A peer-reviewed version of this preprint was published in PeerJ on 11 February 2020.

View the peer-reviewed version (peerj.com/articles/8533), which is the preferred citable publication unless you specifically need to cite this preprint.

Ecosystem antifragility: Beyond integrity and resilience

Miguel Equihua Zamora, Mariana Espinosa, Carlos Gershenson, Oliver López-Corona, Mariana Munguia, Octavio Pérez-Maqueo, Elvia Ramírez-Carrillo

1 Red ambiente y sostenibilidad, Instituto de Ecología A.C, Xalapa, Veracruz, Mexico
2 Doctorado en Ciencias Sociales y Humanidades, UAM-Cuajimalpa., cdmx, Mexico
3 IIMAS, Universidad Nacional Autónoma de México, cdmx, Mexico
4 Centro de Ciencias de la Complejidad (C3), Universidad Nacional Autónoma de México, cdmx, Mexico
5 ITMO University, St. Petersburg, 199034, Russian Federation, St. Petersburg, Russia
6 Cátedras CONACyT, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), cdmx, Mexico
7 Red ambiente y sostenibilidad, Instituto de Ecología A.C., Xalapa, Veracruz, Mexico
8 Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), CDMX, Mexico
9 Facultad de Psicología, Universidad Nacional Autónoma de México, cdmx, Mexico

Corresponding Author: Oliver López-Corona
Email address: lopezoliverx@otrasenda.org

We review the concept of ecosystem resilience in its relation to ecosystem integrity from an information theory approach. We summarize the literature on the subject identifying three main narratives: ecosystem properties that enable them to be more resilient; ecosystem response to perturbations; and complexity. We also include original ideas with theoretical and quantitative developments with application examples. The main contribution is a new way to rethink resilience, that is mathematically formal and easy to evaluate heuristically in real-world applications: ecosystem antifragility. An ecosystem is antifragile if it benefits from environmental variability. Antifragility therefore goes beyond robustness or resilience because while resilient/robust systems are merely perturbation-resistant, antifragile structures not only withstand stress but also benefit from it.
Ecosystem Antifragility: Beyond Integrity and Resilience.

M. Equihua²,*, M. Espinosa⁸,*, C.Gershenson³,⁵,⁶,*, O. López-Corona¹,²,³,*, M. Munguía⁷,*, O. Pérez-Maqueo²,*, and E. Ramírez-Carrillo⁴,*

¹Cátedras CONACyT, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), CDMX, México
²Red ambiente y sostenibilidad, Instituto de Ecología A.C., Xalapa, México
³Centro de Ciencias de la Complejidad (C3), Universidad Nacional Autónoma de México, CDMX, México
⁴Centro de Ciencias de la Complejidad (C3), Instituto de Matemáticas (IIMAS), Universidad Nacional Autónoma de México, CDMX, México
⁵ITMO University, St. Petersburg, 199034, Russian Federation.
⁶ITMO University, St. Petersburg, 199034, Russian Federation.
⁷Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), CDMX, México
⁸Doctorado en Ciencias Sociales y Humanidades, UAM-Cuajimalpa.

Corresponding author:
Following the Hardy-Littleton rule, all authors will appear in alphabetical order. And all are corresponding authors*

Email address: equihuam@gmail.com; mariana.espinosa.aldama@gmail.com; cgg@unam.mx; olopez@conacyt.mx; mariana.mungua@conabio.gob.mx; octavio.maqueo@gmail.com; elviarc@gmail.com

ABSTRACT

We review the concept of ecosystem resilience in its relation to ecosystem integrity from an information theory approach. We summarize the literature on the subject identifying three main narratives: ecosystem properties that enable them to be more resilient; ecosystem response to perturbations; and complexity. We also include original ideas with theoretical and quantitative developments with application examples. The main contribution is a new way to rethink resilience, that is mathematically formal and easy to evaluate heuristically in real-world applications: ecosystem antifragility. An ecosystem is antifragile if it benefits from environmental variability. Antifragility therefore goes beyond robustness or resilience because while resilient/robust systems are merely perturbation-resistant, antifragile structures not only withstand stress but also benefit from it.

1 INTRODUCTION

Sustainable development needs to preserve the structure and functioning of natural ecosystems, i.e. their integrity, as a Sine qua non condition. In previous work [25] an operational framework has been developed to quantify ecosystem integrity as well as viable standards useful for managing the way people intervene ecosystems, promoting development along sustainable avenues.

Humans are starting to be recognized as an overwhelming forcing factor modulating biosphere dynamics. In this view, the Earth system can be interpreted as entering in a geological era that can be called the Anthropocene [99] the Technocene [62] or even Capitalocene [41], depending on the conceptual stance adopted. Because of this driving influence of human decisions, there has been long interest in understanding and measure the way ecosystems recover (or not) from human perturbations. To operationalize sustainability, we require working definitions of this ecosystem ability and metrics to assess it, in addition to ecosystem integrity (as a component of a likely state variable accounting for the amount of natural capital assets: condition × extension). The recovery property has already been encapsulated into the ecosystem resilience concept. Here, we propose that information theory is a suitable framework to encompass both ecosystem integrity and resilience.
According to [25], numerous studies have aimed to find a suitable and inclusive definition of ecological integrity; however, no general consensus has been achieved to date. In their work, Equihua and co-workers embrace a complex systems approach in which ecosystems are considered as self-organized entities constrained in their structure (including biological composition or biodiversity), and function by thermodynamic dissipative system properties [52, 87, 67, 72] and evolutionary processes [61].

The concept of ecosystem resilience was first introduced by Holling [46] to portray the persistence of natural structures in the presence of environmental stressors due to natural or anthropogenic triggers. In his seminal work, Holling follows a system dynamics analysis. There, resilience concept is defined as: “the capacity of a system to absorb disturbance and reorganize while undergoing a change so as to still retain essentially the same function, structure, identity, and feedbacks” [109]. Nevertheless, resilience or stability, which is commonly used as synonym, have at least 163 different definitions (grouped in at least 70 concepts of stability/resilience) [37]. For example, Saint-Béat and co-workers [91] summarize resilience and others related concepts often used interchangeably as follows:

- Resilience is the rate at which a system returns after a disturbance to the equilibrium state [20, Pimm]. Long return time is equivalent to low resilience. A community’s resilience relies on the least resilient species (the slowest to return to equilibrium). This definition of resilience corresponds to the ‘engineering resilience’ defined by [47] and assumes that there is only one balance or a stable state [38].

- Persistence is the time for a variable to remain in the same state before changing to a different one [Pimm]. Persistence is a measure of a system’s capacity to preserve itself over time. [63]

- Resistance is described as the capacity of an ecosystem in the presence of external disturbance to preserve its initial state. [43]. Only small changes (in amount and intensity) within an ecosystem correspond to high resistance. This concept is similar to the ‘ecological resilience’ defined by [47] and suggests that various stable states exist.

- Robustness relates to the durability of the stability of the environment. Robustness is then a measure of the amount of disturbance an ecosystem can endure before it changes to a different state. [63]. The more robust the food web is, the more stable it is.

In this paper, we ascertain that both integrity and resilience frameworks can be formalized using information theory. The second law of thermodynamics is probabilistic by its very nature, because its formulation involves a probabilistic description of the state of a system [78]. It is customary in information theory to relate the Shannon information of a random variable $X$ (microscopic state of a physical system) with the thermodynamic entropy of the system. This relation can be expressed as

$$H(X) = -k \sum_x [p(x) \log p(x)],$$

where $p(x)$ is the probability density and assuming $k$ as the Boltzmann’s constant. Even more, once the connection between entropy (thermodynamics) and Shannon information (information theory) is made, we are able to calculate self-organization as the complement $(1 - H(X))$ of Shannon information [26]. Following [25, 15], an ecosystem that is in a high level of integrity is at full capacity to develop as a natural consequence of the continued operation of the processes of self-organization to dynamically incorporate the original species set at its location, which can be interpreted as the mechanistic basis of what is known as ecosystem resilience.

It is clear then that in order to construct a unified narrative for ecosystem integrity and resilience, information theory is a suitable framework candidate. With that aim, we present in this paper a critical review of the literature and then develop a novel proposal related to what we consider a suitable concept not incorporated in dynamic ecosystem understanding so far: antifragility, which is the non linear (convex) response of a system to profit from variability in the payoffs space, or in simple words the ability of a system to benefit from surrounding randomness.
Figure 1. Ecosystem Integrity three-tier model. Ecological integrity is understood to be an underlying attribute in the constitution of ecosystems that produce specific manifestations in their structural characteristics, development processes, and acquired composition. In short, ecological integrity arises from processes of self-organization derived from thermodynamic mechanisms that operate through the locally existing biota, as well as the energy and materials at their disposition, until attaining “optimal” operational points which are not fixed, but rather vary according to variations in the physical conditions or changes produced in the biota or the environment. In the figure we show the three-tier model of ecosystem integrity (3TEI), the inner tier is hidden to the observer, but its status can be inferred by the information available at the instrumental or observational tier where measurements on structure (including composition or other biodiversity features) and function are obtained, of course considering the context where the ecosystem is developing. Arrow tips indicate the direction of assumed mechanistic influence, although information can go either way.

2 SURVEY METHODOLOGY

It has recently been shown that Web of Science and Scopus is invisible to a big proportion of highly-cited papers in the social sciences and humanities. And even when the percentage of missing highly cited papers in Web of Science (WOS) and Scopus is in the natural, lives and social sciences. The Spearman quotation correlation coefficients in Google Scholar are more powerful in all fields compared to Web of Science and Scopus. The researchers conclude that highly cited papers available in the inclusive Google Scholar database actually show important deficiencies in the coverage of the Web of Science and Scopus in certain study fields. Consequently, using these selective databases to calculate bibliometric indices based on the number of highly cited papers could generate partial evaluations in poorly covered fields [68].

For these reasons we choose Google Scholar as the search engine in which we use the term: “Ecosystem Resilience” AND “Information theory” AND “Ecosystem Integrity”. After excluding patents and citations we end up with 20 items. Of those 20 co-occurrences, books and patents were discarded, leaving 10 entries that where fully read. Finally, only 7 items were selected to be analyzed and included in the present review. However, Google Scholar, does not provide easy access to cited references, which indicate the knowledge background of the selected items. For that reason, the analysis was completed with data from the Web of Science and the Astrophysics Data System to visualise their cited references network using Science of Science (Sci2) Tool and Gephi. To further analyze the literature set, a text corpus was assembled taking the text of the title and abstract of target documents as a bag of words. This small corpus was then processed with latent Dirichlet allocation (LDA) and latent semantic analysis (LSA) techniques.
FINDINGS

Basic scientometrics i.e word clouds

In Table 1 we show basic metrics for papers selected and in Fig. 2 the results of applying LDA analysis to this corpus, based on [95] with an interactive viz that can be opened in any browser. A video explaining the use of this kind of viz could be found in here. According with LDA, papers can be allocated to the topics as indicated in Table 2; although, topics can be concurrently present in any paper.

<table>
<thead>
<tr>
<th>Source</th>
<th>Google Scholar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Papers</td>
<td>7</td>
</tr>
<tr>
<td>Citations</td>
<td>454</td>
</tr>
<tr>
<td>Years</td>
<td>23</td>
</tr>
<tr>
<td>Cites-Year</td>
<td>19.74</td>
</tr>
<tr>
<td>Cites-Paper</td>
<td>64.86</td>
</tr>
<tr>
<td>Cites-Author</td>
<td>149.78</td>
</tr>
<tr>
<td>Papers-Author</td>
<td>1.95</td>
</tr>
<tr>
<td>Authors-Paper</td>
<td>4</td>
</tr>
<tr>
<td>h_index</td>
<td>7</td>
</tr>
<tr>
<td>g_index</td>
<td>7</td>
</tr>
<tr>
<td>hc_index</td>
<td>6</td>
</tr>
<tr>
<td>hl_index</td>
<td>1.75</td>
</tr>
<tr>
<td>hl_norm</td>
<td>6</td>
</tr>
<tr>
<td>AWCR</td>
<td>71.34</td>
</tr>
<tr>
<td>AW_index</td>
<td>8.45</td>
</tr>
<tr>
<td>AWCRpA</td>
<td>17.93</td>
</tr>
<tr>
<td>e_index</td>
<td>20.12</td>
</tr>
<tr>
<td>hm_index</td>
<td>1.95</td>
</tr>
<tr>
<td>QueryDate</td>
<td>2019-02-04</td>
</tr>
<tr>
<td>Cites_Author-Year</td>
<td>6.51</td>
</tr>
<tr>
<td>hl_annual</td>
<td>0.26</td>
</tr>
<tr>
<td>h_coverage</td>
<td>100</td>
</tr>
<tr>
<td>g_coverage</td>
<td>100</td>
</tr>
<tr>
<td>star_count</td>
<td>3</td>
</tr>
<tr>
<td>year_first</td>
<td>1996</td>
</tr>
<tr>
<td>year_last</td>
<td>2018</td>
</tr>
<tr>
<td>ECC</td>
<td>454</td>
</tr>
</tbody>
</table>

Table 1. Table shows basic metrics for the Google Scholar search.

In Fig. 3 we present a main axes plot based in a latent semantic analysis (LSA). Both LDA and LSA suggest it is possible to recognize four groups in the corpus, which are further discussed in the section analyzing perceived literature narratives below. In addition, the analysis of the citation network reveals several unconnected sub-groups, while the cited references in general are very poorly connected. We interpret this findings as evidence of poor interdisciplinary crossover on the conceptual development of ecological resilience and integrity, which prompted our interest in the issues we discuss in this paper.

<table>
<thead>
<tr>
<th>LDA Topic</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cabezas 2005</td>
</tr>
<tr>
<td>1</td>
<td>Sidle 2013</td>
</tr>
<tr>
<td>2</td>
<td>Aronson 1996</td>
</tr>
<tr>
<td>2</td>
<td>Gustavson 2002</td>
</tr>
<tr>
<td>3</td>
<td>Saint-Béat 2015</td>
</tr>
<tr>
<td>4</td>
<td>Filotas 2014</td>
</tr>
<tr>
<td>4</td>
<td>Schmeller 2018</td>
</tr>
</tbody>
</table>

Table 2. Allocation of paper to dominant topic found by LDA.
Figure 2. Latent Dirichlet Allocation (LDA) analysis based on [95] with an interactive viz to be opened in any browser. In short, the interface has two main panels. Topic pattern on the left and terms frequencies on the right. The left panel shows a general perspective of the discovered subjects indicating how common each is in the corpus (the set of papers) and how they relate to each other; the subjects are plotted as circles whose centers are characterized by the computed range between the subjects (projected into 2 dimensions). The prevalence in the corpus of each topic is proportional to the circle size. The right panel has a bar chart showing the meaning of terms, informative of the possibly interpretation of the topics essence. You can pick any subject interactively and find out the function of terms in it. Two overlaid bars are shown at each place when pointing to a subject, displaying the topic-specific frequency of each word (in red) and the corpus-wide frequency (in blue gray). When no topic is selected, the right panel displays the top 30 most salient terms for the dataset. A video explaining the use of this kind of viz could be found in here.

In Fig.5 we show a TreeMap for the type of documents that cite the set of reviewed ones; in Fig6 the organizations of origin for the documents that cite the set of reviewed ones; in Fig.7 we show the number of documents that cite the set of reviewed ones; and in Fig.8 the distribution of documents that cite the set of reviewed ones in terms of research field.

2.1 Literature narratives

We consider that in the context of the relation of resilience with ecological integrity under the lens of information theory, narratives has gone from trying to identify (with information theory tools) ecosystem features that allow them to be more resilient and hence maintain their integrity, to a more technical approach using times series or network analysis in addition to new mathematical concepts (see fig. 9). The importance of interactions and a complex system approach is highlighted. Finally, the field completes a circle getting again back into ecology and refining resilience feature and properties of ecosystems.

2.2 Resilience features and properties I

Noble and Slayter [? ] have described several categories of essential life history characteristics that are helpful in determining a species ’ reaction to recurrent disturbances. In the revised paper by Aronson and co-workers [4], the authors make reference to a previous work [3] where they modified the Noble and Slayter’s concept [77], defining Vital Ecosystem Attributes (VEAs). The VEAs attempt to capture
those features or attributes that are correlated with and that can serve as ecosystem structure and function indicators, the same attributes in the Ecosystem Integrity Model (3TEI) instrument layer from Equihua and colleagues [25]. In that way, one may interpret that a resilient ecosystem is one for which VEAs fall into an optimal range, represented as ecosystem integrity. But unlike the 3TEI model, VEAs requires intense (often cost and not scalable) fieldwork that most likely make VEAs not such a good option for a national assessment of ecosystem condition trends.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perennial species richness</td>
<td>Biomas productivity</td>
</tr>
<tr>
<td>Annual species richness</td>
<td>Soil organic matter</td>
</tr>
<tr>
<td>Total plant cover</td>
<td>Maximum available water reserves</td>
</tr>
<tr>
<td>Aboveground phytomass</td>
<td>Coefficient of rain off efficacy</td>
</tr>
<tr>
<td>Beta diversity</td>
<td>Rain use efficacy</td>
</tr>
<tr>
<td>Life form spectrum</td>
<td>Length of water availability period</td>
</tr>
<tr>
<td>Keystone species</td>
<td>Nitrogen use efficacy</td>
</tr>
<tr>
<td>Microbial biomass</td>
<td>Microsymbiont effectiveness</td>
</tr>
<tr>
<td>Soil biota diversity</td>
<td>Cyclic indexes</td>
</tr>
</tbody>
</table>

Table 3. Vital Ecosystem Attributes according to [3]
From the idea of VEAs (see Table 3), Aronson and his colleagues [4] extracted the insight into considering 16 quantifiable characteristics for use on a more particular spatial scale: the landscape as a multifunctional environment. The writers intend to use the fresh Vital Landscape Attributes (VLAs) to evaluate the outcomes of ecological restoration or rehabilitation conducted from the view of the landscape. Most interesting is the chance that as VEAs relate to the integrity of the ecosystem, VLAs (see Table ??) could give way to a 3TLI model.

In a different line of thought, the reviewed paper by Gustavson and co-workers [39] develops a general index that may serve as a proxy of ecosystem resilience from an information theory perspective. The authors report that attempts have been made to describe and evaluate resilience, but an overall predictive or theoretical connection between resilience characteristics and ecosystem dynamics has yet
to be advanced. Similarly, much has been discussed about possible interactions between stability and structure and, generally speaking, predictable interactions between resilience characteristics and how
ecosystems work are not intuitively evident and may not exist.

To this end, they turn to Ulanowicz’s Ascendancy Theory which is a measure of the magnitude of the information flow through an ecosystem’s network framework. Some constraints for its use are that it requires a comparatively full description of the nature and magnitude of all species interactions. Ascendancy is defined by the average mutual information as presented between component \( a \) to \( b \) is:

\[
A_s = K \sum_i \sum_j p(a_i, b_j) \log \left( \frac{p(b_j | a_i)}{p(b_j)} \right),
\]

(2)

where, \( p(b_j | a_i) \), the probability of \( b_j \) given that \( a_i \) has occurred; and \( p(b_j) \), the probability that \( b_j \) will occur.

The upper limit of ascendancy is the capacity for growth, and the distinction between ability and ascendancy is called the overhead system, which represents a multiplicity of paths and can therefore eventually be linked with the complexity of the ecosystem. A complex structure is key for sustainability because the diversity of processes plays a crucial role on system survives. In particular, to enhance ecosystem’s long-term sustainability, a particular densely connected network structure is advantageous. Such a scheme is sufficiently effective and sufficiently varied. Efficiency-diversity equilibrium is essential to ecosystem resilience. Ultimately, ascendancy captures in a single index the capacity of an ecosystem to prevail against disruption by virtue of its combined organisation and size, it was suggested that, in order to attain sustainability, it should always be possible for systems of human use to regain their ascendancy within culture and ecosystems.

### 2.3 Ecosystems response to perturbations

The main interest in the selected paper form Cabezas and co-workers is not ecosystem integrity nor resilience per se but sustainability. A concept they relate to integrated systems comprising humans and the rest of nature (probably a socioecosystem). They emphasize that the structures and operation of the human element (in terms of culture, economy, law, etc.) must be such that they strengthen or encourage the persistence of the natural component’s structures and operation (in terms of ecosystem trophic connections, biodiversity, biogeochemical cycles, etc.), and vice versa. It is in the idea that “persistence” and “operation of the natural component” that the connection is made. From their perspective a sine qua non condition to achieve sustainability is ecosystem stability which they conceptualize using Fisher information, view that is further developed in several papers [24, 50, 70, 69, 115, 2, 51, 35].

Following [30] and [69] Consider the central problem of estimating the actual value \( \theta \) for state variable. The estimation comes from an inference process from imperfect observation \( y = \theta + x \) in the presence of some random noise \( x \). This kind of measurement-inference process will hence be called “smart
Vital Landscape Attributes (VLAs)

Type, number and range of landform
The number of ecosystems
Type, number and range of land units
Diversity, length and intensity of former human uses
Diversity of present human uses
Number and proportions of land use types
Number and variety of ecotunes-zones
Number and types of corridors
Diversity of selected critical groups of organisms (functional groups)
Range and modalities of organisms regularly crossing ecotunes
Cycling indexes of the flow and exchanges of water, nutrients, and energy within and among ecosystems
Pattern and tempo water and nutrient movement
Level of anthropogenic transformation of landscape
Spread of disturbance
Number and importance of biological invasions
Nature and intensity of the different sources of degradation, whether legal or illegal

Table 4. Vital Landscape Attributes as proposed by [4]

measurement of θ whose result is an estimator ˆθ(y) that is a function of an imperfect observation ˆθ(y). This is a closed system, meaning that it’s well described by {y, ˆθ, x} without the need to consider additional sources of noise. Consider also that the estimator is unbiased in terms of being a good estimator on average ⟨ ˆθ(y)⟩ = θ. In this case, the mean-square error obeys the Cramer-Rao inequality

\[ e^2I \geq 1, \] (3)

where I is the Fisher Information of the system, calculated as

\[ I = \int \frac{dy}{P_0(y|θ)} \left[ \frac{dP_0(y|θ)}{dθ} \right]^2, \] (4)

in which \( P_0(y|θ) \) is the probability density function of measuring a particular value of y given the true value θ of the state variable in question. Then, since the error decreases as information increases, Fisher information may be understood as the quality of the estimation θ from a smart measurement. Then, if the system is characterized by a phase space with m state variables \( x_i \) that define the phase vector \( s = (x_1, \ldots, x_i, \ldots, x_m) \) associated with a smart measurement y, then we can prove that

\[ I(s) = \frac{1}{T} \int_0^T \frac{s'^2(t)}{s^4} dt, \] (5)

where T is the time period required for one cycle of the system; \( s'(t) \) is the tangential speed and \( s''(t) \) is scalar acceleration tangential to the system path in phase space. Both are calculated in terms of the state variables \( x_i \) as

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

\[ s''(t) = \frac{1}{s'(t)} \sum_i \left( \frac{dx_i}{dt} \frac{d^2x_i}{dt^2} \right). \] (7)
A simple and robust approach to calculating tangential velocity and acceleration uses the three-point difference scheme

\[
\frac{dx_i}{dt} = \frac{\alpha x_i(t + \Delta t) - (\alpha^2 - 1)x_i(t) - x_i(t - \alpha \Delta t)}{\alpha(\alpha + 1)\Delta t}, \quad (8)
\]

\[
\frac{d^2x_i}{dt^2} = \frac{\alpha x_i(t + \Delta t) - (\alpha + 1)x_i(t) - x_i(t - \alpha \Delta t)}{\alpha(\alpha + 1)\Delta t^2/2}, \quad (9)
\]

where \(x_i(t)\) is a central data point, \(x_i(t - \Delta t)\) is the next point following the center \(x_i\) and \(x_i(t - \Delta t_p)\) is the previous point to it. For evenly-spaced points \(\Delta t_p = \Delta t\) and \(\alpha = \Delta t_p/\Delta t\) is the ratio of the previous and following time space.

The thesis suggested by [27] is that a shift in Fisher information may signal a change of regime in a dynamic system to [27]:

- Fisher information is a function of measurement variability. Low variability results in high Fisher information and low Fisher information results in high variability.
- Systems in stable regime tends to exhibit constant Fisher information. Then, organization losses points to greater variability and a decrease of Fisher information.
- Self-organizing systems reduce their variability and gain Fisher information.
- "If resilience is defined by the intensity, frequency, and duration of a perturbation that a system can withstand before fundamentally changing in function and structure, then we would hypothesize that Fisher information would return to the same value or higher in more resilient systems." [12]

We found this last point of much interest because not only it provides a formal definition of the resilience concept, but it also provides a specific way to measure it via Fisher information. In order to test this idea, we analyze NDVI data for "US-Me1: Metolius - Eyerly burn" Ameriflux site [40] site in Oregon for which is documented as an intermediately aged ponderosa pine forest that was severely burned in the 2002 Eyerly wildfire. The AmeriFlux network of approximately 100 research stations is the main research group and information supplier for big terrestrial carbon cycling syntheses in the Americas and has established a database for micrometeorological, meteorological and biological information.

Data of NDVI was downloaded using the application for Extracting and Exploring Analysis Ready Samples (AppEEARS) that enables users to subset geospatial data-set using spatial, temporal, and band/layer parameters (https://lpdaacsvc.cr.usgs.gov/apppears/). In particular, we used MOD13A3.006 1km² resolution monthly data of NDVI from 01-01-1990 to 01-01-2018.

Focusing into the 2002 wildfire, we show in Figure 10 that as expected, with the wildfire disturbance the system experience both great changes in NDVI and its corresponding Fisher information. We found that Fisher information returns to previous values after 18 months approximately but not the NDVI values.

On the one hand, recovering Fisher information could be related to the way Filotas and co-workers [27] understand ecological resilience as "the amount of change that an ecosystem can absorb before it loses its ability to maintain its original function and structure". After a disturbance, the authors claim that a resilient system has the ability to recover its initial structure, features, and feedback; in other words, its integrity.

On the other hand, it seems then that the criterion of Fisher information is necessary but not sufficient to ensure ecosystem resilience. For example one should expect that after a disturbance, essential variables as the ones proposed by Schmeller and co-workers [92], which could be seen as a modern version of Aronson’s Vital Ecological Attributes [4], return to previous values. In a recent work Dutrieux [23] combine into one index signaling from TM and ETM+ B4 band, corresponding to Near Infra Red (NIR) with wavelength of 770 – 900nm which provide information about canopy biomass; and B5 band corresponding to Short Wave Infra-Red (SWIR1) with wavelength of 1550 – 1750nm which provide information about canopy moisture content:

\[
NDMI = \frac{NIR - SWIR1}{NIR + SWIR1}. \quad (10)
\]
Figure 10. In red the normalized NDVI time series for the 1km² pixel corresponding to the coordinates of the US-Me1 site of Ameriflux with a monthly sampling. In blue, the corresponding values of Fisher’s information using the Cabezas and collaborators algorithm (https://github.com/csunlab/fisher-information).

Low NDMI values for bare soils and thin forest canopies are anticipated, while greater values correspond to thicker, completely developed forest canopies. [111].

The author created the following harmonic model to compare values before and after a disturbance:

\[ y_t = \alpha_i + \sum_{j=1}^{3} \gamma_j \sin \left( \frac{2\pi j t}{f} + \delta_j \right) + \epsilon_t, \]  

(11)

where the dependent variable \( y \) at a given time \( t \) is expressed as the sum of an intercept \( \alpha \), a sum of different frequency harmonic components representing seasonality and an error \( \epsilon \). In the model \( j \) corresponds to the harmonic order, 1 being the annual cycle, \( \gamma \) and \( \delta \) correspond respectively to the amplitude and phase of the harmonic order \( j \), and \( f \) is the known frequency of the time-series (i.e., number of observations per year).

New values are then estimated for each spectral band and each time series observation using the corresponding matched model, enabling Euclidean distance to be calculated with the following formula:

\[ D_t = \sqrt{\sum_{i=1}^{k} (y_{it} - \hat{y}_{it})^2}. \]  

(12)

The author then applies it to spectral recovery time for a set of 3596 Landsat time-series sampled from regrowing forests across the Amazon basin, thus producing estimates of recovery time in spectral properties, which he calls spectral resilience. On average, he found that spectral resilience takes about 7.8 years, with a large variability (sd = 5.3 years) for disturbed forests to recover their spectral properties. Now we have a new problem, how to determine the thresholds for (a) distance between initial and final values for both state (essential/vital) variables and their Fisher information; (b) the time scale these recovering should occur. In principle we believe (a) could be determined from ecological integrity measurements, but it is currently an open research question we are not addressing here.
In another line of thoughts, Sidle and co-workers [94] focus on ascertainning under what circumstances ecosystems exhibit resilience, tipping points or episodic resetting. They point out that while ecosystem resilience originated from ecological perspective, latest debates concentrated on geophysical characteristics and that it is acknowledged that dynamic system properties may not return to their former state after disturbances (see for example [16, 36, 60, 85, 74, 100]). Tipping points generally arise when chronic (typically anthropogenic but sometimes natural) changes push ecosystems to thresholds that cause process and function collapse even in a permanent way. Resetting ecosystems happens when episodic natural disasters break thresholds with little or no warning resulting in long-term modifications in environmental characteristics or functioning of the ecosystem. Of special interest is the work of Steffen and co-workers [100] who consider earth biosphere as a whole system and study its possible trajectories under the current planetary crisis. In particular, they explore the risk of self-reinforcing feedback that could eventually push the Earth’s biosphere system to a planetary threshold that, if crossed, could prevent climate stabilization near the Holocene temperature regime (the pre-industrial conditions set out in the Paris Agreement). In the worst case scenario Earth could be driven into the ongoing warming track of a “Hothouse Earth” path, even though human emissions were lowered.

As in other papers reviewed, Sidle and co-workers [94], state that “if a system is viewed as resilient, it is generally perceived as remaining within specified bounds, probably close to the optimal operational points” mentioned in [25]. Which sets again the question of which should be the variables under the “bounded ecosystem” and how to determine the range of values to consider the ecosystem as resilient. More to the point, how much time should be spanned between an ecosystem perturbation for the resilience variable returning to their bound limits? In principle, we consider that this should be in the same order of magnitude that the -natural characteristic time scale of the ecosystem. But once again, the measurement of characteristic time scale for an arbitrary state variable of the ecosystem is an open question. The main problem is that in most cases we will not have a mechanistic model for the variable in question but time-series only. In [1] the authors use the Wigner function to explore if there is an special time scale under which the system reaches an optimal representation. For multiple time series observed, they contrasted entropy values covering a variety of distinct time domains. For their natural characteristic time, they found that entropy is highly likely to be minimal, implying minimum uncertainty in time-frequency space. Another alternative might be to consider the $t_0$ time in which the system’s memory tends to be zero, defined by the absolute $\tau$ time value for which the $C(\tau)$ auto-correlation function crosses the horizontal axis [? ].

2.4 Complexity perspective

The Filotas and co-workers reviewed paper [27] provides a remarkable introduction to complexity. The authors decompose complexity into eight features an then goes to relate them into a new narrative for forests, making as a result an interesting connection with resilience and integrity. Generally speaking, a system is complex either it presents a sufficiently number of components with strong enough interaction or it exhibits changes in the configuration space comparable to the observer’s time scale, and in most cases both. Forests as a system and forest management, certainly occupy a high position in the complexity gradient.

The authors focus on forests, but clearly what they describe is applicable to all types of ecosystems. Nevertheless, forests are a good model because they are both widely and intensively managed, and also because they are deeply coupled with human systems. The designed approach can thus assist forest scientists and managers in conceptualizing forests as integrated socio-ecological systems and provide concrete examples of how to manage forests as complex adaptive systems.

There are at least 800 different definitions of a forest. Some of them are used simultaneously in the same country for different purposes or scales [64]. This is in part due to the fact that forest types differ widely, depending on factors such as latitude, climate patterns, soil properties, and human interactions. It also depends on who is defining it. An economist could describe a forest in a very distinct manner to a forester or a farmer, in accordance with their specific interests. One of the most widely used definitions is that by FAO (1998), that defines a forest as “the track of land with area over 0.5 ha, tree canopy cover larger than 10%, which is not primarily subject to agricultural or other specific non-forest uses”. For young forests or regions where tree growth is suppressed by climatic factors, trees should be capable of reaching a height of at least 5 m in situ while meeting the requirement for canopy cover. In general, forest definitions are based on two different perspectives. One, associated with quantitative cover/density variables such as
While their populations become resilient to degraded circumstances and have maximized abundance when work, Danneman and coworkers unveil an essential yet unexplored multi-scale movement property of Anthropocene [99] or Technocene [62]. Human impact in extreme cases may modify forest heterogeneity promoting it through strategic cuts that emulate natural disturbances; leave intact some structures and modern forest management is becoming more compatible with this complexity feature (heterogeneity) by and exploitation, which in turn will benefit the stability and resilience of the population. In that way, in biology of conservation. Their findings indicate that Lévy flights reach a balance between exploration scale foraging from individual to population level, making it of major value to a wide scope of applications Lévy walks, how it play an important role in the stability of populations dynamics. Using Lotka-Volterra methods within and between woodlots. Changing these patterns can significantly influence the capacity of the landscape to maintain materials and energy effectively processed and host the region’s biota; this change in turn decreases its integrity, resulting in a loss of resilience. Even more, in the context of the Anthropocene [99] or Technocene [62], Human impact in extreme cases may modify forest heterogeneity generating new ecological patterns (niche construction) and interactions, without historical equivalents [93].

Spatial heterogeneity can be altered by invasive species threaten biodiversity through predation [21, 86], competition [42], disease transmission [114], and facilitation of the establishment of further invasive species [97]). It has been reported that the decrease and extinction of native species due to invasive predators can generate cascade effects that extend through the whole ecosystem and beyond. [14]. In particular depredation effects resulting from human introduced species can be severe [96, 22]. Both rats (Rattus rattus), cats (Felis catus) and dogs (Canis lupus familiaris) are recognized as the worst threat species following recent studies [48]. In natural areas worldwide, dogs are threatening some 200 species, some of them even included in IUCN threat categories. Likewise, Feral cats and red fox (Vulpes vulpes) predation processes has been documented as a cause of the decline or extinction of two thirds of Australia’s digging mammal species [28, 112]. Reduced disturbance to soil in the absence of digging mammals has led to impoverished landscapes where little organic matter incorporates into the soil and rates of seed germination is low [28]. The predation of seabirds through introduced Arctic foxes (Alopex lagopus) in the Aleutian archipelago has reduced nutrient input and soil fertility, eventually causing vegetation to shift from grassland to dwarf shrubland.

In a recent work [18], a deep relation between Lévy walks and resilience has been shown. In this work, Danneman and coworkers unveil an essential yet unexplored multi-scale movement property of Lévy walks, how it play an important role in the stability of populations dynamics. Using Lotka-Volterra models, they predict that generally diffusing foragers tend to become extinct in fragile fragmented habitats, while their populations become resilient to degraded circumstances and have maximized abundance when individuals undertake Levy flights. Their analytical and simulated findings, change the scope of multi-scale foraging from individual to population level, making it of major value to a wide scope of applications in biology of conservation. Their findings indicate that Lévy flights reach a balance between exploration and exploitation, which in turn will benefit the stability and resilience of the population. In that way, modern forest management is becoming more compatible with this complexity feature (heterogeneity) by promoting it through strategic cuts that emulate natural disturbances; leave intact some structures and
organisms, including dead and living trees and intact patches of forests; and promote mixtures of tree species. These methods are similar to the comparatively recent strategy of using biodiversity to boost yield and resilience in natural and managed ecosystems [27]. Generalizing these ideas we reckon there is important evidence suggesting that in order to preserve ecosystem integrity and resilience, management systems should consider maintaining minimum levels of ecosystem complexity.

Of course, this poses a new challenge: How to measure complexity? Following Gershenson and co-authors [31] one may measure complexity using again the Shannon information. In this information theory framework, in order to have new information, the old one has to be transformed. Thus, we can define information emergence $E$ as the rate of information transformation. Therefor emergence is identified directly with Shannon’s information $H$ or $I$. In addition, self-organization ($S$), a key feature of complex systems, has been correlated with an increase in order (i.e., a reduction of entropy) [31]. Thus, if emergence implies an increase in information, which is analogous to entropy; self-organization should be anti-correlated with emergence in such a way that

$$S = 1 - E = 1 - I.$$

In this way, following [31, 26] complexity can be measured as

$$C = 4 \times E \times S.$$

Under the complex systems perspective ecosystems are not systems that can simplistically be managed top-down. We must explicitly consider that the interactions take place in multiple and hierarchical levels. This is a general feature of complex systems, components are organized hierarchically in such a way that elements at different levels interact to form an architecture that characterizes the system. In this way, complexity asserts that a phenomenon occurring at one scale cannot be understood without considering cross-scale interactions. But it also means that environmental policy, management and intervention needs to be rethought in terms of scale. In this respect Taleb is assembling “Principles of policy under complexity” (draft version available at: http://www.academia.edu/38433249/Fractal_Localism_Political_Clarity_under_Complexity) which include the understanding of policies as scale dependent, and so we should consider that instead of aiming at one monolithic policy for managing an ecosystem, we should go on to develop a range of them linked to different levels of application. Such approach will be required to reduce the risk of catastrophic hidden effects.

Understanding the coupling of natural and human sub-systems provide a whole new narrative that challenges management. Ecosystems management is the outcome of collective actions among different agents such as decision makers, scientists, managers, concerned citizens and so on. As complexity, key for ecosystem integrity and resilience, is at dynamic balance between emergence and self-organization ($S$) (Eq. 2.4), some (and the correct type of) self-organization is necessary to be fostered, but too much of it is bad. Too much (form the wrong type) of $S$ may sustain unwanted feedbacks with detrimental consequences. For instance, illegal logging in Borneo can be seen as a self-organizing phenomenon supported by interactions among all levels in the stakeholder hierarchy [82]. The mechanism is explained by Filotas and co-workers, starting with pit sawyers taking out livings and pirate loggers taking advantage of governance failures. This alone could not generate such a great impact, unless it couples with unscrupulous timber buyers and corrupt governmental officials laundering the illegal wood. Experience in Mexico suggests that corruption might be the common link in practically all-important ecosystem degradation processes. Finally, they say that savvy international traders are the higher link that provides lucrative outlets for ill-gotten goods. According to the authors’ narrative, where illegal logging occurs, wood markets are flooded, wood prices are depressed, and standing trees are undervalued. Under such conditions, community forest managers are not motivated to implement sustainable forest management practices, which often involve short-term investments for only long-term returns. These conditions result in a self-organized feedback that sustains illegal logging.

The characteristic of complex systems not having a unique description scale is related to one of the most omnipresent system-wide phenomena, the $1/f$ behavior on frequency space for the fluctuation time series. This so-called pink noise is one of a family of $1/f^{\beta}$ colored or fractal noises defined by the $\beta$
Therefore, they suggest that building holistic indexes in the ENA framework is a better approach for a thorough knowledge of the food web structure and its role in the functioning of the ecosystem.

If one would be able to construct a sufficiently detailed trophic network (something very difficult to do in general), one could use standard network analysis tools to understand, for example, the topology of the network, such as connectance. In that sense, the authors summarize evidence from the literature to show that an increase in links dissipates the impact of variability in species distribution and increases stability [65]. Higher connectivity thus improves the strength of the ecosystem as well as resilience [20]. If so, connectivity seems to be a useful measure of the robustness of food webs and indirectly of ecosystem stability.

In addition to connectivity, they show the importance of interaction strength diversity. Following ideas of [104], they claim that ecosystem stability requires a balanced presence of weak and strong interactions. Suppression of weak interactions destabilizes the system for a certain amount of species.
Moreover, the food web would be stable if and only if main predator-prey interactions are combined with weak interactions in the context of high diversity. Thus, due to their ability to fluctuate and adapt within ecosystems, weak interactions function as a stabilizing force in food webs and consequently the ecosystem.

To gain a deeper understanding of stability, Saint-Béat and colleagues examine the effect of cycling, the presence of omnivorous and ascending. For instance, the presence of omnivory gives an ecosystem trophic flexibility, a clear beneficial feature that reflects integrity and resilience of the ecosystem. The researchers claim that omnivory provides to the ecosystem a superior buffer to deal with environmental disturbances. Because omnivorous species enable faster ecosystem reaction by rapidly moving trophic routes following disturbance. For example, if a disturbance impacts low trophic levels, omnivorous species that are directly linked to it, would respond rapidly. In comparison, a particular predator must wait until the disturbance reaches its own level; therefore, the response time will be longer.

As in the reviewed paper by Gustavson and co-workers [39], Saint-Béat and co-workers show how ascendency could be used as a key indicator to evaluate ecosystems functioning. The authors indicate that to understand the function of "ascendancy" two kinds of stability must be differentiated. A system with elevated inner stability is a system with adequate inner limitations to enable a strongly organized structure, corresponding to a high ascendancy (high mutual information). Typically under this condition, ecosystems are some how protected against internal perturbations but leave them vulnerable to external ones. On the other hand, since low ascendancy is linked to redundancy, ecosystems become more resilient to external disturbances. Interestingly enough, too high level of ascendancy is recognized as a characteristic of stress and may indicate a decrease ecosystem resilience.

Summarizing, in the dynamic response of ecosystems under the criticality framework a healthy ecosystem is found where a balance between robustness and adaptation develops. In the case of network topology, the ecosystems need to develop a good balance between strong and weak interactions in order to be stable. In the case of the ascendancy narrative, a stable ecosystem should develop a good balance between ascendancy and overhead, which seems to give resistance and resilience to ecosystems. This leads us to think what we develop in the next section, in which we will ascertain whether all these three kinds of balance could be particular cases of a more general evolutionary strategy of living systems: the antifragility.

**BEYOND RESILIENCE, ANTIFRAGILITY**

Living systems can and must do much more than merely react to the environment’s variability through random mutations followed by selection; they must certainty have built-in characteristics that enable them to discover alternatives to cope with adversity, variability and uncertainty. Anti-fragility is one of these characteristics [17, 101].

If one considers what does really mean that something is fragile, the key property is that it gets damaged by environmental variability. Now if we ask our nearest colleague at random, about the exact opposite of fragile, most likely we would get concepts such as robustness or resilience. But at close inspection it is clear that none of them are the exact opposite of fragile. Both represent systems that are insensitive to environmental variability or get affected only momentarily, quickly returning to its initial state.

The exact opposite of fragility as defined by Taleb is antifragility, which is a property that enhances the system’s functional capacity to response to external perturbations [102]. In other words, a system is antifragile if it benefits from environmental variability, works better after being disturbed. Then antifragility is beyond robustness or resilience. While the robust / resilient systems tolerate stress and remain the same, antifragile structures not only withstand stress but also gain from it. The immune system provide significant illustration of antifragile systems. When subjected to various germs at a young age, our immune system will improve and gain different capabilities to overcome new illnesses in the future [81].

A formal definition of antifragility as convexity in the payoffs space is found in [103, 102]. Let’s consider a two times continuously differentiable “response” or payoff function \( f(x) \). Then the function’s convexity will be defined by the relation \( \frac{\partial^2 f}{\partial x^2} \geq 0 \) which can be simplified under the right conditions to \( \frac{1}{2} [f(x + \Delta x) + f(x - \Delta x)] \geq f(x) \). Then the response function \( f \) will exhibit non-linearity to dose, which means that a dose increase will have a much higher impact in relation to this increase. Taleb...
generalizes this result to a linear combination for which \( \sum \alpha_i = 1 \), \( 0 \leq \alpha_i \leq 1 \) in such a way that \( \sum [\alpha_i f(x_i)] \geq f(\sum (\alpha_i x_i)) \). Again simplifying the argument, under the correct conditions we end up with \( f(nx) \geq nf(x) \). This way, if \( X \) is a random variable with support in \([a,b]\) where the function \( f \) is well behaved, and \( f \) is convex, we get Jensen’s Inequality [6],

\[
\mathbb{E}(f(x)) \geq f(\mathbb{E}(x)).
\]  

(15)

Without loss of generality, if its continuous distribution with density \( \varphi(x) \) and support in \([a,b] \) belongs to the location scale family distribution, with \( \varphi(x/\sigma) \) and \( \sigma > 0 \), then, with \( \mathbb{E}_{\sigma} \), the mapping representing the expectation under a probability distribution indexed by the scale \( \sigma \), we have:

\[
\forall \sigma_2 > \sigma_1, \mathbb{E}_{\sigma_2}[f(x)] \geq \mathbb{E}_{\sigma_1}[f(x)].
\]  

(16)

This way, Taleb defines local antifragility as "a situation in which, over a specific interval \([a,b]\), either the expectation increases with the scale of the distribution as in Eq 2.5, or the dose-response is convex over the same interval".

Although Antifragility framework was developed by Taleb in the context of financial risk analysis, due to its universal mathematical formalism it has track attention and has been applied far away its original scope. There are applications of the Antifragility concept from molecular biology to urban planning (see [81] and references inside). In their work, Pineda and co-workers [81] proposed a straightforward implementation of antifragility by defining as payoff function the complexity of the system. which makes a lot of sense in the context of our review because complexity is highly related with critically and hence with these these trade-off balance between robustness and adaptability.

The authors defined fragility as

\[
f = -\Delta C|\Delta x|,
\]  

(17)

where \( \Delta C \) is the change in system complexity due to a perturbation of degree \( |\Delta x| \). As complexity can always be normalized to \([0,1]\), then positive values of \( f \) define fragile systems; when \( f \) is zero the system is robust/resilient; and for negative values of \( f \) the system is antifragile.

Then, Pineda and co-workers [81] apply it to random Boolean networks (RBNs) of a model of genetic regulatory works. They found that ordered RBNs are the most antifragile and demonstrated that, as expected, seven biological well studied networks such as CD4+ T cell differentiation and plasticity or Arabidopsis thaliana cell-cycle, are antifragile.

We know, from Central Limit Theory, that normal distributions can only emerge from (simple) systems without interactions (probabilistic independence). When we take into account interactions (no probabilistic independence) then the corresponding probability distribution will have fat-tails. In that sense complexity is related with fat-tails and fat-tails with fragility/antifragility [101]. In Taleb’s narrative, normal distribution in the response function characterize robust systems; whereas left fat-tailed are fragile, and right fat-tailed are antifragile systems. Most interestingly, Fossion and co-workers [29] have related homeostasis (physiological resilience?) to pairs of physiological variables, one to be controlled (the one that remains in homeostasis) and another one that controls the former. The main idea is that in order to have a homeostatic physiological variable (normal), the body must use other variables (right fat-tailed) to absorb a random injection of matter, energy, information or any combination of them from the environment. In Figure 4 of their paper, they present results for variability analysis of heart rate HR and blood pressure BP for (a) healthy control(s), (b) recently diagnosed diabetic patient(s) and (c) long-standing diabetic patient(s). They show that for healthy patients BP is normal and HR is right fat-tailed. In the case of recently diagnosed diabetic patients, BP start to lose normality and develop a left tail and HR tends to normality. Eventually, long-standing diabetic patients, BP has a clearly left fat-tailed behavior and HR has become normal. This is very compelling evidence of the role of antifragility in human health.

In a general manner, Taleb [101] Suggests the so-called barbell (or bimodal) approach as an archetypal strategy for achieving antifragility. The first step towards antifragility is to reduce downsides instead of increasing upsides. In other words, by reducing exposure to adverse low probability but elevated
adverse payoff occurrences (i.e. "black swans" events) and allowing natural antifragility to function on its own. We follow Taleb with a vulgar finance instance, where the idea is easiest to explain, although most of them are misunderstood. The barbel approach in finances comprises of placing 90% of your resources in safe instruments (provided that you are protected against inflation) or what is referred to as the "value repository number," and 10% in very risky, maximal risky bonds, exposing yourself to unpredicted massive gains in a convex way. In this way, one ends up with some sort of bimodal optimization taking advantage of at the same time of the robustness of safe inversion and on the other hand the adaptability of high risky ones. Anyone who has a 100% stake in so-called "medium" securities (unimodal optimization) is at danger of "complete risk ruin". This Barbel Strategy addresses the issue of incomputability and fragility in the assessment of the hazards of unusual occurrences.

As in the barbell strategy, a basic mechanism to achieve antifragility, is a thorough strategy to risk management under fat-tailed distributions, and those are widely present in nature, then it should be very ubiquitous in natural systems. We identify this barbell risk strategy as the "good balance" property in network topology by means of the relation of strong and weak interactions or between ascendancy and overhead; and balance robustness and adaptability, identified as fingerprint of critically (scale invariant and $i/f$ type of noise), in the dynamic of system’s fluctuations. All these three "good balances" are related, as we showed with ecosystem integrity and resilience.

![Figure 11. Basic characteristics of systems in terms of antifragility, which is the property of a system to respond in a convex way to perturbations or variability.](image)

**DISCUSSION AND CONCLUSIONS**

From the analysis of the literature, we found that the citation network from reviewed network is not percolated, what we interpret as a lack of unification in the research field and an opportunity for inter-
disciplined work. We found (see Figure 9) three main narratives (a) Ecosystem properties that enable them to be more resilient; (b) Ecosystem response to perturbations; and (c) Complexity. From this and complementary literature consulted we have identified 11 possible indicators for ecosystem resilience (See Table 5). In particular we show how to apply Fisher information in a study case which we consider a very promising proxy of resilience, since it has a solid formal framework, it is easy to implement and it can be applied to any kind of system.

<table>
<thead>
<tr>
<th>Key Indicator</th>
<th>Measure/proxy</th>
<th>Requires</th>
<th>Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI</td>
<td>Fisher Information</td>
<td>Stability</td>
<td>Time series</td>
</tr>
<tr>
<td>Dev</td>
<td>Diversity</td>
<td>Optional / use of resource space</td>
<td>Presence field data</td>
</tr>
<tr>
<td>Co</td>
<td>Network Consonance</td>
<td>Stability</td>
<td>Knowing the networks and being able to quantify the intensity of the connections.</td>
</tr>
<tr>
<td>Om</td>
<td>Presence of omnivore species</td>
<td>Communication between different scales</td>
<td>Presence of omnivore species and remaining</td>
</tr>
<tr>
<td>NC</td>
<td>Network Criticality</td>
<td>Balance between robustness (strong interactions) and adaptability (Weak Interactions)</td>
<td>Knowing the networks and being able to quantify the intensity of the connections.</td>
</tr>
<tr>
<td>L-VC</td>
<td>Lotka Volterra Coefficients</td>
<td>Given a community matrix, if all the real parts of its eigenvalues are negative the ecosystem is stable</td>
<td>Community matrix</td>
</tr>
<tr>
<td>As</td>
<td>Ascentancy</td>
<td>Mean mutual information</td>
<td>Given a network of interactions (i.e trophic network) it measures how well; on average; the network articulates a flow event between any two nodes.</td>
</tr>
<tr>
<td>Levy</td>
<td>Levy Flights</td>
<td>Scaling coefficient of foraging patterns for key species such as puma or jaguar</td>
<td>It is a proxy of resources spatial complexity.</td>
</tr>
<tr>
<td>Frac</td>
<td>Fractality</td>
<td>Spatial complexity</td>
<td>High resolution satellite images</td>
</tr>
<tr>
<td>AF</td>
<td>Antifragility</td>
<td>Change in the complexity of a biotic (i.e trophic) network in the face of disturbances</td>
<td>Network of interactions, can be a Rosetean network of co-occurrences of a key species such as puma or jaguar with its prey for example.</td>
</tr>
<tr>
<td>H</td>
<td>Homeostasis</td>
<td>System Homeostasis</td>
<td>Time Series</td>
</tr>
</tbody>
</table>

Nevertheless a new way to reinterpret resilience emerged from this critical literature review: antifragility. This novel framework developed by N.N. Taleb [101, 103, 102] is based on fat-tailed, non-linear responses of the system to variability (see Figure 11). In a simple way, if a system has a concave (non-linear) payoff function dependent of certain variable, then the system is fragile to it. On the contrary, if the payoff in convex then it is antifragile and if the system is essentially insensible to variability, then it is robust/resilient. In Taleb’s work, antifragility is associated with bimodal risk strategy called “The Barbell” which we believe manifest itself in the narratives as “a good balance” between (i) strong and weak interactions in network topology; (ii) adaptability and robustness (criticality); and (iii) ascendancy and overhead.

In the long term, considering the coupling of ecosystem with human systems (i.e. via climate change) we consider that antifragility is a more desirable feature than resilience. Thinking in socioecosystems, we can see that they usually not only keep on living, but they do flourish and evolve, even in the presence of great stressors such as climate crisis or land change. In fact, in a recent work [19], It has been shown that the outcome of using antifragility as a design criterion is that the scheme being studied demonstrates a more favorable behavior than a ”simply” robust model in a setting that is susceptible to black swans (unpredictable, very low frequency of occurrence but very high impact events) . Then, for socioecosystem governance, planning or in general, any decision making perspective, antifragility might be a valuable and more desirable goal to achieve than a resilience aspiration [7].

REFERENCES


disorder: concepts and tools (springer series in synergetics).


