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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. We present a systems dynamics measure of this perturbation response capacity under the Antifragility framework. Here we define, for the first time, Planetary Antifragility as the changes of shortwave global albedo anomalies for the July months in the northern hemisphere from 1982 to 2010, which shows a net reduction of 47.63%. This loss in 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" by Rockström et al. (2009) identified nine core biogeochemical processes, with Planetary Boundaries (PB) for each, within which the authors expect that humanity would operate safely.The central idea of their work is that transgressing one or more PB may lead to catastrophic planetary tipping point most likely incompatible with modern human organization or even with human survival.

Despite PB has been widely accepted, there are some issues that remain open: (a) Although the authors recognize that PB are not interdependent, as transgressing one may both shift the position of other boundaries and cause them to be transgressed, the individual threshold values of the Planetary Limits (LP) do not establish the true threshold configuration. Then it would be necessarily to have a metric of the interaction among the whole network of PB.(b) The impacts of transgressing PB will be a function of the social–ecological resilience the authors say, but as has been raised by Equihua et al. (2020), the concept of resilience is a special and limited case of Antifragility; (c) finally, anthropic activities may be interpreted as a disturbance of the Earth system, then a threshold to define a Safe Operating Space for Humanity should also include planetary Antifragility.

In their work, Rockström and co-workers does recognise 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

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thresholds will also be crossed in other processes, such as the climate system. So resilience is a key concept on PB framework
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Nevertheless, recent work (Equihua et al., 2020) has showed that resilience is a special case in the frafility-antifragility spectrum. It is an intermedate type of response to perturbation near to robustness where the systems tolerate stress and remain the same. But living systems are undergoing evolutionary processes that require them to do far more than simply endure perturbations; they most have some features that allow them to not only cope but gain from stressors (up to a point), variability, and uncertainty. This is simple logic: any system that gain from variability (even by merely random) eventually undergo their competitors because time is the ultimate source of variability and so the system will accumulate any little gain. So through processes of learning and adaptation, what we will observe in the present is the predominance of those systems that have previously gain from environmental variability. This feature is essentially what Taleb called Antifragility (Danchin et al., 2011; Taleb, 2012)

A formal definition of Antifragility as a non-linear convex response in the payoffs space is found elsewhere (Taleb and Douady, 2013; Taleb, 2018) and can be summarized as follows.

Let $f(x)$ be a two times continuously differentiable payoff function $f(x)$ with a convexity defined by $\frac{\partial^2 f}{\partial x^2} \geq 0$ which can be simplified as $\frac{1}{2}\left[f(x+\Delta x)+f(x-\Delta x)\right] \geq f(x)$.

Then we can see that a dose increase will have 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 $\sum\left[\alpha_i f(x_i)\right] \geq f\left[\sum(\alpha_i x_i)\right]$. Simplifying the argument, under the correct conditions we end up with $f(nx) \geq nf(x)$.

If the payoff function $f(x)$ of the random variable X with support in $[a,b]$ is well behaved and convex; the Jensen's Inequality implies that

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

Or as shown in (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 capture the idea of Planetary Antifragility in the context of an enhanced "Safe Operating Space for Humanity" that incorporate not only PB alone but also the capacity of the Earth to respond in a convex way to anthropogenic stressors.

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2 Methods

2.1 Entropy production as Payoff function

As noticed in previous work by Michaelian (2005) and Michaelian (2015), Ecosystems arise and evolve, as any other physical system, under the laws of thermodynamics; in particular under the imperative of dissipating the solar photon flux into heat. In his work, Michaelian as Ulanowicz and Hannon (1987) before, 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

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

where

$$L(\lambda) = \frac{n_0 k c}{\lambda^4}\left[\left(1 + \frac{\lambda^5 I(\lambda)}{n_0 h c^2}\right)\ln\left(1 + \frac{\lambda^5 I(\lambda)}{n_0 h c^2}\right) - \left(\frac{\lambda^5 I(\lambda)}{n_0 h c^2}\right)\ln\left(\frac{\lambda^5 I(\lambda)}{n_0 h c^2}\right)\right] \quad (4)$$

Nevertheless, it is necessary to find a systemic variable that contains relevant information on the entropy production of ecosystems and is measured at a planetary scale. Following original ideas discussed by Ulanowicz and Hannon (1987) and Michaelian (2015), the possibility of using satellite measurements of Albedo as a proxy of Eq(3). In this work we took 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 Fisher information in the same way Ahmad and Co-workers has done for global-mean temperature (1880-2015) (Ahmad et al., 2016). In their work, the authors organized the time series data such that each month represents one system variable and end up with 12 variables describing global temperature anomalies from January to December for each time step (year).

In previous work it has been propose how as both Complexity and Fisher Information are maximum at Criticality, which has also been proposed as a fingerprint of Ecosystem Health (López-Corona and Padilla, 2019; Ramírez-Carrillo et al., 2018); and as Ecosystem Antifragility may be measured using Complexity, then Fisher Information of ecosystems key variables in form of a time series (for example albedo) could be a good proxy of its Antifragility.

2.2 Data inputs

Data used here, 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 component; one for surface reflectance and one for 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 (Pedelty 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 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 2)(He et al., 2014).

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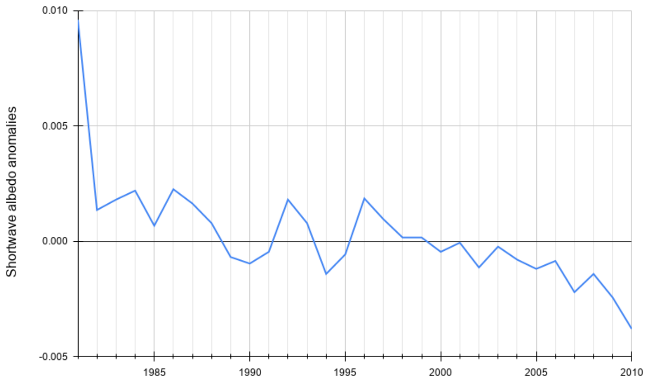

Figure 1. July shortwave albedo time series from GLASS data for Northern Hemisphere

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 Ahmad et al. (2016) algorithm for asses Fisher information, available at https://github.com/csunlab/fisher-information.

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, 2007; Cabezas and Fath, 2002) implies that if the system is 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 being stable.

In this way, dynamic stability corresponds itself 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 looks

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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. 3 we show the Fisher Information for 1988–2010 (the algorithm requires the first 7 points to start the calculation) 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 in a linear fashion, but shows an oscillating behaviour: A first decrease happened between 1988 and 1998, followed by a gradual increase until 2007 to again decrease until 2010.

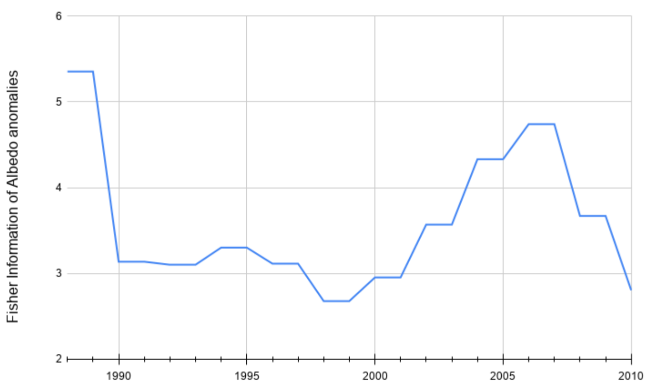

Figure 2. Fisher information for July albedo time series

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 ecosystem really goes trough 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 and Suding (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 proxy of planetary entropy production could by interpreted as a systemic response that integrate all drives and responses.

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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, that has been re-framed in terms of time series analysis by Fossion 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. In their work 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 et al. (2018) with Taleb's ideas about Antifragility (Taleb, 2012). This made us reconceptualise 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 have discussed it is planetary entropy production, which may 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%. So it is not only that the planet is decreasing its albedo as a response of human perturbations (mainly Climate Change and Land use change) as the data show, 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 a confidence of 99% for land; and a decrease of 0.66% per decade, with a confidence of 99% for land. As albedo is a proxy of Entropy production, what Michaelian recognized as the thermodynamic function of life (Michaelian, 2012), loss of albedo's stability means the planet is losing a key feature of its dynamics: the planet'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 to reduce or capture CO2 emissions, but we should also restore Earth's Antigrafility which means to restore its ecosystems.

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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

Competing interests

The authors declare that they have no conflict of interest.

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References

Johan Rockström, Will Steffen, Kevin Noone, Åsa Persson, F Stuart Chapin, Eric F Lambin, Timothy M Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, et al. A safe operating space for humanity. *nature*, 461(7263):472–475, 2009.

Miguel Equihua, Mariana Espinosa Aldama, Carlos Gershenson, Oliver López-Corona, Mariana Munguía, Octavio Pérez-Maqueo, and Elvia Ramírez-Carrillo. Ecosystem antifragility: beyond integrity and resilience. *PeerJ*, 8:e8533, 2020.

Antoine Danchin, Philippe M Binder, and Stanislas Noria. Antifragility and tinkering in biology (and in business) flexibility provides an efficient epigenetic way to manage risk. *Genes*, 2(4):998–1016, 2011.

Nassim Nicholas Taleb. *Antifragile: Things that gain from disorder*, volume 3. Random House Incorporated, 2012.

Nassim Nicholas Taleb and Raphael Douady. Mathematical definition, mapping, and detection of (anti) fragility. *Quantitative Finance*, 13 (11):1677–1689, 2013.

Nassim Nicholas Taleb. (anti) fragility and convex responses in medicine. In *International Conference on Complex Systems*, pages 299–325. Springer, 2018.

Karo Michaelian. Thermodynamic stability of ecosystems. *Journal of theoretical biology*, 237(3):323–335, 2005.

Karo Michaelian. Photon dissipation rates as an indicator of ecosystem health. In *Environmental Indicators*, pages 15–36. Springer, 2015.

Robert E Ulanowicz and Bruce M Hannon. Life and the production of entropy. *Proceedings of the Royal society of London. Series B. Biological sciences*, 232(1267):181–192, 1987.

Tao He, Shunlin Liang, and Dan-Xia Song. Analysis of global land surface albedo climatology and spatial-temporal variation during 1981–2010 from multiple satellite products. *Journal of Geophysical Research: Atmospheres*, 119(17):10–281, 2014.

Nasir Ahmad, Sybil Derrible, Tarsha Eason, and Heriberto Cabezas. Using fisher information to track stability in multivariate systems. *Royal Society open science*, 3(11):160582, 2016.

O López-Corona and P Padilla. Fisher information as unifying concept for criticality and antifragility, a primer hypothesis. *Researchers. One*, 2019.

Elvia Ramírez-Carrillo, Oliver López-Corona, Juan C Toledo-Roy, Jon C Lovett, Fernando de León-González, Luis Osorio-Olvera, Julian Equihua, Everardo Robredo, Alejandro Frank, Rodolfo Dirzo, et al. Assessing sustainability in north america's ecosystems using criticality and information theory. *PloS one*, 13(7):e0200382, 2018.

Shunlin Liang, Xiang Zhao, Suhong Liu, Wenping Yuan, Xiao Cheng, Zhiqiang Xiao, Xiaotong Zhang, Qiang Liu, Jie Cheng, Hairong Tang, et al. A long-term global land surface satellite (glass) data-set for environmental studies. *International Journal of Digital Earth*, 6(sup1): 5–33, 2013.

B Qu, Z Xi, and C Chen. A method for toa location based on scattering models in nlos environments. *Fire Control and Command Control*, 39(5):27–30, 2014.

Jeffrey Pedelty, Sadashiva Devadiga, Edward Masuoka, Molly Brown, Jorge Pinzon, Compton Tucker, Eric Vermote, Stephen Prince, Jyotheshwar Nagol, Christopher Justice, et al. Generating a long-term land data record from the avhrr and modis instruments. In *2007 IEEE International Geoscience and Remote Sensing Symposium*, pages 1021–1025. IEEE, 2007.

Qiang Liu, Lizhao Wang, Ying Qu, Nanfeng Liu, Suhong Liu, Hairong Tang, and Shunlin Liang. Preliminary evaluation of the long-term glass albedo product. *International Journal of Digital Earth*, 6(sup1):69–95, 2013.

B Roy Frieden. Introduction to fisher information: its origin, uses, and predictions. In *Exploratory data analysis using Fisher information*, pages 1–41. Springer, 2007.

https://doi.org/10.5194/esd-2021-26
Preprint. Discussion started: 12 May 2021

Heriberto Cabezas and Brian D Fath. Towards a theory of sustainable systems. *Fluid phase equilibria*, 194:3–14, 2002.

Helmut Hillebrand, Ian Donohue, W Stanley Harpole, Dorothee Hodapp, Michal Kucera, Aleksandra M Lewandowska, Julian Merder, Jose M Montoya, and Jan A Freund. Thresholds for ecological responses to global change do not emerge from empirical data. *Nature Ecology & Evolution*, 4(11):1502–1509, 2020.

Joan Dudney and Katharine N Suding. The elusive search for tipping points. *Nature Ecology & Evolution*, 4(11):1449–1450, 2020.

Ruben Fossion, Ana Leonor Rivera, and Bruno Estañol. A physicist's view of homeostasis: how time series of continuous monitoring reflect the function of physiological variables in regulatory mechanisms. *Physiological measurement*, 39(8):084007, 2018.

F Marcianesi, G Aulicino, and P Wadhams. Arctic sea ice and snow cover albedo variability and trends during the last three decades. *Polar Science*, page 100617, 2020.

Karo Michaelian. Hess opinions" biological catalysis of the hydrological cycle: life's thermodynamic function". *Hydrology and Earth System Sciences*, 16(8):2629–2645, 2012.