How-To-Do-It

Wind Stress

An Experimental Investigation into the Structure-Function Relationship of Leaf Architecture

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Can a noisy electric leaf blower turn on your science students with a multipurpose experiment investigating functional plant morphology? Will students learn and use leaf terminology and tree species identifications? Our trials with students and secondary school science teachers answer "yes" to all of the above.

Plants display an amazing variety of leaf forms. At one extreme are the firm, evergreen, needle-like leaves of some conifers and at the other extreme are the large, soft, twice-compound leaves found in species such as Kentucky coffee tree, honeylocust and devil's walking stick. Evergreens are not necessarily needle-leafed, as evidenced by the familiar holly tree or southern bull bay magnolia. Deciduous leaves can be soft, such as those of cherry trees; or quite firm, as in many oak species. Some trees have very large rounded simple leaves, as found in catalpa; while the large leaf size of other trees is the result of compound structure where each leaf is composed of several leaflets. The leaves of weeping willow and Bradford pear are both simple and of similar length, but contrast markedly in shape, texture and leaf area.

In the mid 1980s, biomechanist Dr. Steven Vogel presented a seminar to the Duke University Department of Botany showing the responses of leaves from various species of trees to wind stress. The height, size and leaf area of trees provide obvious competitive advantages in light capture, but these architectural features also subject trees to potential problems: blowdowns exacerbated by drag on leaf surfaces (Vogel 1996; Mayhead 1973); leaf damage caused by wind forces acting on flexible structures (Vogel 1989); and desiccation associated with sustained winds. In a wind tunnel, Vogel subjected freshly collected leaves of various tree species to wind stress. He used stop frame photography to study the role of different leaf architectures on reconfiguration in wind and to evaluate the effect of leaf morphology on drag (Vogel 1989). Vogel's experiments employed various non-leaf controls including rigid metal plates and flexible plastic sheets.

Tree species with pinnately compound leaves, such as walnuts, and species with pinnately arranged simple leaves in close linear arrangements, as found in sourwood, experienced less drag than did species with distantly spaced simple leaves. However, the relationship of drag to wind speed was species-specific. In addition, simple leaves of some species such as those of tulip poplars and red maples could roll into cone-like shapes that channel wind down the leaf blade without harm. In contrast, the firm leaves typical of oaks provide a rigid structure that confers resistance to movement in low winds but that is susceptible to mechanical damage at higher wind speeds (Vogel 1993).

The experiments Vogel outlined left a lasting impression because they highlighted the structure-function relationship, suggested potential biomechanical limits on leaf design, and presented an experimental approach to interpreting leaf architectures. Moreover, if students were to use such an experimental approach, they would learn different leaf arrangements (alternate versus opposite; simple versus compound; broad leaf versus needle-like) and leaf textures (soft, firm, hairy) as a by-product of conducting a rigorous experiment, rather than as an end point in a descriptive lesson on leaf terminology geared toward tree identification. In the process of formulating a specific question on leaf architecture, students must select and identify tree species from which they will collect samples. Therefore, learning tree species names and using leaf terminology are integrated into the students' experiments on leaf design.

Natural selection for different leaf types undoubtedly involves many factors. The behavior of leaves in wind is likely one of those factors. Leaves with a large surface area may be efficient for photosynthesis, but if those leaves are easily damaged by wind, the plant must expend extra energy to produce replacement leaves. The goal of this exercise is to determine experimentally if particular leaf characteristics are especially resistant or vulnerable to wind stress. Careful examination of leaf architecture and learning to identify species by leaf type are two desirable by-products of a dynamic experiment on wind resistance.

Methods

The major obstacle to performing an experimental investigation of leaf architecture is the lack of access to wind tunnels. Professional quality wind tunnels can be relatively expensive and they may require considerable permanent space allocation. Our early attempts to construct portable, inexpensive alternatives using home box fans failed because wind force was too low and not well-concentrated on the leaf blades. We attempted to construct a "makeshift" tunnel to narrow the wind path and thereby increase speed, but these *ad hoc* wind tunnels were

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either opaque if built of cardboard, metal, or wood, or they tended to collapse if constructed from transparent plastic. A colleague suggested an ingenious alternative—electric leaf blowers whose wind speeds can exceed 150 mph and which can be purchased for less than $30 each. These leaf blowers provide high wind effects without the need for an enclosing tunnel.

The experimental system consists of a leaf blower (inexpensive models work fine) with two nylon string cross hairs across the exit nozzle (Figure 1). Masking tape is sufficient for holding the cross hairs in place. A short (<4 cm) string tied to the intersection of the cross hairs is used to attach the leaves, with masking tape wrapped around the end of the leaf petioles. This simple attachment holds the leaf onto the string at even the highest wind speeds. An optional rheostat or variable voltage regulator between leaf blower and power source permits adjustment of wind speeds. The blowers are noisy, so safety earplugs may be necessary if more than a few are operated indoors simultaneously.

The simple experimental system presented here provides great flexibility, so that many aspects of the wind-leaf relationship can be investigated. Once students have been introduced to the experimental setup and to basic leaf types, the class can be divided into groups of three to six students. Each group is asked to formulate and test one aspect of this multifaceted question: How are different types of leaves affected by wind? Each group should be asked to select an experimental design that specifies the variable to be tested. An appropriate control should be included in their design, the number of replicates required should be considered, and they must plan a method to measure the degree of leaf damage sustained in each test.

In our classroom trials of this experimental procedure, we found that students choose to test a wide range of questions involving leaf structure and wind stress. Many students compare differences in wind endurance of simple versus compound leaves. Some groups of students proceed by choosing one species possessing each leaf type, collecting several leaves from a single individual of each, and subjecting those samples to the wind test. The minimal sampling in this design is inherently flawed, but highlights some important aspects of experimental design. With only a single species representing each leaf type, conclusions cannot be general but must be restricted to differences between those particular two species. Furthermore, one individual of each species cannot be representative of the entire species so the conclusions must be further restricted to differences among two individual trees rather than among trees with simple and compound leaves! Nevertheless, allowing students to construct and test their own hypothesis provides experience in designing experiments which can be followed with a discussion of potential modifications that would more precisely test the chosen hypothesis. Beginning with their own simple experiments, students step up to the practical and theoretical considerations of empirical research.

Another approach which students choose is to lower wind speed, to assess a minimum below which no damage is apparent. For example, our tests showed the highest speeds we generated caused no observable damage to pine needles, but these wind speeds shredded buckeye leaves. This result suggests that needle-leafed species are less susceptible to wind damage than broad-leaved species, but more species within each category

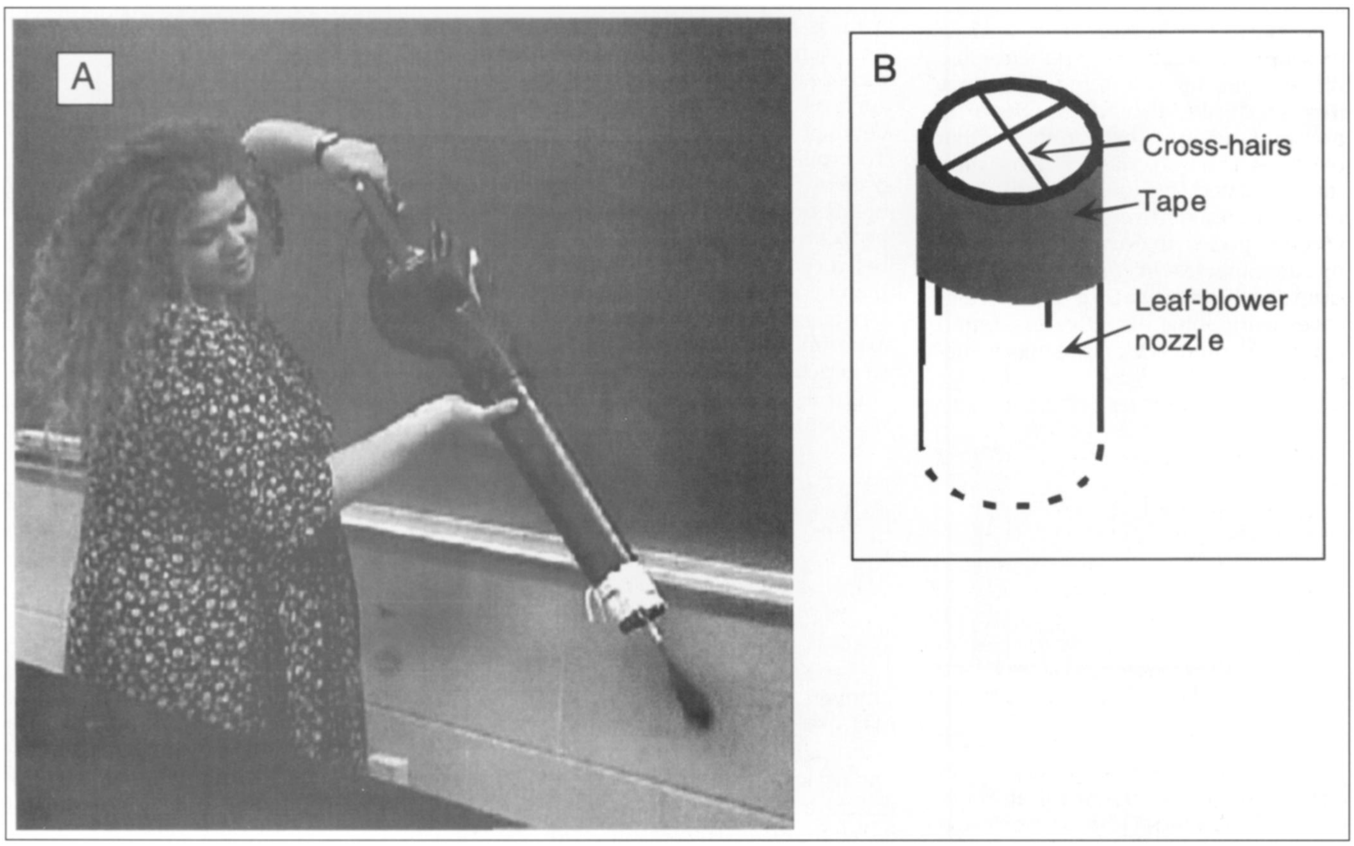

Figure 1A. A student demonstrates the leaf blower experimental system. 1B. Diagram of leaf blower exit nozzle showing cross hairs attached with tape.

must be tested to support a general conclusion. Some student groups in our classes tested the effect of increasing duration of sustained wind on sycamore leaves. They found that a threshold was present below which no damage occurred and above which damage was sudden and severe, primarily manifested as breaking off of the terminal lobes (Figure 2). Subsequent discussion led to the conclusion that the drying of the leaves by high wind resulted in the delayed breakoff of the leaf lobes. Other student groups tested the hypothesis that smaller leaves are more wind resistant than larger leaves. Accordingly, they sampled different leaves from individual trees of one species, but their results unexpectedly showed that the larger leaves were less susceptible to damage. A full class discussion brought out the important point that small leaves were likely to be immature, and therefore less likely to have developed fortifying fibers, leaving them more susceptible to damage. Again, the discussion was valuable in highlighting the need for a follow-up experiment because the initial design confounded two variables: leaf age and leaf size.

Some students may wish to test a more ecological rather than morphological hypothesis. For example, leaves of subcanopy and mature forest interiors may be expected to experience less intense selection for wind resistance because of the protective effects of the forest canopy. The hypothesis that interior species are less wind resistant can be tested by comparing leaves from a representative sample of forest interior species to leaves of old field invader species. A related question could use house plants to ask whether leaves with long drip tips, as found in tropical rain forests, are more susceptible to tip wind damage than leaves with blunt tips. Regardless of the question addressed, the nature of the experiment leads to a lively discussion when each group presents its hypothesis, design and results. Therefore, adequate class time should be allotted for questions and discussion after the groups have completed their experiments and analyzed their results.

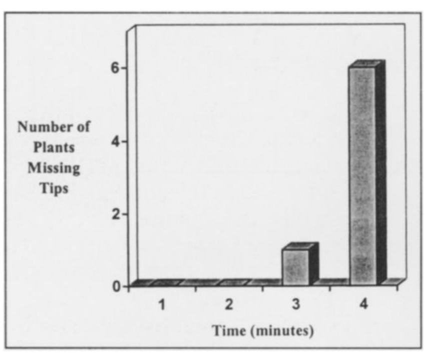

Figure 2. Number of sycamore leaves with missing tips after wind stress of various duration. Six leaves were tested for each time period. The plot illustrates a non-linear relationship between time of stress and tip loss.

Controls & Data Collection

A particular benefit of the wind stress experiment is that it lends itself to involvement of students in all aspects and stages of experimental design. At the outset, students must decide on the appropriate test unit, which may consist of individual leaves with petioles or short sections of branches with one or more attached leaves. They must also select an appropriate control for comparison to the wind-stressed sample. Each leaf before wind treatment can be used as its own control (Figure 3). Students may quantify results by tracing (or electronically digitizing) the leaf outline onto graph paper before testing and then counting the number of squares of leaf area missing after treatment to calculate loss of leaf area due to wind damage (Figure 3). The number of leaf tears is another possible measure for leaf damage that can be refined to include specification of tears to areas such as leaf lobes or leaf sinuses or depth of tear into the leaf blade (Table 1). To provide an alternative or additional control for leaf shape effects, a cardboard or paper tracing of the leaf can be tested. Differences in damage between control and real leaves can then be attributed to structural characteristics of the leaves tested. Thus, the experiment is a vehicle for students to practice with the key concepts of controlled and quantifiable experimental methods.

Leaf Damage Assessment

1. Qualitative Results

To permit wind stress experiments to be conducted by students at lower grade levels and by students with minimal quantitative skills, we suggest a qualitative assessment of susceptibility to wind stress. For example, "leaf tears" and "complete breakage" may be considered different levels or categories of damage (Table 1). Each category of damage can be subdivided into relative degrees of damage such as "few tears" or "many tears." This sort of categorization is somewhat subjective, but it is useful nonetheless, and provides a means to uncover patterns of damage that may be correlated with leaf architecture. The results of these damage ratings can be presented in tabular form which will benefit students who are not prepared for statistical analysis (Table 1).

One qualitative effect of wind stress noted by some of our student groups was the brown-purple discoloration that accompanied sustained wind. A discussion of possible causes led the class to invite the departmental plant biochemist to visit and we learned that the potential causes of discoloration included high rates of oxidation of lysed vacuolar contents and/or breakdown of chlorophylls. Moreover, the students noted that as leaves desiccate, they become more susceptible to mechanical damage. The discussion then turned to factors limiting tree growth in the Midwestern plains states, which prompted the hypothesis that sustained winds may strongly exacerbate the effects of drought caused by reduced rainfall. The desiccation effect can be observed in the change of vegetation as one travels from the eastern deciduous forest to the Midwestern prairies.

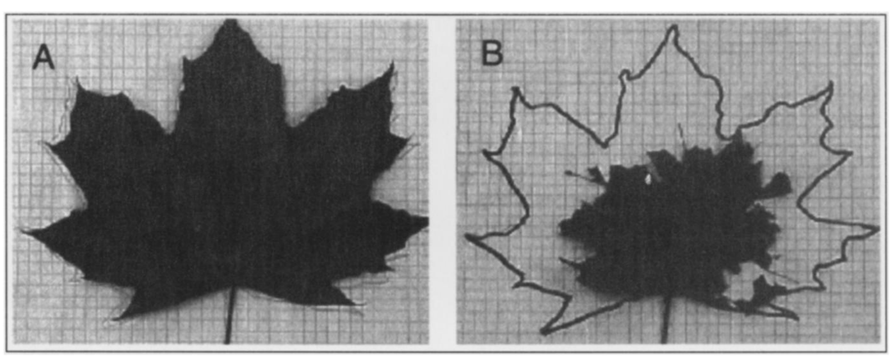

Figure 3. Assessing leaf damage by quantification of leaf silhouettes on graph paper. A. Maple leaf before testing occupies more than half of 451 squares. B. Leaf after testing occupies 163 squares representing a loss of 64% of leaf area.

Table 1. A qualitative method of tabulating leaf damage with an example showing red maple leaves are more likely to tear compared to buckeye leaves which are more likely to break.

			Damage					
			Tears			*Breaks*		
Species	*Leaf Type*	*Leaf Number*	*None*	*Few*	*Many*	*Few*	*Many*	*Shredded*
Red Maple	simple, palmately lobed	1		x				
		2			x			
		3		x				
		4	x					
		5		x				
Buckeye	compound, leaflets palmate	1						x
		2					x	
		3						x
		4						x
		5					x	

2. Quantitative Analysis

An easy, inexpensive and rapid method to quantify leaf area loss would be to trace leaf outlines onto graph paper and express loss as the difference in number of squares greater than 50% occupied or as the number of squares lost (Figure 3). Alternatively, the tracings can be cut out and weighed on a balance with the difference in weight proportional to loss of leaf area. If a group of students chooses to compare two leaf types, a rigorous nested ANOVA can be conducted in which leaves within species and different species are nested within each leaf type. Groups that choose to test hypotheses related to wind time or speed may present data graphically and test for non-linearity by asking whether a curve provides a better fit to the data than a straight line (Figure 2). Experiments with complex designs can be conducted by asking the entire class to test a single hypothesis. For example, a class may choose to compare simple and compound leaves. If a common protocol is used, groups of students can each test a different species and the data can be pooled for synthesis and class discussion. However, it is important to remember that unless methods are rigorously standardized, pooling may introduce an additional source of bias.

Avoiding Anarchy

The windstream and noise of leaf blowers in a classroom may cause concerns for maintaining order during and after the experiment. A reasonable solution would be to first ask each group to design an experiment, collect samples, and prepare them for wind testing. When all groups are prepared, the class can reassemble as a whole with one group at a time explaining its hypothesis and conducting its leaf blower test in the front of the room before the rest of the class. In addition to maintaining discipline, all class members will see each experiment being conducted and each team gets to perform before its peers. After each team has subjected its samples to the wind stress, it can reform into groups to measure leaves and assess damage. The class would reconvene in full to present and discuss results.

Conclusions

The wind stress experiments described above were conducted with both high school teachers in a workshop and in middle school classes. Both groups showed high enthusiasm, both conducted experiments that generated intriguing data, and the results led to lively discussions. The experiments afford students direct, hands-on practice in genuine investigations of structural biology. Students conducting these experiments will learn to work with fundamental but elusive concepts such as experimental controls, sample sizes and replication, and quantification and presentation of results. The open format and flexibility of the basic experimental system—leaves subjected to high wind speeds generated by electric leaf blowers—allows students to use their creativity and critical thinking to invent their own test and address their own hypothesis. In the process, they will acquire the basic terminology of leaf morphology and apply it to broader concepts of plant anatomy, physiology and ecology. Learning to identify and recognize various tree species is a collateral benefit of this process. The "nuts and bolts" of the procedure—tying strings, taping petioles, running loud blowers, and tabulating leaf damage—intrigue and engage many students who might be uninterested in a more conventional presentation of leaf variation. But most of all, this experimental method gives students the experience of original, empirical scientific inquiry. In so doing, it empowers them to observe the natural world with a questioning mind and to use the tools of experimentation to find their own answers.

Acknowledgments

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References

Mayhead, G. J. (1973). Some drag coefficients for British forest trees derived from wind tunnel studies. *Agricultural Meteorology, 27*, 171–184.

Vogel, S. (1989). Drag and reconfiguration of broad leaves in high winds. *Journal of Experimental Botany, 40*, 941–948.

Vogel, S. (1993). When leaves save the tree. *Natural History, 102*, 59–62.

Vogel, S. (1996). Blowing in the wind: Storm-resisting features of the design of trees. *Journal Arboricultural, 22*, 92–98.