Letter from the Desk of David Challinor
February 2006

My interest in giants probably began with childhood tales of Jack and the Beanstalk and David and Goliath. As an adult, this fascination has focused on the limits to growth in natural organisms, and since trees are my special interest, I have delighted in following the recent research that is expanding our understanding of tree growth limits. The ideal subjects for such investigation are the California sequoias—two relict species within closely related genera that once grew around the globe but are now confined to California and Oregon. This month's letter considers the constraints on tree height and, particularly, the problem these giants have of raising water to their crowns.

The world's tallest trees are coastal redwoods (*Sequoia sempervirens*), which tower more than 330 feet (100m); but the biggest existing trees in terms of mass are their close relatives to the east in the Sierras—the giant sequoia (*Sequoiadendron giganteum*). Perhaps the best known sequoia is the Wawona Tunnel Tree, through whose base an arch was cut in the 1880's large enough for a stagecoach to pass through. The tallest current measured tree to date is a coastal redwood at 370'3" (112.87m) and still growing about four inches a year. There is good evidence, however, that until the 1920's a few coastal redwoods before they were cut exceeded the mass of the present giant sequoia record holder.

At first glance, a tree able to raise water to almost 400 feet without pumps seems impossible. We know, for example, that in a continuous unobstructed tube with one end below the water surface at sea level, water can be sucked up the tube to a height of only 30 feet (10m). This is because the water in the tube will then match the weight of the air in a similar-sized tube stretching from the same water surface to the top of the earth's atmosphere. The water in the tube is then in balance with the earth's atmosphere and will remain at that level unaided. To raise water higher in a building, for example, powerful pumps and stout pipes are necessary to offset the pressure from the weight of the water being raised. This phenomenon has long been understood and helps explain why the ancients were puzzled by trees taller than 30 feet being able to raise water above that level without a visible pump, especially on hot summer days when even medium-sized trees transpire (lose to the atmosphere) 50 or more gallons (>190L) daily.

In the XVII century, scientists thought that tree sap circulated similarly to blood flow in animals—up and down and transversely along branches. Nehemiah Green, writing in the 1670's, hypothesized that sap rose through woody tissue in the spring and through the bark in the summer. He wrote that roots took in water by capillary action and that somehow it was raised in the tree stem by the pumping action of parenchyma cells. We know today that these cells arise from the cambium layer just inside the bark.

Initially their walls are soft and the cells expand until their walls harden and further growth stops. When mature, about 90% of parenchyma cells die and become hardwood tissue. The remaining 10% or so (it varies between species) stay alive in the sapwood for a few years. These living cells occur in wood rays, which are bands of parenchyma cells lined up horizontally that radiate out from the first annual ring of the tree. These rays are essential for nutrient transport and storage. Hardwoods have about twice as many rays as conifers. The cells, both living and dead, of the sapwood are the main path of water from the roots to the leaves.

Finally in 1727 Stephen Hales, an English physiologist, experimented with cut sections of both grape vines and small trees. He found that both vines and trees exuded sap in the spring, but that this exudation vanished when the foliage was full. He concluded that "capillary sap vessels imbibe moisture plentifully; but they have little power to protrude it further without the assistance of the perspiring leaves, which do promote its progress." He was the first scientist to grasp the current concept of how sap ascends, although he was not clear about the role of leaf transpiration. Further theories were advanced in the XIX and early XX centuries, all based on a pulsing action of the stem's parenchyma cells that forces sap upwards; all were shown to be invalid. By the 1890's scientists determined that water loss by transpiration from the crown's foliage caused water to be pulled up from the roots and lower trunk, and eventually discovered how cohesive was the water to the cell walls when confined in the small vertical tubes in the trunk's xylem layers, located just inside the cambium and phloem layers.

The cohesion theory explaining sap's upward movement is based on water's high tensile strength and the strong adhesive force of water to the cell walls of the tree's conducting tissue. To simplify the process, picture all the water inside a tree being part of a continuous system. As water rises in the xylem, it has to pass through the walls of connecting cells. The water is thus under tension and slowly rises to replace the water being lost by transpiration from the crown. Scientists still do not fully agree on the fine points of arboreal water transport but, for the lay reader, the cohesion/transpiration theory is a reasonable one to consider for the present.

Understanding the complexities of vertical nutrient transport in a tree is key to explaining what limits tree height growth. To help clarify how the system works, researchers, such as Steve Sillett at Humboldt State University in the heart of California's redwood forests, have developed techniques enabling him and his colleagues to climb to the very top of the world's tallest trees. Heretofore, Smithsonian scientists in Panama studied the canopy of a mature tropical forest whose height is only about half that of a redwood grove's by erecting either a guyed tower in the forest or a tall building construction "T-crane." The latter requires a crane operator to adjust the elevation of a gondola from which scientists take their measurements and observations. Cranes are expensive to build and operate in a tropical forest, but they have proved to be an innovative research tool. Redwoods 300 feet or more high are too tall for either cranes or towers and must, therefore, be climbed.

Sillett uses a modified tree climbing technique developed by arborists who ascend all kinds and sizes of trees as part of their profession. Among mature redwoods, however, the lowest branches are often as much as 200 feet or more high. If the distance from the ground to the first branch is clear, the climber shoots a small line with a weighted arrow attached to the end over the branch and, if on target, the weight carries the line to the ground. Heavier climbing line is then attached and pulled over the branch, which becomes an anchor point. Ascent to the first branch is then made by mechanical ascenders; one connected to the climber's harness and the other to foot stirrups. Once in the crown, one end of the heavy line is attached to the looped line by a Blake's hitch, a special kind of knot developed recently by an arborist in California. This is a friction knot and, depending on how it is manipulated by the climber, can either slide or hold fast. The knotted end is attached to the climber's harness to enable him/her to ascend or descend. Clearly it takes courage, stamina, judgment and much practice to climb to the top of a redwood.

Sillett and his colleagues found that leaves at the top of the crown are much smaller than those near the bottom. Water stress within the leaf cells caused by gravity, and the resistance within the stem cells that carry water aloft for that distance, limit leaf size and photosynthetic efficiency, thus, ultimately limiting growth. It is a remarkably slow process for the water to rise to the crown from the roots. By using dye tracers, scientists have found that it takes more than three weeks to make an ascent of 300 or more feet. The slow crown growth of about four inches a year (10cm) of redwood giants contrasts with that of young redwoods, which can grow two or three feet (60-90cm) annually.

Redwoods are conifers and thus belong to a tree group called gymnosperms (naked seeded or not enclosed in an ovary). The wood structure of gymnosperms differs from that of angiosperms, the other major tree phylum. The water transport cells of the former group seem to be better adapted for water to rise to such extreme heights than the wood of angiosperms; but among the latter, there are at least two species of giant eucalyptus, one growing in southeastern Australia (Victoria) and Tasmania, locally known as Mountain ash (*Eucalyptus regnans*), and the other in southwestern Australia called karri (*E. diversicolor*). The tallest Mountain ash growing in Tasmania is 318'3" (97.0m), but it has a dead top. The tallest with a live top is 302'2" (92.1m) is in Victoria. Fortunately, these trees are now protected and a few centuries hence there may be, once again, eucalyptus giants to rival the redwoods in size.

Redwoods are particularly adapted to longevity and steady growth. The wood is strongly rot-resistant and thick bark protects the stem from lethal fire damage. Fire scars are common, however. When major branches break off near the stem in the high canopy, the large cavities that result collect water. Over time fungi reduce some of the cavity wood to soil-like consistency in which large patches of huckleberry often grow. The pulpy cavity mass stays moist, both from rain and from the effect of the tree intercepting fog that rolls in from the nearby Pacific. The fog precipitates on the crown's foliage and the resulting water drips over the leaves and along the bark, leaching out nutrients that allow redwoods, like many tropical forest trees, to fertilize themselves. Even more remarkable are redwood roots which, unlike those of most trees, can be negatively geotropic—that is, instead of growing down or sideways, can grow up should the substrate on a flood plain be suddenly overlain with a deep layer of silt. Such a deposit would be fatal for all but flood-adapted trees like willow and pond cypress. Furthermore, there may be some evidence that adventitious redwood roots can sprout from sound wood inside rotted cavities, thereby enabling the tree to feed on itself.

We can all be thankful for the dedicated efforts of organizations like "Save-the-Redwoods" for their success in protecting these giants for future generations; if only such foresight had been manifested in Australia for their giant trees. We can be grateful to scientists like Steve Sillet and his colleagues who, at great risk, explore and study this heretofore uninvestigated canopy. The more we learn about our arboreal Titans, the better we can care for them. Those fortunate enough to have stood in a giant redwood grove are awe-inspired, just as when viewing other natural wonders as the Grand Canyon, the northern lights, or breeching humpback whales. What a responsibility our generation has to safeguard these awesome wonders for those still to come!

David Challinor
Phone: 202-633-4187
Fax: 202-673-4686
E-mail: ChallinorD@aol.com

P.S. I owe special thanks to both Scott Sillett, for his many references, and to his brother Steve for his insightful comments:

G.W. Koch, Stephen S. Sillett, *et al*. *The limits to tree height*, *Nature* 428 (22): 851 (2004);
Ian Woodward. *Tall Stories*, *Nature* 428 (22): 807 (2004);
Elizabeth Pennisi. *The Sky is Not the Limit*, *Science* 310: 1897 (2005);
R. van Pelt. *Forest Giants*, University of Washington Press (2001);
J. Balog. *Tree: A New Vision of the American Forest*. Barnes & Nobel Books (2004);
R.Preston. *Climbing the Redwoods*, the *New Yorker*. Feb.14 & 21 (2005) pp.212-225;
See also D. Challinor. *Letter from the Desk…* (August 1998).