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Editorial

Sensing Linked Cues for Ecosystem Risk and Decisions

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Ecological indicators of ecosystem anomalies are fundamentally important to sensing how close we are to slow or catastrophic ecosystem shifts and to targeting systemic controls for preservation, restoration and eco-based development. Ecosystem anomalies, I argue, are grounded in *ecohydrological determinants* and lead to alterations in socio-ecological functions and services, including the collapse of species or hydroclimatological disasters such as floods, droughts and heatwaves on land and in the ocean. Therefore, linked ecological cues in the form of multiscale data are salient for predicting the risk of ecological change.

The aim of this Special Issue was to gather advances in ecosystem monitoring and monitored data, including technology and ecological data (phenotypical, phylogenetic, eDNA, macroecological, etc.), data fusion, pattern reconstruction and analysis, and inference models for the extraction of predictive information aimed at guiding ecosystem engineering (integrated ecological and environmental engineering), considering both predictions and field restoration.

The centrality of data must be seen as connected data as follows.

(1) Ecological *data* address biodiversity and water as green-blue foundational elements beyond biogeochemical fluxes that are the byproducts of the baseline ecological configuration. Species sense the quality of the environment, and ecological data reflect the functioning of eco-environmental ties. There is no environment that is fully abiotic, and yet efforts to compile ecological data must be comprehensive of the flows of ecosystems over time;

(2) The spatial connections among habitats (natural and self-emergent habitats and those of human-made *design*, which are reflected in geomorphological and infrastructural data, respectively) are the basis of any ecological function with strong climate feedback; thus, "climate neutral" efforts must consider the engineering of salient hydrologic flows and eco-geomorphological connections (broadly defined as *ecological ties*) whose scale-free organization is the optimal configuration of our ecosystem;

(3) Networks of people's *decisions*, from the behavior of citizens to stakeholder development and management strategies, are critical for an ecosystem's function and intelligence, in which the latter is as much a conscious action as the reactions of species to information sensed in ecosystems. All these decisions are associated with ecological information (extracted by models as perceptrons) for which digitized information carries values and thresholds with respect to the functions of ecosystems to create forecasts, assess indicators and ecosystem states and define ecosystem services and controls (what is needed and/or desired, for which the definition of optimal trade-offs is essential).

Despite their tremendous importance for understanding the function, integrity, and future trajectories of biodiversity, *ecological networks* (or, more broadly, ecological ties) are traditionally restricted to the biological interactions of species. However, ecological networks represent the structures of food webs, hydro-bio-geochemical/energy flows, and the many and diverse types of interactions between all species in ecosystems the

underpinning ecosystemic function that defines fitness and risks. Multilayer networks, sensu lato, are connecting people, habitats, and climate with feedback that affects our conscious and unconscious behaviors, health, evolution and existence in the long term. In general, any tie, or set of knots, is ecological information about biotic components in "abiotic" environments that we need to sense, map and frame.

Can we infer visible and invisible collective networks from ecosystem patterns? More importantly, can we intelligently engineer salient eco-hydro-geomorphological networks to adaptively optimize our collective (biodiverse) beliefs and decisions, enhancing climate/human-impacted ecosystem services? Can we design key indicators, controls, plans, portfolio investments and policies for our desired future ecosystems? Indeed, we can, and we must.

Various initiatives are targeting global information gathering of ecological communities and their restoration, such as GeoBON (https://geobon.org/ebvs/indicators/) (accessed on 10 September 2023), Restor (https://restor.eco/), Allen Coral Atlas (https://allencoralatlas.org/), the UN Biodiversity Lab (https://unbiodiversitylab.org/en/), Global Forest Watch (https://www.globalforestwatch.org/), NEON (https://www.neonscience.org/), BioTIME (https://biotime.st-andrews.ac.uk/), the Living Planet (https://www.livingplanetindex.org/), PREDICTS (https://www.nhm.ac.uk/our-science/our-work/biodiversity/predicts.html) and GBIF (https://www.gbif.org/). Global environmental databases such as BioClim (https://www.worldclim.org/data/bioclim.html), WorldClim (https://www.worldclim.org/), Copernicus Climate Data Store (https://cds.climate.copernicus.eu/#!/home), and NOAA Climate Data (https://www.ncei.noaa.gov/cdo-web/) address the "abiotic" spheres of ecosystems. It is desirable that these eco-environmental databases are used together to pinpoint risks and solutions to global challenges, considering local–global "butterfly effects" in space–time (i.e., ecological ties).

In this Special Issue, many papers highlighted data and methods used to infer patterns across multiple scales and ecosystems, as well as to provide solutions, including predictive capabilities. For marine ecosystems, the delicate nature of the phytoplankton–environmental nexus was highlighted is in determining the extent and persistence of algal blooms [1], and the ways in which the phenology of coastal vegetation in a cold temperate intertidal system impacts remote sensing (and the subsequent classification of coastal habitats) was addressed [2]. Both studies actually emphasize how ecological conditions affect the information that can be gathered and yet add intrinsically uncontrollable (but measurable) uncertainty into monitoring technology; this is rather important and unappreciated since a large number of scientists and policy makers assume that all data are the undisputable, golden truth. This far from reality, and data fusion and selection should be dynamical processes based on the value of information constrained via predictive patterns predict.

Other papers showed the potential of extracting vegetation information from tree attributes [3] to study gross ecosystem production [4] and plant seasonal phenomena like flowering [5]. More importantly, several studies highlighted the critical role of hydrogeomorphology in shaping vegetation patterns [6] by also introducing new methods such as the use of a "geodetector" [7] which includes spatial and risk dependencies. Species have been shown to be bioindicators of ecosystem structures, such as geese for basin vegetation [8] and fish in rivers, which are also affected by climate and other anthropogenic factors [9].

Hydrological dynamics was also studied in its complexity, considering river runoff [10] and its consequences when poorly managed, i.e., floods [11]. Hydrological dynamics which also experience variability due to changes in temperature extremes can trigger wildfires [12] in water-depleted landscapes where vegetation is largely combustible.

The roles of human decisions, such as land management practices, which are largely affecting woody invasive species [13] as undesired species, and human disturbances like mines, which alter vegetation [14], are critical in positive and negative human–ecological feedback respectively. Capturing this feedback is necessary, including in important natural

world heritage sites, such as through remote sensing [15]. The advancement and refinement of methods in treating ecological data, for example, for tracking salient changes in species distributions [16], is constantly important due to the availability of new technology such as satellite imagery [17] and small-scale biological data [1].

In conclusion, ecological data are the sine qua non condition for making optimal *ecosystem decisions* in which the *collective design and engineering* of ecological components (changing an ecological structure by taking advantage of species' collective behaviors and human enhancements) optimizes systemic function. We argue that we must transition from a reductionist way of thinking to consequentialist thinking in which data-informed, nature-based patterns are the ultimate objective achieved via optimal strategic decisions. Top-down ecosystem inputs (natural flows and infrastructure) coupled with well-placed bottom-up ecological components and enhancers create self-organized habitats and ecosystems: this is *Pareto optimal dynamics*, leading to scale-free ecological patterns.

This is particularly important when thinking about the future climate and the co-existence of natural and future human habitats which support each other in risks and needs. The collectivity of data, design (natural and human-made) and decisions is necessary for all ecosystems in which we are the primary *ecosystem engineers*.

Conflicts of Interest: The author declares no conflict of interest.

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