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1 **Plants show us the light**

2

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8 **In a recent article published in *Science*, Arp et al. propose a new theory as to why plants**
9 **are green: plants prioritize the management of light fluctuations over maximal**
10 **efficiency. Beyond plant science, this conclusion may inspire our sustainability**
11 **strategies, to shift our societal goals from performance to resilience.**

12

13

14 Life on our planet largely depends on the ability of plants to harvest light and convert it into
15 metabolites and energy sources. However, it may come as a surprise to many that
16 photosynthesis is in fact very inefficient. In theory only up to 2% of the energy of the incident
17 solar radiation is captured, and this number drops to 0.3 to 0.85% when measured in real
18 ecosystems [1]. This is reflected in part by the color of plants: they are green, because they
19 absorb much less green light than red and blue light (Figure 1). What could be the
20 evolutionary advantage of such a wasteful strategy? A recent study goes one step further to
21 explore the biophysical mechanism behind such apparent inefficiency. Plants are exposed to
22 dynamic light properties and fluctuating molecular structures. Dealing with such noise has a
23 cost, and this implies wasting a lot of energy [2].

24

25 Some of the plant strategies that deal with light intensity fluctuations were already known.
26 For instance, a sudden burst of light can lead to photo-oxidative stress in the photosynthetic
27 light harvesting complexes. One of the functions of carotenoid pigments is precisely to
28 convert this excess of light energy into heat, i.e. to dissipate the excess of energy input. What
29 is new here is that the authors dealt with the systemic response of light harvesting complexes
30 to noisy light fluctuations and internal cell dynamics.

31

32 In short, the quantum conversion of photons into energy is a physical process that works best
33 when the input is steady. In theory, to reduce the fluctuations in the rate of energy flow, one
34 would need to have absorbing peaks in very close light wavelengths (e.g. red and red-orange).

1 However this is not observed in real living systems, simply because both light and protein
2 properties fluctuate: a light harvesting system cannot be tuned like one fixes a radio [3]. What
3 the authors find instead is that spread-out absorption peaks, i.e. red and blue, can effectively
4 reduce noise, allowing steady input of energy, while being robust to fluctuations. This theory
5 is strongly supported by the fact that the well-known absorption spectra of photosynthetic
6 systems peak in red and in blue, also explaining why plants appear green [2][4].

7

8 This is a remarkable example illustrating how living organisms have selected robustness over
9 performance during evolution. Efficiency is indeed not the common denominator of life. At
10 the molecular scale, living systems are very random, redundant, heterogeneous, inconsistent...
11 in short, not very efficient. This is in line with an ongoing revolution in molecular biology,
12 where the many roles of stochasticity are beginning to be understood through quantitative
13 approaches [5][6]. The recent work by Arp et al. [2] illustrates the need to take into account
14 much longer time scales, within which local inefficiencies can balance each other to generate
15 robustness. In other words, this analysis of photosynthesis illustrates the trade-offs between
16 efficiency and resilience in biology.

17

18 Back to societal questions, the current Covid-19 crisis illustrates how such a trade-off may
19 also be relevant to other sectors [7]. Seeing the Anthropocene as the era of man-made
20 uncertainties, taking inspiration from such a viewpoint might be very timely. The
21 environmental crisis is indeed largely caused by the blind compass of humans towards
22 efficiency increments, a bit like the light harvesting complex going into photo-oxidative
23 stress. This is a trivial observation when considering the green revolution and the associated
24 negative externalities on desertification, pollutions and biodiversity collapse. The same
25 applies to strategies supporting over-fishing, over-mining or over-consumption. Gains in
26 efficiency can be counterproductive, and this has already been theorized [8]. It is even the
27 basis of the rebound effect, or the so-called “curse of efficiency”: gains of efficiency usually
28 make a technology more attractive, meaning that resource consumption is not reduced, but
29 does increase globally [9][10]. Many reports, and most notably the Meadows reports on the
30 limits to growth, have implicitly warned humanity against such excesses for the long-term
31 viability of our civilization [11][12].

32

33 The lesson from plant light harvesting complexes does not only shed light on our past, it
34 could also question our future sustainable development strategies. Dealing with noisy

1 environments is a well-known challenge in engineering, e.g. when designing energy grid
2 architecture [13]. More broadly, such suboptimal strategy can be observed in many contexts,
3 from technological to cultural spheres [14]. How could this translate into our future
4 sustainable strategies? For instance, should we first consider the stochastic nature of supplies
5 (e.g. rare earth availability) and environmental conditions (e.g. increasing wind variance
6 following the climate crisis), instead of prioritizing the gains in efficiency in energy
7 conversion when developing renewable energy solutions? With geo-engineering, are we not
8 trying to optimize our climate, i.e. to make it more efficient for our needs in a reductionist
9 framework, instead of embracing uncertainty.

10

11 During Earth's history, living organisms have demonstrated their ability to adapt to
12 unthinkable conditions. Organisms do not build such resilience on increased efficiency, but
13 instead on their intrinsic inefficiencies [15]. How can this work? As shown in the
14 photosynthetic light harvesting complexes, robustness is an emerging property of the
15 interactions between apparent weaknesses. This can be illustrated in other biological contexts
16 too. For instance, most of the molecular factors in our cells occur in very small numbers,
17 which partly explains the unpredictability of living beings, even at that scale. However, there
18 is great redundancy in these families of molecules and in biological processes, which partly
19 compensates for randomness. Finally, two "weaknesses", randomness and redundancy,
20 balance each other out. It is a bit like a car, where acceleration and braking allows a stable
21 speed regardless of the slope of the road. For living beings, the maintenance of such
22 autonomy allows resilience in the face of environmental fluctuations. This also applies to
23 biomechanics: most living systems are experiencing a balance between tension and
24 compression. This balance provides them with a mechanical resistance to external noise, a bit
25 like a suspension bridge (with its threads under tension and its deck under compression) when
26 it is exposed to wind.

27

28 Such suboptimality may very well be a source of inspiration for our future sustainability.
29 Three key principles could be put forward:

- 30 1- Based on how inefficient biological systems are intrinsically (see e.g. the 2% maximal
31 yield of photosynthesis), we might vastly underestimate the "slack" needed for true
32 resilience in our societies;
- 33 2- Biological systems can afford many internal weaknesses, because those are also often
34 antagonistic (e.g. randomness vs. redundancy); conversely, this generates a form of

1 autonomy and thus a built-in shield against environmental fluctuations (a
2 component of resilience)

3 3- Efficiency is more easily understood when referring to the individual scale, whereas
4 resilience usually always applies to the population and thus implies systems thinking.
5

6 Although suboptimality is likely to be a key element of our sustainable future, we could be
7 blinded by the attractive and shiny prospect of short-term efficiency. In that respect, our green
8 world is not only harvesting the light, it may very well show us the path to resilience.
9

10 11 12 **Acknowledgments**

13
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16

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17

1 **Figure legend**

2

3

4 **Figure 1.** Plants reflect green light, dissipating and wasting a lot of solar energy.

5 Designing future sustainable bio-inspired strategies will depend on our ability to avoid the
6 trap of over-optimization, i.e. on our ability to understand what resilience entails. Credit

7 photo: Technology photo created by jannoon028 - www.freepik.com

8 https://www.freepik.com/free-photo/plant-growing-bulb_969640.htm

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