most often lead to Euler buckling and thus fracture well above the ground.) Healthy trees fail both by snapping and uprooting. Which type of failure predominates varies greatly with both kinds of trees and habitats. Indeed, the scarcity of reported cases in which either one or the other represents over 90% of failures (see, for instance, 7,15,21) implies an impressive balance of risks in the construction of trees, with a good match between strengths of stems and anchorage.

To put the matter in personal terms, how might a tree in a competitive situation achieve both an acceptably low chance of mechanical failure and an acceptably low investment of material? Shortening the moment arm—growing less tall—is a viable option if its neighbors do likewise; after all, growing tall brings no single tree appreciably closer to the sun. But such a cooperative height-limitation treaty isn't something at all likely among unrelated individuals for reasons deeply rooted in the competitive character of their interactions. Improving anchorage by altering the character of the substratum is only slightly more likely, at least at the level of the individual. The principal variables left for manipulation are thus the drag of the leaves, the size and material properties of the trunk, and the geometry of the roots as a system of anchorage.

What follows is a somewhat speculative analysis of the mechanical components involved in keeping a tree from uprooting in a severe wind. I'll work upward from the roots, alluding to data where they are available, but connecting what's known with some unavoidable guesswork. At the start, it should be made clear that the guesses should be viewed skeptically. Where we have done specific measurements, we've found that the designs of trees work in humblingly subtle (one is tempted to say clever) ways. Furthermore, the very success of the mechanical design of a living system such as a tree may effectively disguise the fact that it has managed to solve daunting problems of engineering.

Roots as Anchorage

While no systematic study has yet been done, at least 4 distinct schemes seem to be used to keep roots and soil in decent contiguity. Combinations of more than a single scheme certainly occur, and a given tree may use different schemes or a varying mix of several as it grows from a sapling. (Ennos and Fitter (6) provide information on anchorage in small plants or very young trees.) We might look in turn at each.

Compressive buttressing. Uprooting most often involves elevation of a large weight of roots and associated soil. Increasing the work necessary to achieve that elevation decreases the chance that a tree will blow over. One arrangement for doing so involves the development of a stiff, wide base so the pivot point or axis of turning is well aside the center of trunk and root mass (Figure 1). The key component, then, is a broad base that acts primarily as a set of buttresses on the downwind (compression-loaded) side, pushing the pivot point laterally and thus increasing the work needed for turning. On the upwind side, it will secondarily help as a contribution to the weight that must be lifted as the tree is turned. For simplicity, we might refer to the scheme as "compressive buttressing." Partly burying the broad base improves matters by using the substratum to increase the weight that must be lifted. Soil and stone are conveniently dense material, so a small volume goes a long way. Beneath the tree the substratum is subjected to compression, which under most circumstances will be well resisted. The effectiveness of the arrangement is improved if the trunk is stiff, minimizing downwind drift of the center of gravity in the wind. The paradigmatic case of such compressive buttressing might be a large specimen of an oak such as *Quercus alba* or *Q. robur.* It may well be the most important arrangement used by the large angiosperms of temperate North America, and it is certainly not uncommon among gymnosperms that lack vertical tap or striker roots, as indicated by work on Sitka spruce (1,3).

Tensile buttressing. Trees usually described as buttressed, occurring mainly in tropical rain forests, appear to make little use of compressive buttressing. Their conspicuous buttresses are simply too high and broad for their thickness, limiting their ability to withstand compressive loads without buckling. Instead, the buttresses work in quite the opposite way from the masonry buttresses of Gothic architecture with which they are visually analogous. According to Mattheck and Bethge (11) and Ennos (5), they are tension-resisting structures, as shown in Figure 2. The scheme, then, might be termed "tensile buttressing." These tensile buttresses transmit and redirect the forces on the upwind side of a trunk to the roots. Thus, the upwind roots are strongly loaded in tension, almost certainly more strongly than those of trees using the first scheme. Soil, of course, has almost no tensile strength of its own, but the general tangle of roots just beneath the surface in a rain forest ought, in practice, to permit resisting substantial tensile loads. And stabilizing the center of gravity with a very stiff trunk should be less important than in compressive buttressing, a significant factor for the very tall, thin trunks of the trees that form the canopy of a rain forest. Trees that rely mainly on tensile buttressing will usually be inappropriate for planting in isolation.

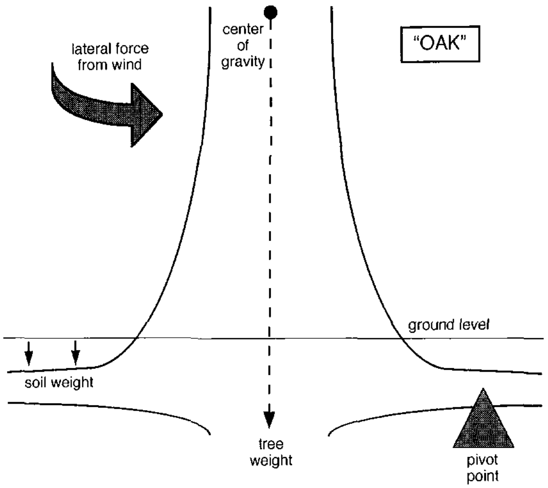

Figure 1. The factors involved in compressive buttressing.

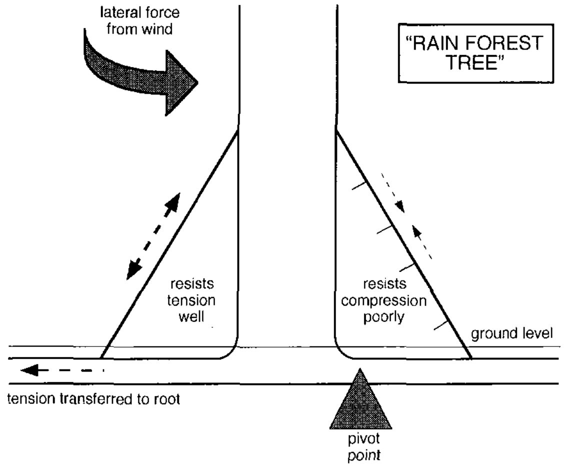

Figure 2. Tensile buttressing.

Taprooting. An alternative scheme capitalizes on little more than the ability of soil to withstand compressive force. If the trunk is continued downward beneath the soil as a stiff taproot, and if ramifying lateral roots near the soil's surface fix the location of the tree, then pushing the trunk in one direction will push the taproot in the other (4). Soil, especially when beneath a layer of superficial roots, ought to resist this sideways push quite well; the scheme, which we could call "taprooting," is shown in Figure 3. Again, good resistance of the taproot to bending, a high level of so-called flexural stiffness, is crucial, as is sufficient broad-side area to push against rather than penetrate sideways through soil. (Additional substantial vertical "striker" roots (14) may supplement the mechanical role of taproots.) A tree that uses the scheme without a healthy taproot is crippled. In over 25 years only 1 tree of the stand of over 70 loblolly pines (*Pinus taeda*) around my house has blown over with less than really severe provocation; that one had a rotted taproot. My casual observations of several excavated pines suggest that taproots may develop noncylindrical cross sections in response to wind from a prevailing direction. The relative importance of taprooting is perhaps the least certain of that of the schemes mentioned here.

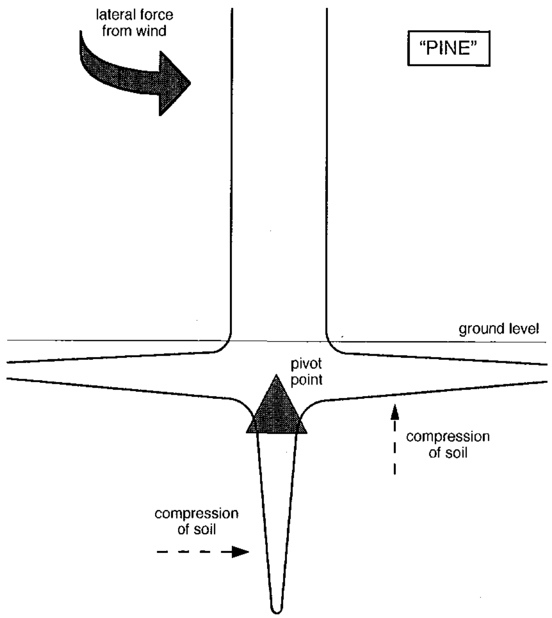

Figure 3. Taprooting.

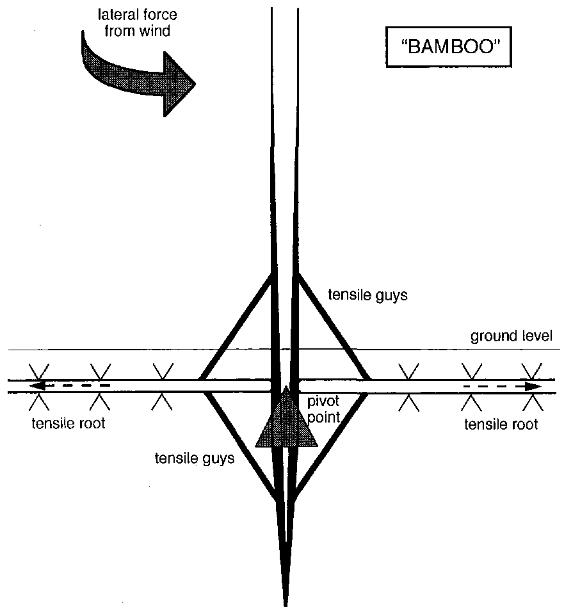

Figure 4. Diagonal guying.

Diagonal guying. One further scheme that is rare in true trees but certainly can keep upright woody structures of comparable height is the culms of bamboo. These use what amounts to a variation on tensile buttressing that we can call "diagonal guying" and which is shown in Figure 4. Here again, tensile forces on the upwind side are transmitted through tension-resisting structures to lateral roots, the lateral roots must withstand substantial tensile forces, and a dense tangle of other roots in the superficial layer of soil must be a distinct advantage. The diagonal guying of bamboo is relatively symmetrical above and below the lateral roots, with a taproot and a set of guying roots below as well as above. The scheme seems especially elegant in using ropes rather than solid buttresses for guying, since in a tensile buttress the most lateral region will carry almost the entire load. But the otherwise admirable ability of at least dicotyledonous trees to grow in girth probably renders ropes impractical. The guying ropes would need not only to grow but would have to be gradually shifted further outward from the base.

Trunks and Force Transmission

Different schemes for anchorage make somewhat different demands on trunks. Note the particular role of the weight of a compressively buttressed tree in keeping it upright, at least if it's large and stiff enough to use its weight to oppose the turning moment caused by the drag of the leaves. Even though a hollow cylinder can be very nearly as resistant to bending as a solid one, with this scheme a hollow and thus less weighty tree will be less able to stay erect in a wind than will a solid one. Furthermore, stiffness will be an especial virtue due to its role in keeping the center of gravity above the base. In general, a structure that is built to a criterion of adequate stiffness is more than amply strong (9); together with the positive role of weight, this may explain what look like excessively bulky trunks in many isolated trees. Maximizing weight and minimizing sway will be much less important for trunks of trees that use any of the other schemes.

One additional reason for a generous investment of material in a trunk is that some level of mechanical damage must be tolerable—damage caused by insects, beavers, and fungi; imbalance from loss of branches; and so forth (12). Reconstruction may go on, but storms cannot be postponed until the process is complete.

Most tree trunks are very nearly circular in cross section, a form that ordinarily gives very good resistance to both twisting (torsional) and bending (flexural) loads. I-beams or cylinders with lengthwise grooves, for instance, resist bending much better than they resist twisting. A case can be made that trees ought to behave more like the latter, bending with difficulty but twisting relatively more easily—first, because bending may contribute to uprooting or direct breakage, and second, because twisting might reduce the bending load itself by allowing branches and leaves to reorient in ways that reduce drag.

Relative resistance to twisting and bending is a property, not only of the cross-sectional shape of a beam or column, but of the material of which it is made. Dry wood cut from the trunks of trees has a twistiness-to-bendiness ratio 5 to 15 times higher than that of simple materials such as metals (2). It is now clear that the high range of values is not an artifact of cutting and drying but characterizes fresh, intact trunks as well. Indeed, very similar values are obtained for softwoods, hardwoods, and even bamboo culms (Table 1). Conversely, roots and vines do not yield such high values. Thus, even without noncircular cross sections, trunks twist more easily than they bend; this convergent specialization is appropriate for the particular loading regime faced by tree trunks (20).

Further information about the mechanics of trunks and branches is given by Mattheck (10).

Table 1. Twistiness-to-bendiness (flexural stiffness over torsional stiffness) ratios (from 14).

Material	Ratio
trunks, bamboo culm	7.6
roots	2.3
woody vines	3.6
aluminum cylinder	1.3

Leaves and the Minimization of Drag

Exposing a large area of leaf surface to sun and sky must be the most important facet of the design of a tree. Thus, a high level of drag a long way above the substratum appears unavoidable—but at least high winds are typically intermittent and most commonly associated with low light intensity. However, the situation may be worse than it appears at first glance. Stiff structures of great area require great material investment. Flexible structures of great area take less material but suffer much more drag. A flexible flag of ordinary shape experiences an order of magnitude more drag than does a rigid weathervane of the same shape and area.

What, then, might a tree do about the drag of its leaves? The first indication that trees don't simply endure a lateral force on their crowns that increases with the square of the wind speed came in 1962 from measurements on a pine (*Pinus sylvestris*) in a very large wind tunnel (13). Drag increased with an exponent of less than 1 (0.72) rather than the expected 2.00 up to a speed, 38 m/s or 85 mph, at which the tree started to shed pieces (16). With increasing wind the tree reconfigured its form, with needles and then branches coalescing into clumps. Instead of being a pure liability, as in a flag, flexibility is at least in part a virtue in the upper portions of a tree.

Such reconfiguration isn't limited to pine needles that bend inward toward their twig. More spectacular and at least equally effective temporary and reversible changes of form occur in broad leaves as well. The leaves of holly *(Ilex opaca)* turn sideways by bending their petioles and end up as a tightly pressed sandwich of laminae on top of their twig (16). A wide variety of leaves are marked by relatively long petioles and stem-ward protruding lobes on each side of the attachment of petiole to blade (Figure 5). The arrangement occurs (probably convergently) in at least 15 families of plants. These, at least all that have been wind tunnel tested, roll upward into cones whose open apices point upwind toward the stem and which become tighter (more acute) as the wind speed increases (Figure 6). These cones are stable in even highly turbulent flows. They open and close quickly enough to respond to even brief gusts, and they're associated with levels of drag much closer to that of a weathervane than of a flag (18). Drag even a little lower (relative to leaf area) is achieved by pinnately compound leaves, again to the extent (2 species) that these have been tested. The leaflets bend and curl upward, interacting to form elongate, hollow cylinders just above their common rachis.

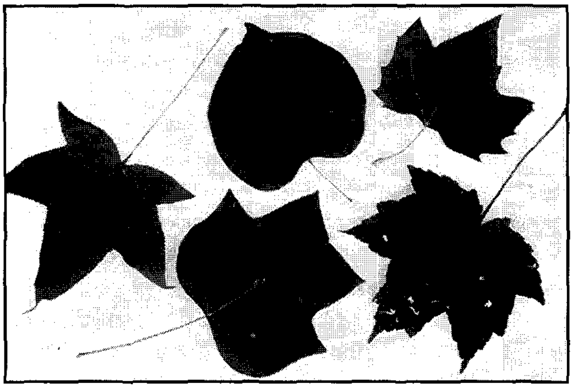

Figure 5. Leaves that reconfigure into cones in strong winds—sycamore, red maple, redbud, tuliptree, and sweetgum.

Groups of leaves reconfigure as well, often forming tight, conical clusters with lower overall drag (again relative to area) than achieved by individual leaves of the same species. For some trees, such as white oak, the individual leaves aren't especially effective in reconfiguration, but they do relatively well

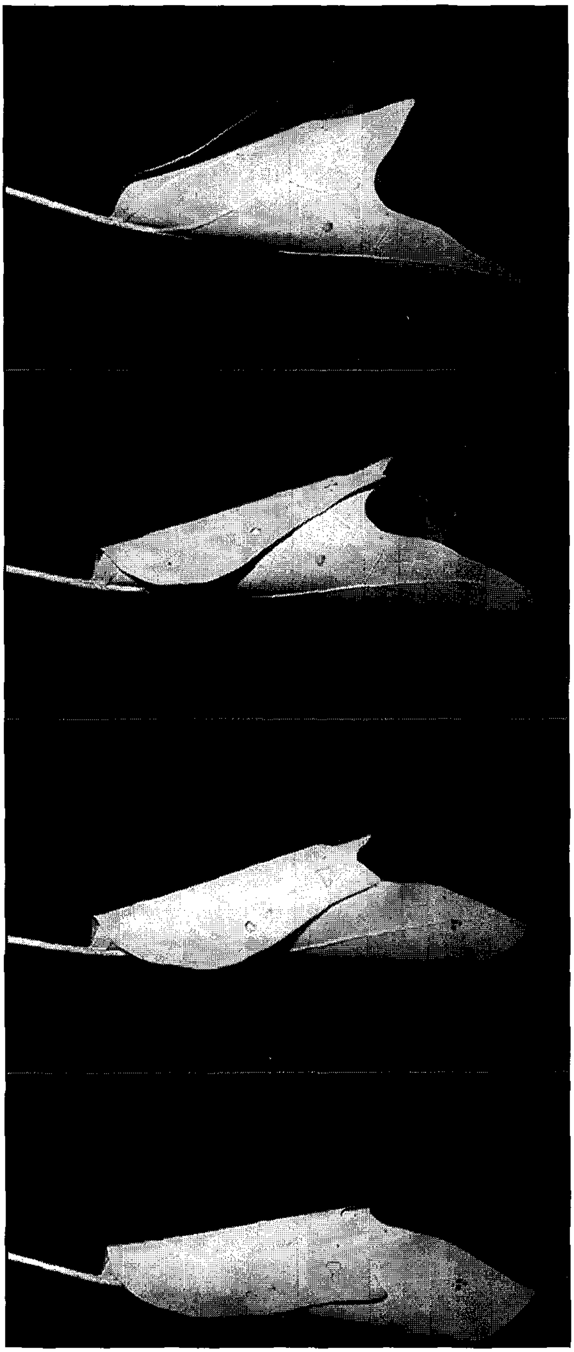

Figure 6 (from top to bottom). A leaf of tuliptree (yellow-poplar) in turbulent winds of 5 (11), 10 (22), 15 (33) and 20 (44) m/s (mph).

as groups. Such oaks, in any case, may derive a compensatory advantage from their less extreme reconfiguration. In modest winds, they maintain their normal, skyward orientations where others, such as maples have begun to turn and flutter. In general, some instability at low speeds seems to be associated with good facility for dealing with higher winds. The shimmering of quaking aspen *(Populus tremuloides)* leaves may just represent the low-speed instability associated with an especially good ability to reconfigure stably (in its case as multileaf clusters) in strong winds. At least that's the indication gained from work with the congeneric white poplar *(P. alba)* (18).

To reconfigure into clusters, petioles must be able to twist. But to support protruding leaves, they have to work as cantilever beams and resist bending. Thus petioles, like trunks, ought to have a high ratio of twistiness to bendiness. And indeed they do. Whereas the trunks achieve a high ratio by manipulation of their material, the petioles do so by adjusting geometry as well. Short petioles in particular quite often have lengthwise grooves on top, side-to-side flattening, or other kinds of noncircular cross sections that effectively increase that ratio (19).

Perspectives and Prospectives

If a central theme pervades this analysis, it is how nature uses flexible structures—leaves, branches, trunks, and roots. Human technology mainly uses more rigid materials—metals, ceramics, dry wood, and so forth. We thus have little experience in designing things that change shape in strong winds, and we reveal our underlying prejudice when we speak of "deforming" rather than the less pathological "reconfiguring." Quite beside learning about the trees themselves, a careful look at the mechanics of their wind resistance ought to reveal the subtle tricks possible when flexibility is embraced and treated as a complex, multidimensional, and positive phenomenon. The flexible structures and materials that make up trees not only twist and bend but do other things as well. They can absorb and either store or dissipate energy. They can change properties reversibly or irreversibly over time scales from seconds to years. They can engage in complex trade-offs among properties that the engineers call strength, stiffness, extensibility, toughness, and so forth. We might just learn things from this unfamiliar but certainly effective technology.

Even in a given habitat, trees are a diverse lot. Almost nowhere has one design emerged as clearly superior. Parts of the explanation must lie in the very large number of factors involved in standing up to the wind and the number of functions to which each structural element must contribute. That may make the world a great deal more attractive and provide a wide range of arboricultural options, but it certainly complicates any analysis. One should perhaps begin by looking for recurring arrangements such as those noted here—the long petioles with basal lobes of many leaves and the high twistiness-to-bendiness ratio of trunks. Such convergent patterns (ones that don't simply reflect common ancestry) are a first indication of functional significance.

What is especially striking about the present topic is the very limited amount of experimentally based information in the primary scientific literature of fields such as botany, agriculture, and forestry that might naturally address its questions. We know a great deal about wood—cut and cured—but far less about trees. To the extent that work is being done, a relatively large contribution is coming from people outside of the traditional plant sciences. Of those cited here, Gordon and Mattheck come from engineering; Ennos and I are biologists who began by working on insect aerodynamics. General background for the subject is easily available from paperback books such as those of Gordon (8) and Vogel (17). The questions are neither scientifically arcane nor practically irrelevant.Neither do they present particular technical difficulties or expense. Indeed, addressing many of them is so cheap and easy that good basic work should be quite practical for nonacademic arboriculturists working avocationally.

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Zusammenfassung. Viele Eigenschaften der Bäume stellen ein Arrangement dar, welches verhindert, daß sie, wenn sie starken Winden ausgesetzt sind, zu entwurzeln drohen. Zumindest vier Schemata, einzeln oder in kombination, bewahren die Basis der Bäume vor einer Rotationsbewegung angesichts des Kippmoments, wenn die Blätter starkem Winddruck ausgesetzt sind. Stämme und Blattstiele sind gegenüber Verbiegen relativ widerstandsfähiger als gegenüber Verdrehen, was ihnen zwar einen guten Halt gewährt aber belastungsreduzierende Gestaltsveränderungen unter starkem Windeinfluß erlaubt. Blätter rollen sich und wachsen in Büscheln in verschiedenen Variationen, welche alle großteils die Belastung, der sie ausgesetzt sind, reduzieren - vergleichbar mit den Werten von gewöhnlichen flachen und flexiblen Objekten wie Flaggen. Aber die Informationen über solche mechanischen Eigenschaften, die aus diesen Messungen und Experimenten resultieren, sind immer noch sehr begrenzt.