

Tall storeys

Ian Woodward

The tallest living organisms are trees, but how tall could they be and what stops them growing any taller? Measurements at the tops of the world's tallest trees now provide quantitative answers to these questions.

Record-holders are of enduring interest¹, and in the plant world none stands out more than the tallest tree on Earth. This tree, coincidentally the tallest living organism, is found in California. It is a giant redwood (*Sequoia sempervirens*), which, at 112.7 m high, is equivalent to a 30-storey building.

Theories about the control of tree height have moved from a realization that trees are more than sufficiently engineered to cope with the mechanical stresses of height, to focus on their capacity to deliver water reliably to the treetop^{2,3}. However, until now there has been no direct test of this at the top of the tallest trees. In a breathtaking field study described on page 851 of this issue⁴, Koch and colleagues have now done so, carrying out research on five of the eight tallest trees in the world (all giant redwoods), including the tallest (Fig. 1) and second tallest. The results of linked field and laboratory studies indicate that the fundamental control of maximum tree height is water supply to the treetop.

Water rises to treetops by transpiration, the process by which water evaporates from leaves through stomata, the pores on the leaf surface. Transpiration pulls water into the plant through the roots and up to the very top through the water-conducting cells of the xylem tissue. This pull overcomes the opposing forces of gravity and friction, with the greatest pull occurring at the treetop. Water columns endure this tension until they reach a threshold at which they break, undergoing embolism with the introduction of air bubbles. Koch *et al.* measured the maximum tension on the water column above 100 m in the tallest redwoods. They found that the maximum tension is close to the point of embolism, establishing this value as the first major control on height.

Water reaching the leaves at the top of the tree actively drives cellular growth. Growth occurs by pressurizing the cells with a flow of water from the xylem, after the gravitational and frictional forces at the treetop have been overcome. These forces increase monotonically with height, decreasing the growth capacity of water flow^{4,5}.



Figure 1 High and mighty. This composite image of trees in the Humboldt Redwoods State Park includes the 'Stratospheric Giant', the tallest tree on Earth. The image consists of more than 700 photos taken by James Balog — spot the human climbers!

One effect of the reduced water flow is that cells at the top of the tree are small, with thick cell walls, and consequently the leaves produced are small and dense. At 110 m, redwood leaf density is the highest ever recorded, suggesting that growth has been significantly impaired: this is a second limitation on height. The increased invest-

ment in non-photosynthetic leaf tissue leads to a constant photosynthetic decline per unit of tissue investment to the treetops⁴; this fall in photosynthetic efficiency imposes a third constraint on height.

Maintaining xylem water status above the point of embolism affects gas exchange in the leaf, where carbon dioxide is absorbed for photosynthesis and oxygen is produced as a waste product. Koch and colleagues' *in situ* measurement of photosynthesis at over 110 m, a remarkable achievement in itself, shows the leaf CO₂ concentration to be close to the lowest ever measured at ambient atmospheric CO₂ concentrations. This limitation on CO₂ diffusion through the stomata imposes a fourth control on height.

The four physiological constraints on tree height are shown in Fig. 2 (overleaf), from which a narrow range (122–130 m) for the maximum possible tree height can be predicted. If this is correct, then the tallest trees, which may be more than 2,000 years old, still have some way to go. The observation that they are continuing to grow at about 0.25 m per year supports that idea.

These magnificent redwoods offer features that only the tallest of trees can deliver; the work of Koch *et al.* is only the latest in a line of very diverse, but highly relevant research on tall trees. For example, flow through the xylem is slow⁶: water entering the base of a redwood trunk could take as long as 24 days to reach the treetop. During periods of drought, this long delay in the replenishment of transpired water could lead to closure of stomata and inhibition of photosynthesis. But tall trees have a water store in the form of the water-conducting sapwood — an outer zone of wood, only 4–5 cm deep, that lies between the heartwood and the bark. In 60-m Douglas fir⁷ trees, this stored water provides 18% of the water supply for photosynthesis, nearly double that observed for a 15-m tree. The sapwood may be only 2–3% of the total trunk volume, but in the tallest trees it constitutes a substantial liquid reservoir.

Tall trees use considerable quantities of

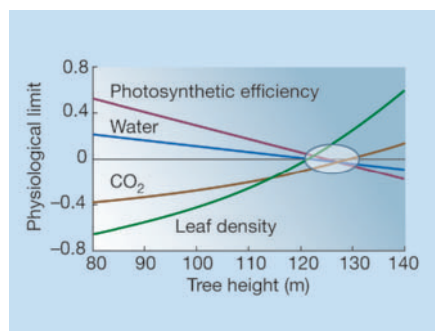


Figure 2 Physiological responses to tree height². Each curve is normalized so that a zero value indicates the maximum sustainable tree height based on photosynthetic efficiency, the point of xylem embolism (water), CO₂ supply to the leaf, and leaf density. The ellipse shows the predicted range of maximum heights. Water supply is the key constraint on height, given that it is essential for the other physiological factors.

water. For example, a 45-m redwood uses about 600 kg of water each day⁸, a figure that increases substantially with height and size⁷. It seems surprising, therefore, that the redwoods live in a climate with an annual dry season of 3–4 months. Offsetting such an apparent drawback, however, is the oceanic influence on local climate, which means that dry-season fog occurs for up to two weeks at a time: fog reduces transpiration, a benefit in the dry season. Moreover, tall trees actually increase the interception and capture of fog coming in off the sea, to the tune of 34% of the annual incidence of precipitation; in

their absence, the precipitation input from fog is halved.

Koch *et al.*⁴ have taken research on redwoods to new heights in testing and quantifying theories about the control of tree growth. There is substantial scope for further research, however, not least in exploring the processes that lead to the particular limiting values used to predict maximum height, as depicted in Fig. 2. Finally, it is remarkable how research by Koch's group has evolved: this latest paper dealing with redwoods follows early research on the lowly radish⁹. Yet that is no real surprise: despite the very different packaging and longevity of the two species, their physiological processes are much the same.

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Applied physics

Speed limit ahead

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Are there any limits to what science and technology can achieve? When it comes to recording data in magnetic media, the answer is yes: there is a natural limit to the speed at which data can be encoded.

In magnetic recording, information 'bits' are stored in regions of a magnetic material as opposite magnetizations or spins, corresponding to the values '1' and '0'. High information density is a major requirement, but even the highest density is useless if the information cannot be stored and retrieved sufficiently quickly. On page 831 of this issue, Tudosa *et al.*¹ show that there is likely to be a limit to how quickly a bit of magnetic information can be reliably written. This minimum time is on the picosecond scale — 10⁻¹² seconds — which is a thousand times faster than has so far been achieved in state-of-the-art devices. However, this is still ten thousand times slower than the duration of the shortest laser pulses that are already available² and would ideally be used for data-writing.

The standard way to reverse the direction of a spin, and thereby write or re-write information, is to apply a magnetic field along the spin axis. This is a 'zero-torque' configuration: the torque is the vector product of the spin and magnetic field and hence is zero when these are aligned. Fluctuations such as thermal excitations can, however, create a misalignment between the spin and the applied magnetic field, generating a non-zero torque that will cause the spin to change its direction. This 'viscous switching' has been the method of choice because the rise times of magnetic-field pulses were limited, but it is a rather slow process, of some nanoseconds' duration.

However, a basic knowledge of magnetic resonance suggests that reversing the spin requires a magnetic-field pulse that is per-

pendicular, not parallel, to the spin direction. This is a maximum-torque configuration. The spin changes its direction by precessing (or turning) around the applied field direction, doing so at maximum speed³ as defined by the Larmor frequency of precession. Unfortunately there is a drawback to precessional switching: once the spin begins to precess, it does not necessarily stop when it reaches the required, opposite direction⁴.

Although this problem might be overcome³, a new obstacle in the path of viable precessional-switching technology has been revealed by Tudosa and colleagues¹. Their experiment is the first to use the magnetic-field pulse generated by a tightly packed bunch of electrons from the Stanford Linear Accelerator in California as it passes through the centre of a magnetic recording film at almost the speed of light. This magnetic-field pulse is probably the shortest and most powerful available on Earth, with a maximum strength of about 3 tesla and a duration of only 2.3 picoseconds.

The pulse causes switching, provided the minimum angle of precession ($\pi/2$) is achieved. This means that if the pulse duration is reduced, the magnetic-field strength must be increased so that the product of duration and strength is still larger than the critical value needed for switching to occur. The critical value depends on the initial direction of each spin just before and during application of the magnetic-field pulse. For smooth recording, it is essential that the initial state of every spin is well defined and uniform while the pulse is in place. Otherwise some spins will switch, others will relax back to the initial state and the final state of the switching operation will no longer be a well-defined bit.

In their experiment, Tudosa *et al.*¹ detected switching through the pattern of magnetic domains left behind after exposure to successive electron bunches. The field strength decays as the inverse of the distance from the bunch, so although some regions of the magnetic film will undergo one or more switching processes, other more distant regions will remain unaffected. A pattern of black and white concentric rings develops, corresponding to domains of opposite magnetization (see Fig. 1 on page 832).

If precessional switching were totally reliable, repeated field pulses would cause the domains to change, from black to white and back again, in a very precise way. But Tudosa *et al.* report that, although the overall picture does indeed reflect black–white domain interchange, there is a remarkable deterioration in the sharpness of the boundaries separating the domains during repeated pulsing. This deterioration matches the predictions of a very simple model that assumes some small non-uniformity in the initial spin directions. Such non-uniformity affects the switching field and introduces a kind