ESD Ideas: Planetary Antifragility: A new dimension in the definition of the Safe Operating Space for Humanity

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Abstract. The Safe Operating Space for Humanity is not fully characterized by the state values of Planetary Boundaries because not only does interaction among them matter, but more importantly the perturbation response capacity dimension is missing. Combining well-established non-equilibrium thermodynamic principles and a system dynamics approach, we define for the first time the concept of Planetary Antifragility as changes of Fisher information of Earth's entropy production. As a first approximation for entropy production, we propose to use shortwave global albedo anomalies and made a first example of measurement with data for the July months in the northern hemisphere from 1982 to 2010. These preliminary results show a net reduction of 47.63% on albedo's Fisher information. This loss of Antifragility implies a compounding problem because human perturbations such as climate or land-use changes are increasing but at the same time, the planet is losing its capacity to respond to them.

1 Introduction

The seminal work "Planetary Boundaries: Exploring the Safe Operating Space for Humanity" (Rockström et al.2009) identified nine core biogeochemical processes with threshold values for each variable called the Planetary Boundaries (PBs) for each one of them, within which the authors expect that humanity could operate safely. The central idea of their work is that transgressing one or more PBs may lead to a catastrophic planetary tipping point most likely incompatible with the modern human organization survival. Despite the concept of PBs being widely accepted, there are some issues that remain open: (a) Although Rockström and coworkers (2009) recognize that PB are not interdependent, as transgressing one may both shift the position of other boundaries and cause them to others to be transgressed, the individual threshold values of the PBs do not establish the true threshold configuration because it is necessary to have a metric of the interaction among the whole network of PBs; (b) Rockström and co-workers say that impacts of transgressing PBs will be a function of the social-ecological resilience, but as has been raised recently (Equihua et al. 2020), the concept of resilience is a special and limited case of Antifragility; (c) in their work, Rockström et al. (2009) do recognize that although not all processes or subsystems on Earth have well-defined thresholds, human actions that undermine the resilience of such processes or subsystems can increase the risk that thresholds will also be crossed in other processes, such as the climate system, in that sense the capacity of Earth system to response to perturbation under resilience concept is a key feature in PBs framework, but resilience is a limited special case of the wider concept of Antifragility consisting of an intermediate type of response to perturbations near to robustness where the systems tolerate stress and remain the same.

To emphasize the importance and rationale of switching from resilience to Antifragility, consider that all living systems are undergoing evolutionary processes that require them to do far more than simply endure perturbations; they must have some features that allow them to not only cope but gain (up to a point) from perturbations, stressors, variability, and uncertainty. This is simple logic: any system that gains from variability (even by mere randomness) eventually will undergo its competitors because time is the ultimate source of variability and so the system will accumulate any little gain.

So through evolutionary processes, what we will observe in the present is the predominance of those systems that have previously gained from environmental variability and perturbations. This feature is what Taleb called Antifragility (Danchin et al., 2011; Taleb, 2012) has a formal definition as a non-linear response in the payoffs space and can be summarized as follows (Taleb and Douady, 2013; Taleb, 2018):

Let $f(x)$ be a two times continuously differentiable payoff function $f(x)$ with a convexity defined as usual by its second derivative $\frac{\partial^2 f}{\partial x^2} \geq 0$ which can be simplified without loss of generality as $\frac{1}{2}\left[f(x+\Delta x)+f(x-\Delta x)\right] \geq f(x)$.

From this, we can see that as the dose increases there will be a much higher impact (non-linear) response in $f(x)$ which generalizes to a linear combination as $\sum \alpha_i = 1, \quad 0 \leq \alpha_i \leq 1$ in such a way that $\sum\left[\alpha_i f(x_i)\right] \geq f\left[\sum(\alpha_i x_i)\right]$. Then under the correct conditions we may simplify the argument to $f(nx) \geq nf(x)$, which implies that the payoff function $f(x)$ of the random variable X with support in $[a, b]$ we will satisfy the Jensen's Inequality and then

$$\mathbb{E}(f(x)) \geq f(\mathbb{E}(x)). \tag{1}$$

Or as shown in previous work (Taleb and Douady, 2013), the expectation of f under a probability density distribution $\varphi(x)$ with support in $[a, b]$ indexed by the scale σ is

$$\forall \sigma_2 > \sigma_1, \mathbb{E}_{\sigma_2}\left[f(x)\right] \geq \mathbb{E}_{\sigma_1}\left[f(x)\right]; \tag{2}$$

which means that we have either a convex dose-response behavior over $[a, b]$ or the expectation increases with the scale of the distribution.

Given this precise mathematical definition of antifragility, the problem at hand is to identify a suitable systemic payoff function that adequately captures the idea of Planetary Antifragility in the context of an enhanced "Safe Operating Space for Humanity" that incorporates not only PBs state value but also the capacity of the Earth to respond in a convex way to anthropogenic stressors.

From previous work on ecosystem antifragility (Equihua et.al. 2020) we know that it can be be measured using changes in ecosystem complexity and so the most healthy state should be the one that is at maximum complexity, a state that is reached when ecosystems are in criticality, a dynamic regime characterized by scale invariance in Fourier space and also in good balance between informational emergence and self-organization (Ramírez-Carrillo et.al. 2018). Finally, we also know that in criticality, the system also reaches its maximum of Fisher information (López-Corona and Padilla, 2019). In this way, antifragility may be approximated using the Fisher information of payoff time series.

The main idea in this context is that a safe human operating space should consider not only a "safe" range of important state variables in terms of tipping point but also the dynamics of the system (see for example unpublished work by Toledo-Roy and co-workers https://www.youtube.com/watch?v=WzfdnoC3Kik), especially its capacity to respond to perturbations. The dynamic interpretation of Fisher information could be understood as a measure of the system stability or as we have proposed elsewhere (López-Corona and Padilla, 2020) as a universal payoff function for antifragility.

Also there is cumulative evidence presented on our previous work on Ecosystem Antifragility (Equihua et.al. 2020), that points to the conjecture that Earth System should be not only under a limited range values for key biogeochemical variables but also in a criticality regime (Hidalgo et.al. 2014) in which the system is in its maximum complexity, maximum Fisher Information and balance between emergence (flexibility/randomness), and self-organization. Under these conditions, the ecosystems (including Earth systems) exhibit the greatest computational and inferential capacities related to the system capacity to respond and adapt to perturbations.

2 Methods

2.1 Entropy production as Payoff function

As noticed in previous work by Michaelian (2005, 2015), Ecosystems arise and evolve, as any other physical system, under the laws of thermodynamics. In particular, the relation between entropy production and ecosystem functioning up to Earth system is well established and has been studied since 1972 in the pioneering work of Prigogine and co-workers; then by Ulanowicz and Hannon (1987); Aoki (1989); Schneider and Kay (1994); Schymanski et.al. (2010); Michaelian (2005, 2011, 2012, 2015); Kleidon (2005, 2009, 2010a, 2010b, 2010c, 2021); Panwar et.al. (2021).

In the current paper, we build our new planetary Antifragility concept mainly on the work of Michaelian (2015) who proposes that healthy ecosystems have greater entropy production than unhealthy or stressed ones and entropy production should then be a reliable indicator of its health, given by the following expression of total entropy production (more precisely photon dissipation) per unit area of the ecosystem (J) (Michaelian, 2015):

$$Health = J = \int_{0}^{\infty} 2\pi L_{rad}\left(\lambda\right) - 0.04 L_{in}\left(\lambda\right) d\lambda, \tag{3}$$

in which the 0.04 factor comes from the cosine of the angle of the incident radiation, and both the $L_{rad}\left(\lambda\right)$ and $L_{in}\left(\lambda\right)$ comes from the following expression using I as measured by a detecting spectrometer or as solar spectrum at surface, respectively.

$$L\left(\lambda\right) = \frac{n_0 kc}{\lambda^4}\left[\left(1+\frac{\lambda^5 I\left(\lambda\right)}{n_0 hc^2}\right)\ln\left(1+\frac{\lambda^5 I\left(\lambda\right)}{n_0 hc^2}\right)-\left(\frac{\lambda^5 I\left(\lambda\right)}{n_0 hc^2}\right)\ln\left(\frac{\lambda^5 I\left(\lambda\right)}{n_0 hc^2}\right)\right], \tag{4}$$

Where λ is the wavelength of radiation $I\ [Jm^{-2}]$; c is the velocity of light; n_0 is the photon's polarization sate ($n_0 = 1$ for polarized and $n_0 = 2$ for unpolarized); h and k are as usual the Planck and Boltzmann constants.

The key point here is that we don't need to account for all individual living systems, that have several non-linear couplings among both biotic and abiotic (i.e. water cycle) components of the Earth system, but a global planetary good enough approximation of the entropy production (more precisely photon dissipation) contribution by the biosphere is achievable by measuring the difference between the incident and outgoing light spectrum as defined above using as proxies remote sensing data from already existing satellites.

Nevertheless, it is necessary to find the specific proxy that contains the most relevant information on the entropy production of ecosystems, that is measured at a planetary scale and available from existing databases. So, following original ideas discussed by Ulanowicz (1987) and Michaelian (2015), we went with satellite measurements of Albedo as a fair proxy of Eq(3).

With that selection in mind, in this work, we used published data for Surface Albedo anomalies on the Northern Hemisphere during the months of July (GLASS albedo product) for 1981–2010 (He et.al., 2014) and calculate its Fisher information in the same way Ahmad and Co-workers (2016) have done for global-mean temperature (1880-2015). In their work, the authors organized the time series data such that each month represents one system variable so that 12 variables describe global temperature anomalies from January to December for each time step (year).

2.2 Data inputs

Data used here (Fig.1), comes from The Global Land Surface Satellites (GLASS), which is built using very high resolution radiometers (AVHRR) and MODIS data (Liang et.al. 2013). Two direct albedo calculations are incorporated for the MODIS (Moderate Resolution Imaging Spectroradiometer) component; one for surface reflectance and one for Top of Atmosphere (TOA) Reflectance (Qu et.al. 2014). The AVHRR observation GLASS albedo component is based on a direct measurement algorithm using radiometric calibration and atmospheric correction surface reflectance (Pedalty et.al. 2007) comparable to that used on MODIS data (Liu et.al. 2013).

We used the 1982 to 2010 time series of July months for the Northern Hemisphere (more land area implies more albedo changes and higher rates of CC are expected), which show a decrease rate of 0.0013 per decade ($p < 0.01$) (Figure 1)(He et.al.

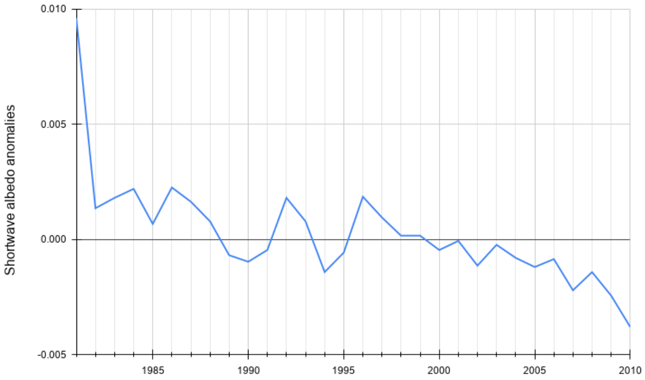


Figure 1. July shortwave terrestrial albedo time series from GLASS data for Northern Hemisphere

2014). We took this data set because it is the season when less snow or ice may be found in the Northern Hemisphere and so, a more clear response to Climate Change could be found. We used then a Python implementation of the algorithm created by Ahmad et al. (2016) to assess Fisher information, available at https://github.com/csunlab/fisher-information.

In this work, we are only using land albedo that does not include any oceanic contribution. The different albedo products derived from satellite imagery, in general, are processed only for terrestrial surfaces because ocean albedo is rather stable and low which may cause that higher fluctuations get masked/averaged by ocean albedo, and thus the original input does not include ocean surface albedo. So, the influence of periodic phenomena like El Niño Southern Oscillation (ENSO) could not affect the results because of the change in ocean surface albedo. But it must be considered that land cover, which influences terrestrial albedo to a large extent, is heavily influenced by the teleconnections caused by “spatially and temporally large-scale anomalies that influence the variability of the atmospheric circulation” (ENSO, Arctic Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation, Pacific-North America Index (https://www.ncdc.noaa.gov/teleconnections/). This leads to climate anomalies linked across geographically separated regions, and also to bigger or smaller changes in land cover type (e.g. arid environments with abrupt growth of annual plants after unusual precipitation or drought-related phenotypical changes in normally humid areas).

We are using also only northern hemisphere data and it would be also interesting compare both hemisphere, which as far as we understand would be possible but we do not think that it is necessary for making a proof of concept analysis as the one we present here as we argue in discussion section.

2.3 Stability analysis using Fisher Information

Consider a dynamical system characterized by a phase space $s = (x_1, ..., x_{i,} ..., x_m)$ built up n state variables x_i under which a measurement y is made, then we can define the quality of the measurement by its Fisher information

$$I(s) = \frac{1}{T}\int_0^T \frac{s''^2}{s'^4}dt, \tag{5}$$

where τ is the time period required for the system to complete a cycle; $s'(t)$ and $s''(t)$ are the tangential velocity and acceleration of the system in the phase space, calculated as a function of the state variables x_i given by

$$s'(t) = \sqrt{\sum_i^m \left(\frac{dx_i}{dt}\right)^2}, \tag{6}$$

$$s''(t) = \frac{1}{s'(t)}\sum_i^m \left(\frac{dx_i}{dt}\frac{d^2x_i}{dt^2}\right). \tag{7}$$

This dynamic interpretation of Fisher information (Frieden et.al. 2007; and Fath, 2002) implies that if the system is a constraint to small tangential velocities and acceleration, then in a specific measurement time range the system will occupy a small hyper-volume which is interpreted as the system is stable.

In this way, dynamic stability corresponds with higher levels of constant Fisher information. Then self-organized systems would tend to reduce their variability by gaining Fisher information. On the other hand, a loss of stability would look like a reduction in the system's Fisher information, and even more, sudden sharp changes could be used as an early warning of tipping points.

3 Results

In Fig. 2 we show the Fisher Information for 1988–2010 (the algorithm requires an initial calculation using the first 7 data points) of Northern Hemisphere albedo, which exhibits an oscillation with a mean value of 3.59, a maximum value of 5.35 in 1988, minimum of 2.55 in 1998 and a net reduction of 47.63% between 1988 and 2010. The reduction does not occur linearly, but shows an oscillating behavior: A first decrease happened between 1988 and 1998, followed by a gradual increase until 2007 to again decrease until 2010.

These results are not meant to provide a complete data analysis on Planetary antifragility using Fisher information of land albedo (consider the already discussed oceanic and hemispheric contributions). We are presenting some preliminary analysis to show that the idea presented is scientifically sound and more importantly, to point to further future development of the this original idea. In Fig.3 we present a visual conceptual abstract of the Planetary antifragility IDEA that is the main result of the paper.

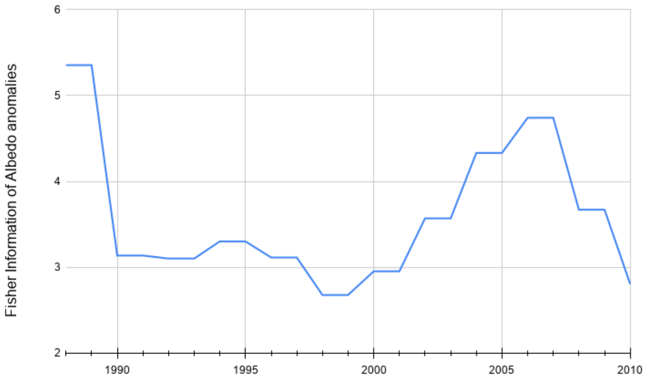


Figure 2. Fisher information for July shortwave terrestrial albedo time series from GLASS data for Northern Hemisphere

It is important to remark that an ESD Ideas article type as the present one, "presents innovative and well-founded scientific ideas in a concise way that have not been comprehensively explored"; and then the main result of the article is the *Planetary Antifragility* idea itself, that opens several paths: (1) a way to use a unified co-evolutionary representation for coupled human and natural systems (CHANS); (2) introduce a precise and quantifiable mathematical framework to systematize the interdisciplinary nature of CHANS; (3) promote and enhance the understanding of the dynamics of emerging, transitional and extreme regimes; (4) increase the interest in developing Artificial Intelligence tools (including Machine or Deep Learning) for interdisciplinary analysis beyond a mechanistic paradigm; (4) the potential to incorporate mathematical methods to improve decision making processes, incorporating CHANS risks aspects.

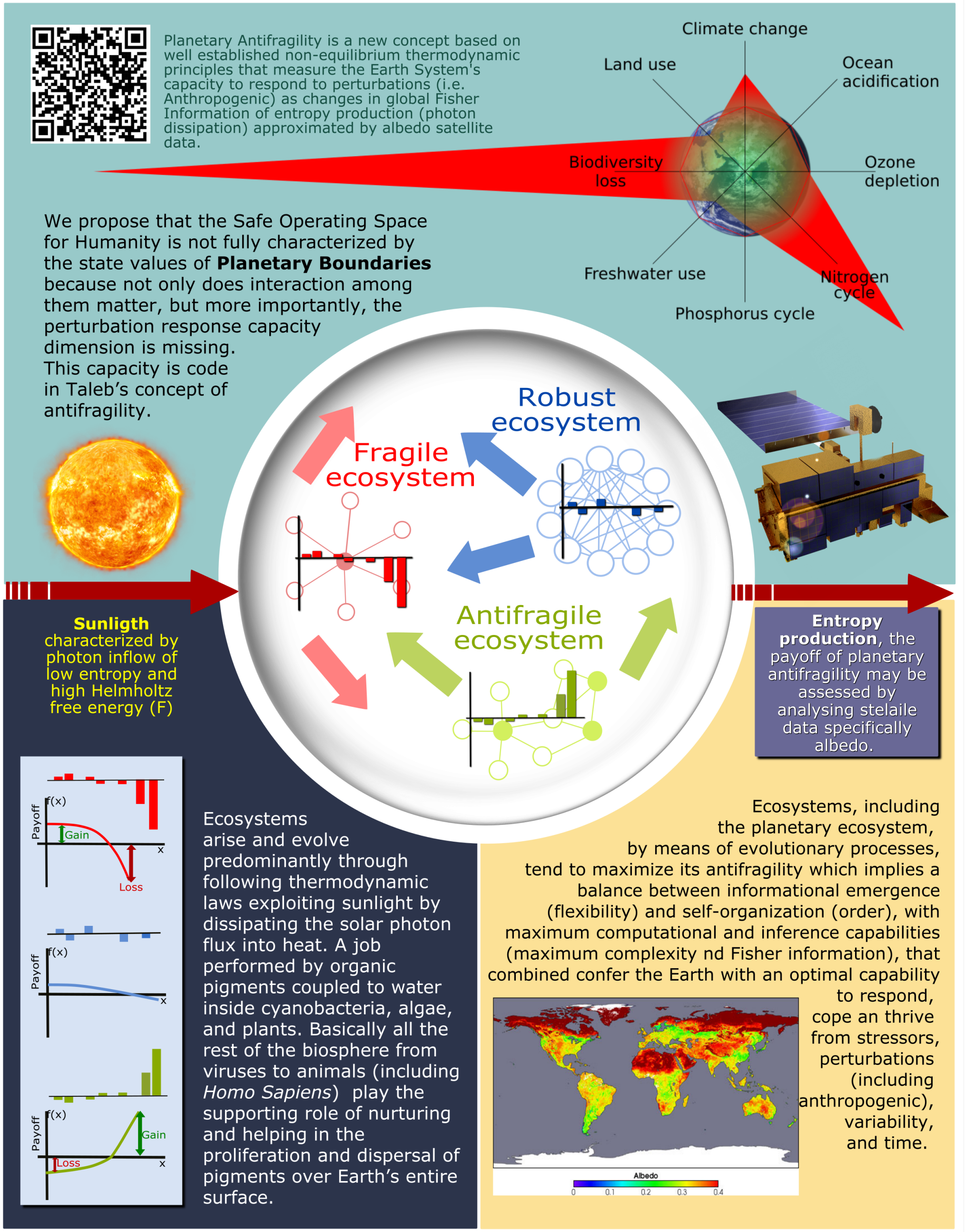
4 Discussion

The Safe Operating Space for Humanity is not fully characterized by the state values of Planetary Boundaries because not only does interaction among them matter, but more importantly the perturbation response capacity dimension is missing.

As pointed out in a recent work (Hillebrand et.al. 2020), to understand ecosystem responses to anthropogenic global change, it is key to test if the ecosystem really goes through thresholds or tipping points. In their work, the authors found that threshold transgressions were rarely detectable, either within or across meta-analyses.

On the one hand, as we have been highlighting in this work and also commented by (Dudney et. al. 2020), ecosystems seldom respond to environmental drivers in isolation, and the inclusion of interacting drivers may indicate more frequent threshold dynamics than expected from the discussed meta-analyses (Hillebrand et.al. 2020). In this way, our thermodynamic framework using global albedo as a proxy of planetary entropy production could be interpreted as a systemic response that integrates all drives and responses.

On the other hand, our informational approach using Fisher Information as a measure of the entropy production stability leads very straightforward to the medical notion of homeostasis, which has been re-framed in terms of time series analysis (Fossion



Planetary Antifragility is a new concept based on well established non-equilibrium thermodynamic principles that measure the Earth System's capacity to respond to perturbations (i.e. Anthropogenic) as changes in global Fisher Information of entropy production (photon dissipation) approximated by albedo satellite data.

We propose that the Safe Operating Space for Humanity is not fully characterized by the state values of **Planetary Boundaries** because not only does interaction among them matter, but more importantly, the perturbation response capacity dimension is missing. This capacity is code in Taleb's concept of antifragility.

Sunligth characterized by photon inflow of low entropy and high Helmholtz free energy (F)

Entropy production, the payoff of planetary antifragility may be assessed by analysing stelaile data specifically albedo.

Ecosystems arise and evolve predominantly through following thermodynamic laws exploiting sunlight by dissipating the solar photon flux into heat. A job performed by organic pigments coupled to water inside cyanobacteria, algae, and plants. Basically all the rest of the biosphere from viruses to animals (including *Homo Sapiens*) play the supporting role of nurturing and helping in the proliferation and dispersal of pigments over Earth's entire surface.

Ecosystems, including the planetary ecosystem, by means of evolutionary processes, tend to maximize its antifragility which implies a balance between informational emergence (flexibility) and self-organization (order), with maximum computational and inference capabilities (maximum complexity nd Fisher information), that combined confer the Earth with an optimal capability to respond, cope an thrive from stressors, perturbations (including anthropogenic), variability, and time.

Figure 3. Planetary Antifragility is a new concept based on well established non-equilibrium thermodynamic principles that measure the Earth System's capacity to respond to perturbations (i.e. Anthropogenic) as changes in global Fisher Information of entropy production Photon dissipation) approximated by albedo satellite data.

et. al. 2018). In their work, they found that when the human body needs to maintain some homeostatic physiological process (keep it within a defined range of values) such as blood pressure, this is only achieved by coupling it with another process that absorbs variability from the environment. For homeostasis of blood pressure, heart rate needs to absorb environmental volatility. They show that healthy people have a blood pressure that is normally distributed, while heart rate is fat-tailed to the right. Whereas when there is a chronic disease such as diabetes, blood pressure is no longer Gaussian and generates a fat-tail to the left, while heart rate becomes normally distributed. When a process is normally distributed, it means that there is a well-defined characteristic scale around which all values are clustered, with very few extreme values. Conversely, having fat-tails means that there are many extreme events, which in fact dominate the phenomenon to the degree that the characteristic scale can be lost.

Considering the above, we could explain why threshold transgressions were rarely detectable as an effect of the homeostatic processes in Ecosystems that actually tries to prevent tipping point events. For example, we could consider ecosystem functions as homeostatic processes maintained by the fluctuations in species composition. Then compositional shifts should be much more prone to threshold dynamics than ecosystem functions.

Also interesting is the similarity between the results of Fossion and co-workers (2018) with Taleb's ideas about Antifragility (Taleb, 2012). This made us reconceptualize ecosystem homeostasis or resilience, as it is generally identified in ecology, as a particular case of Taleb's conceptual framework, in which a system can be fragile, robust, or antifragile, depending on how it responds to disturbances in its environment (see Fig. 1). As quantitative Antifragility is measured as the system's response to perturbation, in order to evaluate it one needs to identify the adequate payoff function; in this case, we argue that planetary entropy production can be approximated by Earth's albedo.

Using published data (He et.al. 2014) we calculated Fisher Information for 1988–2010 of Northern Hemisphere albedo which exhibits an oscillation with a mean value of 3.59, a maximum value of 5.35, minimum of 2.55, and a net reduction of 47.63%; with a rate of 0.0013 per decade ($p < 0.01$) that is in agreement with findings by (Marcianesi et. al. 2020) who calculated, for example, a global Clear-sky albedo ($\%$) decrease of 0.24% per decade, with the confidence of 99% for land; and a decrease of 0.66% per decade, with the confidence of 99% for land. In this context land-use changes might be an important driver for antifragility loss.

Observed oscillation in Fisher information values could be interpreted as a cyclical decrease in Fisher information, as the increase after the completion of one cycle does not rebound to the original value but stays below. This decrease would be associated with a loss of stability (degradation?) overlapped with oscillations caused by changes in terrestrial albedo as a response to teleconnected climate oscillations.

Another interpretation related to this cyclical pattern could be based on critical slowing down: Strogatz 1994 proposed critical slowing down as representing the major contribution from the authors. Critical slowing down "implies that recovery upon small perturbations becomes slower as a system approaches a tipping point" (Scheffer et al. 2015). This could explain why the recovery after the first cycle of loss of Fisher information does not reach the original value, as a slowing down means less recovery in the same amount of time. If the time of recovery and loss of Fisher information is determined by oscillating climate phenomena, a slowing down of recovery would mean less recovery between cycles.

But considering the overall fisher information lost, it is not only that the planet is decreasing its albedo as a response to human perturbations (mainly Climate Change and Land use change) as the data show: if albedo is a proxy of Entropy production, what Michaelian recognized as the thermodynamic function of life (Michaelian, 2012), then loss of albedo's stability means the planet is losing a key feature of its dynamics: it's Antifragility.

This means that we may have a compounding problem because human perturbation such as Climate Change is increasing but at the same time, the planet is losing its capacity to respond to it. In that sense, we need to not only reduce or capture CO2 emissions, but we should also restore Earth's Antigrafility, which means to restore its ecosystems.

Now let us consider some problems or limitations: (1) In human health assessment the first-order approximation has been identified with the previously known reference range of value of some key physiological variables such as heart rate and systolic blood pressure. So one problem with using visible albedo as a proxy for global entropy production is we do not have the equivalent of those reference values, which in this case should be determined for each ecosystem type. In that sense, visible albedo should be applied in a spatially explicit way, not averaging mean values over large regions, but using local values because the values need to be evaluated about the correct reference values.

(2) Another problem would be considering visible albedo values without their dynamics, as can be illustrated with an analogy to human health: Consider a person with a broken arm (unhealthy state) but a healthy heart (healthy dynamics) versus an olympic athlete (healthy state) but with a condition prone to sudden cardiac syndrome (unhealthy dynamics). Given these two considerations, we decided not to rely on the direct value of albedo but rather its Fisher information, which encodes the system's dynamics in terms of its capacity to respond to perturbations.

(3) As suggested by Michaelian (2015), other problems could be that the real extent of the ecosystem considered in the measurement depends on the height of the remote sensor because of the relation with the solid angle of the detector.

(4) Consider that an albedo value is an "instant" measurement and it could be necessary to integrate measurements across a 24 h cycle (if possible) or other longer cycles; but perhaps this is not important for a long term analysis, as presented in this work. Nevertheless, it does point to the fact that this work does not present a fully developed framework for Planetary Antifragility, we still need to resolve if remote sensing measurements of albedo really can capture sufficiently well entropy production or if other signals would be needed, which most likely would be the case in a more detailed scale, for example, a particular ecosystem in a concrete region.

As the type of publication indicates, this is a first illustration of the general idea of using antifragility as a new dimension in the definition of the Safe Operating Space for Humanity and after discussing some aspects of the advantages and problems with using albedo measurements derived from satellite imagery in this manuscript, we would very much like to further explore other variables that could be used to construct indicators for planetary antifragility.

In addition to albedo, we think it would be very interesting to eventually incorporate other entropy production sources as could be the bioacoustic signals and maybe also ecosystem respiration. Every sound emitted by a living agent in an ecosystem somehow is coding a part of the ecosystem metabolism into the signal. Also, important bioacoustic signals are produced by members of the Animalia kingdom and would prevent the problem posed by defaunated ecosystems, which from a plant perspective could seem to be healthy (in the short term). For its part, ecosystem respiration includes soil respiration and soil is a complex system that incorporates all spheres (biosphere, geosphere, atmosphere, hydrosphere), several biogeochemical processes, many spatial and time scales, so it conjugate many sources of information about the ecosystem. Although there are great projects as Ameriflux (https://ameriflux.lbl.gov/) that collect data of ecosystem respiration (among others) in many places of America (mostly North America), currently there is not enough data for considering these variables at a planetary scale, but the concept may downscale to ecosystem-scale both using remote sensing and in situ data, which could work also as a benchmark against other ecosystem health metrics such as Integrity.

Finally, as happens always when we introduce new concepts, they lead us to revisit others, in this case, the Ecosystem definition that traditionally is understood in its basic form as a spatially explicit community of living organisms in conjunction with the nonliving components of their environment, interacting as a system. As pointed out by Jax (2007) managing ecosystems or increase their theoretical understanding, requires a clear conceptualization of what ecosystems are (Schaeffer and Cox 1992; Sagoff 2003; Jax 2005); however, there are different and sometimes incompatible definitions of the notion of ecosystem (see e.g. Jax et al. 1998; Jax 2006).

Depending on the specific definition under use, there might be different sets of questions difficult to answer. In particular, under the basic definition given above: How many different species and interactions are necessary to constitute an ecosystem? Is a community of trees of different species an ecosystem? What about function, dynamics, stability? Are there any requirements in terms of spatial extension and connectivity? Are there different types of ecosystems for example, what happens with modified, degraded, or perturbed “ecosystems”? To what extend is a “modified” ecosystem of type A, still as an A ecosystem? Based on what characteristics a type of ecosystem should be defined? What happens with different ecosystems that share some interactions, species? Does this definition allow us to understand predict succession, and ecological tipping points?

Also, as commented by Sagoff (2003), to improve our understanding about ecosystems including the planetary, its definition should: (1) define and classify them, and thus determine the conditions under which it remains the "same" system through time and change; (2) find ways to reject as well as to create mathematical models of the ecosystem functioning and evolution; (3) make possible to identify efficiently the causes of ecosystem organization; (4) show how Ecology can potentially help to solve socio-environmental problems.

We think that the Antifragility framework could help to improve ecosystem definition in a manner that many of these questions and goals are easier to tackle. So we are incorporating the ideas of this paper in this new definition: An ecosystem is an open thermodynamic system constituted by a community of living organisms in conjunction with the nonliving components of their environment; that through its interactions and evolutionary processes, constrained by the external conditions; self-organized in a maximum solar photon flux dissipation , in which the system is at criticality, with maximum computational and inferential capabilities that allows it to respond and thrive under uncertainty, stressors, perturbations and ultimately time, in a well defined geographic context.

Code/Data availability

Code available at:https://github.com/csunlab/fisher-information

Data is published and available in the corresponding reference (He et.al. 2014).

Author contribution

OL-C contributions: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft preparation, Writing – review and editing

MK contibutions:Conceptualization, Investigation, Methodology, Supervision, Writing – original draft preparation, Writing – review and editing

ERC contributions: Major revision writing, editing.

JL contributions: Major revision writing, editing.

Competing interests

The authors declare that they have no conflict of interest.

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