spectroscopy to be used to weigh exoplanets have been the High Resolution Echelle Spectrometer (HIRES) on the Keck telescope[6], with which Howard *et al.* made their observations, and the High Accuracy Radial velocity Planet Searcher (HARPS) at the European Southern Observatory's 3.6-metre telescope in La Silla, Chile[7]. HARPS has been particularly successful for these demanding measurements because it was designed for exactly this purpose. A Northern Hemisphere version, HARPS-N, became operational in 2012 on the 3.57-metre Telescopio Nazionale Galileo at the Roque de los Muchachos Observatory in La Palma, Spain, and has made a spectacular debut by enabling Pepe *et al.* to measure the mass of Kepler-78b.

If applied to exo-Earths that TESS discovers, HARPS-N and HIRES will produce mass measurements for exoplanets whose environments are more temperate than that of Kepler-78b. By focusing particularly on small stars cooler than the Sun, TESS should find exo-Earths whose mass can be measured by trading the close-in orbit of Kepler-78b for more distant orbits around low-mass stars, approaching orbital zones where life is possible. That trade-off probably cannot be pushed to the point of measuring an Earth twin orbiting once per year around a Sun twin, but it will allow future scientific teams to probe habitable planets orbiting small stars. Kepler-78b thereby foreshadows leaps forward in the search for life beyond the Solar System. ■

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PLANT BIOMECHANICS

High-endurance algae

Breaking waves place repeated loading on marine algae, which can lead to death by fatigue. But observations of one alga suggest that its joint structure, which lacks transverse connections, confers fatigue resistance.

EMILY CARRINGTON

Rocky shores are pounded by surf, with each wave delivering a fresh assault on the attached plants and animals about once every ten seconds — more than 8,000 times a day or almost 3 million times a year. Most organisms are simply not up to the task of surviving in this environment; only a select few are able to endure these high-intensity workouts and proliferate. Writing in the *Journal of Experimental Biology*, Denny *et al.*[1] reveal a key design feature of one of the most successful surf-zone competitors: the strong, fatigue-resistant joints of coralline algae.

The authors focused on an alga that is common to the waviest coasts of California: *Calliarthron cheilosporioides*, a beautiful branched plant the size of your hand. Each branch of this red alga resembles a necklace of pink beads, with a pale decalcified joint (geniculum) connecting each calcified bead (intergeniculum) to the next. The authors knew that these numerous joints conferred flexibility on what would otherwise be a rigid structure, allowing the plant to sway to and fro and reduce the impact of large breaking waves. But they also knew, from previous studies[2], that most flexible algae are constructed of tissues that are prone to fatigue arising from accumulated progressive and localized structural damage caused by repeated loading from wave forces. This damage comes in the form of microcracks that concentrate stress and then elongate and propagate catastrophically through the material — a process elegantly described in 1921 by the engineer Alan Arnold Griffith[3]. As a result, many algae get weaker with each passing wave and die from fatigue sooner than would be expected on the basis of their nominal strength.

Calliarthron, however, has a lifespan of up to six years, which is relatively long for a surf-zone plant. Could it be resistant to fatigue? One clue lies in the microstructure of the genicular joint. Denny and colleagues observed that the elongated cells of the joint are arranged in a single tier that runs parallel to the axis of growth, with each joint cell terminating at one end of a calcified bead (Fig. 1a). They proposed that because these joints are not connected transversely to each other, there is no structure to concentrate stress and propagate cracks from one cell to the next.

A simplified illustration of this concept is given by a dancing marionette. The puppet's body and appendages are suspended by strings, each with a direct attachment to a control bar above. As the puppeteer manipulates the bar, force is transmitted through the strings to make the puppet dance. If one string snaps, the arm or leg it supported will fall lifeless,

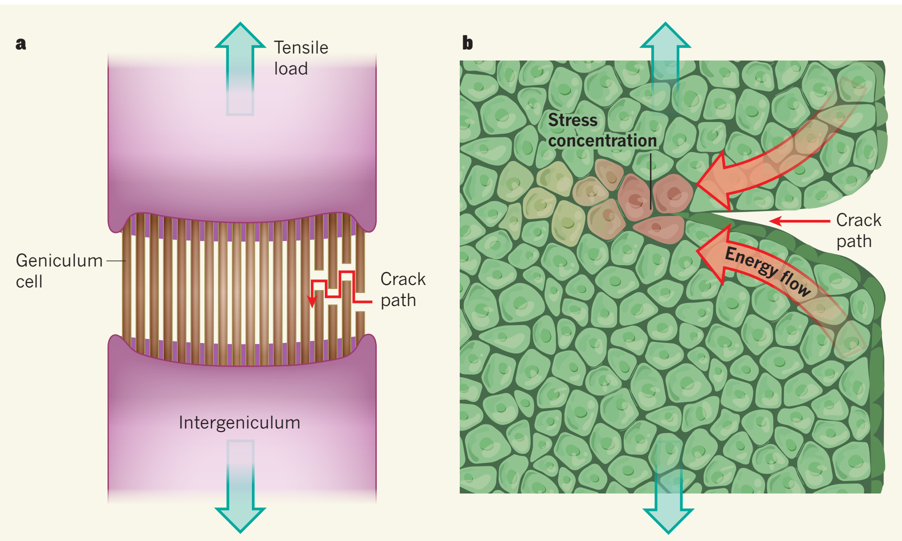

Figure 1 | No stress. a, The tissue of the alga *Calliarthron cheilosporioides* comprises flexible genicular joints connecting calcified intergeniculum regions. Each geniculum contains a single tier of elongated cells that lie parallel to the axis of growth. Denny *et al.*[1] show that this cellular structure helps the alga to withstand the repeated tensile loading of waves — the lack of transverse connections between the geniculum cells means that when one cell breaks, strain energy is not passed to the next cell. Furthermore, stress does not concentrate at the crack tip, so the crack path will 'meander' through the tissue and not propagate readily. **b,** The tissues of other algae more closely resemble a homogeneous material of interconnected isodiametric cells. Once a crack path forms in this material, strain energy can flow more easily towards the tip of the crack, allowing stress to concentrate so that the crack propagates in a more directed way, perpendicular to the axis of loading.

but the rest of the doll will continue to follow the puppeteer's guidance — the failure of one string has little impact on the performance of the others. The key is that the strings are not connected directly to each other and therefore act independently.

Denny *et al.* hypothesized that the genicular joint material of *Calliarthron* is not homogeneous, but instead comprises a bundle of parallel cells acting as independent cables. They sought indirect support for this view by comparing the stiffness of a joint in tension with its stiffness in shear (denoted E and G, respectively, and measured in pascals). Materials-science theory establishes a ratio E/G of 3 for a homogeneous material; the loss of transverse connections between cells reduces shear stiffness and causes E/G to be much greater than 3. Denny and colleagues' experimental data showed that the E/G ratio for *Calliarthron* is more than 10, confirming that each joint acts as a bundle of strong, extensible, loosely connected parallel cables. This suggested that the alga's structure resists crack propagation and fatigue.

The authors next directly measured fatigue in *Calliarthron* by placing the alga in a custom-made device that mimicked repeated loading by waves. When loaded to 60% of its nominal strength, the alga survived more than ten million cycles, the equivalent of more than three years of waves crashing on it every ten seconds. Because the majority of waves encountered by *Calliarthron* produce lower forces, the predicted longevity of this alga is much longer than its observed lifespan of six years. In short, the authors conclude that failure by fatigue is not likely in *Calliarthron*, and that only rare, extreme waves that exceed the nominal strength of the joints would cause death.

Most of the macroalgae that compete with *Calliarthron* for space and light have a tissue construction that is more prone to crack propagation (Fig. 1b). Over time, repeated loading by the surf gradually prunes back new tissue growth. The net result is a population of algae that are much smaller — and therefore less competitive — than would grow according to estimates based on the nominal strength of the algal tissue[2]. By contrast, the crack-stopping tissue construction of *Calliarthron* joints confers a competitive edge by minimizing pruning by waves.

The single tier of genicular cells is the feature of the joints of *Calliarthron* that confers fatigue resistance. The authors point out that the joints of other lineages of coralline algae are constructed differently, with multiple tiers that may not act independently in shear, and therefore might be less resistant to fatigue. Although this evolutionary story awaits further investigation, we now know how *Calliarthron*, with a joint structure that resists crack propagation, is able to sway back and forth indefatigably to the beat of the surf. ■

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BIOGEOCHEMISTRY

Conduits of the carbon cycle

Emissions of carbon dioxide from inland waters to the atmosphere are a crucial link in the global carbon cycle. A comprehensive analysis reveals that this connection is much stronger than was previously thought. **SEE ARTICLE P.355**

BERNHARD WEHRLI

The global river system acts as a gigantic transportation network for water and dissolved substances, but this pipeline is leaking carbon dioxide to the atmosphere at surprisingly high rates. On page 355 of this issue, Raymond *et al.*[1] report that rivers emit about five times times more CO_2 to the atmosphere than all lakes and reservoirs put together. The authors' spatial analysis reveals a flux of this greenhouse gas that is larger than previously estimated and dominated by hotspot regions in the tropics.

Only about half of anthropogenic CO_2 emissions accumulate in the atmosphere[2]; their effects on climate are being mitigated by mechanisms that bring about uptake by the oceans and by terrestrial vegetation. To promote carbon sequestration on land, we need to know how and where these large amounts of carbon are removed from the atmosphere.

Climate scientists estimate the strength of carbon sinks on land by running global circulation models of the atmosphere, and by identifying regional sinks using monitoring stations that measure the global distribution and variability of atmospheric CO_2 concentrations. This top-down approach is limited by the spatial resolution of both the models and the data. By contrast, ecosystem scientists approach the problem from the bottom up: they measure the CO_2 uptake and release rates of different natural and agricultural vegetation systems. The large spatial and seasonal variability of photosynthesis and respiration poses a significant challenge in scaling up these local observations. The lateral export of carbon from land to river networks is a complicating factor in determining regional carbon budgets[2,3], but solving this problem also provides the opportunity to monitor and model this important flux with high spatial resolution.

To calculate global estimates of CO_2 emissions from inland waters, Raymond *et al.* created spatially resolved data sets of three parameters: CO_2 concentrations in surface waters; the velocity of gas transfer to the atmosphere; and the surface areas of rivers and lakes. It has long been known that most rivers and lakes are supersaturated with CO_2 — that is, the measured concentration in river water usually exceeds the equilibrium value for the exchange between CO_2 present as a gas in the atmosphere and that present as a dissolved substance in water[4]. This excess concentration in water drives molecular diffusion across the water–air interface. The available measurements of CO_2 in surface waters cover North America, parts of Europe, South Africa and Japan, but the data are still sparse for Africa and Asia, which adds significant uncertainty to the authors' global analysis.

To obtain regional gas-transfer velocities, the researchers analysed the results of published tracer experiments[5] of gas-exchange rates across the air–water interface, which are related to the level of turbulence. For lakes, this gas-exchange parameter correlates with lake size and the average wind field. In rivers, the gas-transfer velocity is rapid in steep terrain — in the headwaters — and slower towards the lowlands.

To estimate the global surface area of river systems, Raymond *et al.* made use of high-resolution geographical data obtained from space-shuttle missions, detailed river monitoring in the United States, and climate parameters from the COSCAT database (which collects information about river catchment areas globally) to derive statistical correlations between surface area and climatic parameters such as precipitation and temperature. They also revised an earlier census of lakes and reservoirs[6].

This global analysis reveals an annual CO_2 flux of 1.8 petagrams (Pg; 1 petagram is 10^9 tonnes) from rivers to the atmosphere, and 0.32 Pg from lakes and reservoirs. The study