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Nature's search for a quiet place

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The predominance of green terrestrial plants stems from chlorophyll's absorbance wavelengths. Those spectral selections ensure consistent energy harvesting and avoid photo-oxidative stress.

A patch of green grass is full of life and likely to host fungi, bacteria, and insects. Temperature, wind, and sunlight fluctuate constantly. Every biological system—including the food chain and the hardware of DNA replication—is fraught with noise. Given that context, how do living systems establish themselves and work so well?

Take photosynthesis, for example. In certain light conditions, 99 out of 100 photons that enter a plant's light-harvesting antenna complex excite a chlorophyll electron and make its energy chemically available. That efficiency is possible because of the configuration, or spatial arrangement, of photosynthetic antenna arrays, which consist of pairs of chlorophyll pigments that have been tuned to absorb photons in narrow frequency windows. To help explain the principle that regulates the selection of those frequencies, let's consider the difficulty of photosynthesis in light of that faced by networks in general.

Goldilocks

For a network that experiences rapidly changing environmental conditions and internal fluctuations, what is the best way

to achieve just the right flow of energy? The process of converting noisy inputs to quiet outputs has relevance in nearly every practical application of network design, including multi-component, large-scale energy grids and auditory and visual stimuli in neural networks.

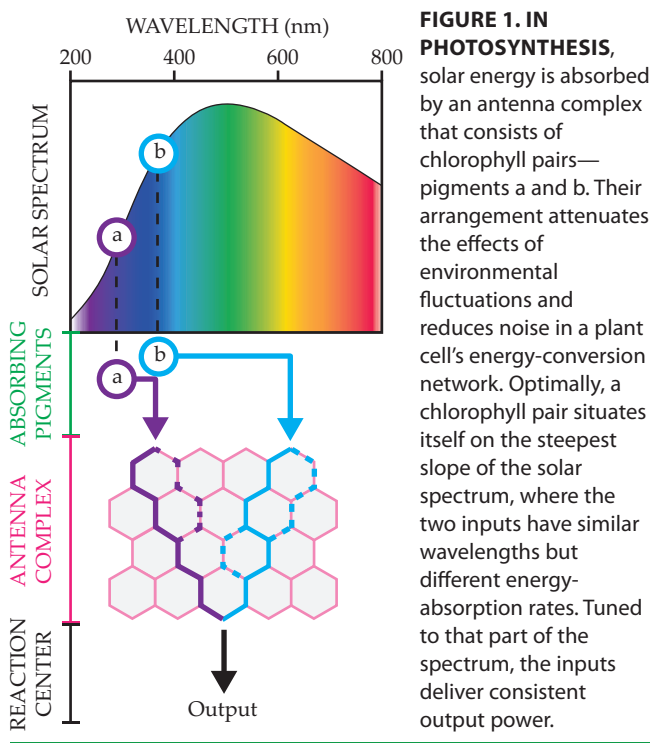
The issue is especially acute for networks composed of delicate quantum states. What's more, when a network fails to manage the over- or underflow of energy or information, the results can be disastrous. Uncontrolled surges can trigger blackouts in the energy grid; likewise, too much input through our five senses may lead to sensory overload in the brain. In plants, such overloads lead to photo-oxidative stress. For the photosynthetic network to avoid that outcome, it must be optimized for a consistent flow of energy.

To make sense of how photosynthesis achieves that Goldilocks state, the three of us and our colleagues in the lab started with a straightforward intuition—namely, that there must be a relationship between the visible spectrum and the biological apparatus that harvests the Sun's energy. We sought to characterize that relationship using a minimalist model. A famous example of such a model is the parable of Daisyworld, proposed in 1983 by Andrew Watson and James Lovelock to explain biofeedback's role in global temperature stability.

Daisyworld

Daisyworld is an imaginary planet with just two daisy species, one black and the other white. At first, the planet is too cold to support much life. But the black daisies start bucking that trend by absorbing most of the light that falls on them and gradually heating up the planet. In turn, the white daisies thrive. But they also reflect light, which reverses the planet's heating trend. As the temperature continues to fluctuate, each daisy species keeps the effect of the other in check. Over time, their combined effects stabilize the planet's temperature. Watson and Lovelock's model illustrates how a simple system can render an environment more consistent and more favorable to life.

Even so, large, homeostatic systems, such as Earth's atmosphere, experience a variety of fluctuations. How, then, do plants tune their photosynthetic antenna arrays to account for such changes? Earlier, we noted that networks should optimize for consistent power delivery rather than for maximum power. Photosynthetic networks accomplish the task by diversifying their inputs. They tune pairs of pigments to parts of the solar spectrum that yield similar wavelengths but different power levels. For each pigment pair, those wavelength selections result in one low-power input and one high-power input.



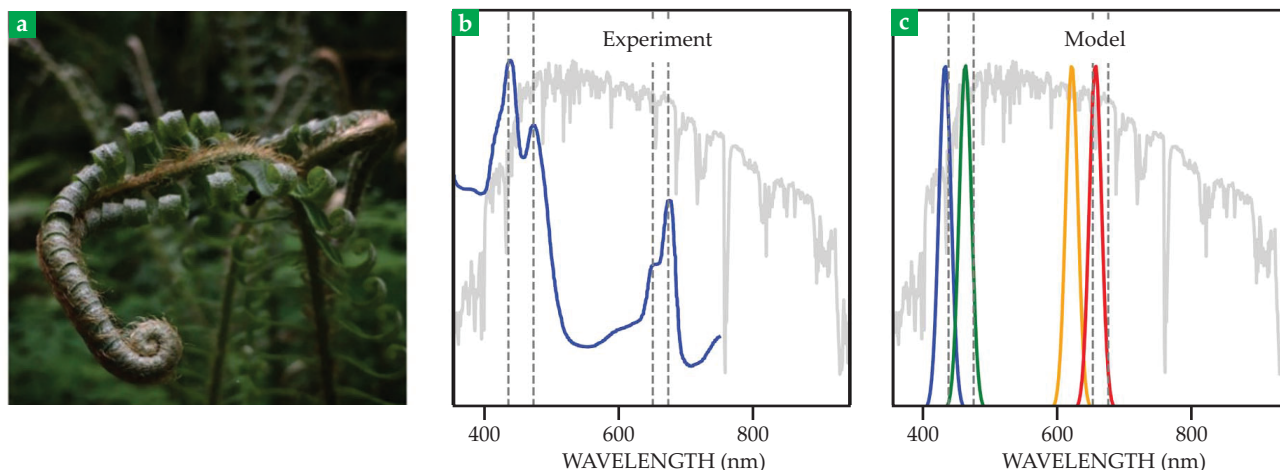


FIGURE 2. A FERN sunbathes (a). Its experimentally observed absorption spectrum (b) is shown in gray, superimposed with peaks (blue) that mark the wavelengths at which chlorophyll pairs in terrestrial plants absorb light. Against the same solar power spectrum (gray), dashed lines mark the spectral frequencies to which the plants' antenna complexes are tuned. (c) Colored lines represent our model's predicted peaks. They closely match the frequencies at which plants absorb light. (Adapted from T. B. Arp et al., *Science* **368**, 1490, 2020.)

To understand the principle at work, let's turn to our own minimalist model, shown in figure 1, which describes a simple, light-energy-harvesting antenna complex. It is a network in which two inputs are directly coupled to a singular output. Energy enters the network from input channels (chlorophyll pair a and b) that correspond to light absorption through different pigments. Each channel is defined by the wavelength and rate at which it absorbs. The overall absorption rate is determined by the external light spectrum—that is, the intensity of available light at the two wavelengths.

Although many pathways exist in the network, all of them lead to a single output channel that represents an electron excitation. With multiple inputs and only one output, the network is inherently noisy. External noise comes from rapid fluctuations in incident light, whereas internal noise arises from structural dynamics and mismatches between different input rates. The result is a noisy output that fluctuates between underpowered, optimal, and overpowered states. The underpowered state is metabolically insufficient. The overpowered state risks cell damage from photo-oxidative stress.

How then should the two inputs be arranged so that the output spends most of its time at the optimal state? If two input channels are identical—effectively becoming a single channel—the antenna minimizes internal noise since there is no mismatch between different input rates. Unfortunately, committing to a single frequency would make the system highly sensitive to external noise. If the external light conditions suddenly change, the absorber is stuck, left with too much or too little power. Conversely, if the two channels differ strongly in both absorption rate and wavelength, internal noise dominates. Although the system is robust to external variations, it would suffer from a large mismatch between the two very different inputs.

Optimum output occurs when the two channels are balanced—that is, when we tune the two inputs to similar wavelengths but different absorption rates. When we examine the spectrum of available light, we find a means of achieving a Goldilocks solution. To get just the right amount of energy flowing out of the antenna complex, the absorbance peaks of the pair of pigments should be located in a region of the spectrum that has the steepest slope. That approach yields

similar input wavelengths relative to different absorption rates, which smooths the power delivery.

Pairs in quiet places

With surprising consistency, we have found that numerous phototrophic organisms exhibit those exact absorption characteristics: pairs of pigments situated on the steepest slopes of the light spectrum (see figure 2). Indeed, our research group predicted—accurately, it turns out—the absorption profile of green plants, purple bacteria, and green sulfur bacteria, among other organisms. Those organisms depart from our single-pair model in that many have two pairs of chlorophyll receivers, one for each slope of the solar spectrum's peak in power.

Because the absorption parameters of those organisms determine their color—terrestrial plants absorb in the blue and red and therefore reflect green light—one can predict how the organisms would appear in a given light environment. Most plants on Earth are green because they abhor the noise in the high-power portion of the light spectrum.

As a result of that abhorrence, plants have made evolutionary selections that are fundamental to life as we know it. By tuning their chlorophyll pairs to receive at frequencies just below the solar spectrum's irradiance peak, plants have nestled themselves into some of nature's relatively quiet places. Our research has isolated the general design principles behind that trend. And future solar-energy-harvesting grids can benefit from those principles.

Additional resources

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