00017 Delta Connectome: Ecohydrology-Carbon Feedback and BioTerraforming Ecofolios

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Abstract

Coastal ecosystems are presented in the purview of ecohydrological and carbon feedback determining baseline ecosystem function and services. The co-organization of structural drainage and species interaction networks is shown as major determinant of primary vegetation fitness, such as for mangroves and other coastal wetlands, and yet for carbon sequestration and climate regulation. Oysters are introduced as key bioterraforming species in the context of blue carbon habitats and spatial ecological portfolios to enhance coastal multifunctionality and services. Lastly, information-theoretic models grounded on multiscale eco-information are shown in their ability to infer ecosystem patterns and networks to quantify ecosystem risks and,fitness, and future trajectories.

Key Points

- Understand how ecohydrological organization affects carbon flow dynamics.
- Define ecosystem health as ecological fitness determined as the divergence from the optimal ecohydrological organization.
- Recognize bioterraformation via habitat-forming species such as bivalves as a suitable way to enhance blue carbon socio-ecological services.
- Implement spatio-temporal portfolios of ecohydrological re-organization for enhancing coastal and marine ecosystems.

Introduction

“there is no good sea without a good coast”, in memory of Andrea Schiavon

Introduction

What are the best ecological indicators to track in coastal ecosystems -- emerging from species senses of the environment -- in order to make optimal ecosystem decisions countering hydroclimatic and socio-ecological risk? How close are we to critical ecosystem collapse? Answers to these questions are still vague despite the rapid decay of Earth’s coastal ecosystems and the advancement of ecosystem science and technology.

Delta ecosystems, and more generally coastal ecosystems, are the fastest changing ecosystems worldwide considering their land-ocean position that determines enormous pressure from natural and anthropogenic sources impacting biodiversity and habitats. Within coastal ecosystems, blue carbon ecosystems (primarily vegetated habitats at the land-ocean interface) are particularly sensitive to changes due to their rich resources and suitability host human activities and habitats. For these motivations, it is really important to investigate the poorly known ecogeomorphic-hydroclimatic feedback and alterations underpinning multitrophic species health, habitat stability and potential societal risks. Due to the large heterogeneity and socio-ecological trade-offs, Shenzhen, the Pearl River Delta, and Guangdong are hotspots of change in a worldwide context and would be presented as a epitome considering critical species (keystone vegetation and connected threatened/endangered, bioterraforming species) and habitats (coastal wetlands, intertidal, beach and reefs). Commonality of ecological stress exists for worldwide coastal ecosystems with a different degree of development

The chapter presents novel probabilistic network-based models assessing and predicting the dynamics of ecological communities, environmental footprint as ecological traits, critical ecological corridors, and eco-climatic teleconnections including ecological information useful to improve hydroclimatic shifts. The ecosystem information is constructed from high-resolution elevation maps to characterize the degree of habitat fragmentation related to geomorphological and eco-hydrologic changes. The analyses allow to create high-resolution digital biodiversity, Multispecies Conservation Values (accounting for food-web linkages), and environmental impact pathways affecting ecological communities. Yearly map of ecosystem health would be ideally provided, such as blue carbon habitat health that accounting for social and ecological services.

The quantification of spatio-temporal and functional ecosystem connections (critical ecosystem connectome) is the basis of optimal ecosystem management portfolios (ecofolios, i.e. ecohydrological solutions such as species-specific management, Ecosystem Protection area, and habitat restoration) to counter undesired and irreversible ecosystem shifts including the avoidance of societal impacts. Portfolios that leverage future trajectories of ecosystems and multimedia data (audio/video) collected at the local scale for inferential models defining ecosystem states, connections and socio-hydroclimatological impacts, that are useful for guiding ecosystem monitoring.

Ecological Organization, Ecosystem Function, and Socio-environmental Impacts

Ecosystems are composed by hundreds or thousands of species linked together in equilibrium by functional food-webs, habitat networks and water flows, i.e., *ecosystem connectome* (or ''eco-ties'') related to trophic and non-trophic species senses and feedback. Species make decisions after inferring risks in relation to surrounding environment and species, and alterations of these senses (from baseline or theoretical optimality) have profound consequences for their dynamics and ecosystems as a whole. Habitats are interconnected by natural drainage corridors that are more and more interrupted by man-made transportation networks and urbanized areas altering ecosystem structure. The ecosystem fabric is like an infrastructure or an organism where diverse components must be carefully assembled together (*ecological organization*) in order to maximize *collective function*. Alterations of the optimal eco-environmental nexus is largely compromising ecosystem function (e.g., natural resources, nutrient cycling and climate regulation) and yet causing irreversible ecological impacts such as critical habitat and species loss (such as coastal wetlands, keystone vegetation and fish). This is particular true for *''Delta'' ecosystems* comprising traditionally-defined deltas and all other tide-affected coastal ecosystems where tensions between natural and built environments are the highest among all ecosystems worldwide. This *ecological stress*, related to both overdevelopment from land (increasing nutrients and compound spillover) and ocean pressures, results into the fastest ecosystem shifts implicating hydroclimatological changes that trigger eco-environmental extremes such as flooding, algal blooms, emergence of pathogens and toxins. These problems are evident in all major coastal cities worldwide that are situated along or in proximity of delta ecosystems (e.g., like Shenzhen and all other Greater Bay Area cities for instance that experienced the largest transformation of coastal habitats in the last 30 years): problems that will rise in the future considering the rapid rise of coastal reclamation and population as well as climate change impacts (sea-level rise and temperature increase) of oceans (**Vitousek *et al*., 2017; Mentaschi *et al*., 2018**). In the history of civilization major social collapse occurred when biodiversity and water were compromised. Thus, a major question is which *preferential connections* in terms of species and habitats and which major environmental indicators (that are also causes and controls of ecosystems) should we target?

The critical issue is about how do we counter the already occurring ecological collapse (''eco-deltas'') facing future anthropogenic change that can tip ecosystems (**Schuerch *et al*., 2018; Barnard *et al*., 2021; Ban *et al*., 2022**), and yet how can we measure (and define corresponding indicators to monitor) *how close we are to ecosystem shifts* considering historical trends. This is a very practical ecosystem problem that embraces a consequentialist ecology perspective, and limitations of purely environmental engineering efforts. A problem that must also embrace *computation, data, policy and society* at large for tangible solutions, including *redefinition of priorities for ecosystem conservation, restoration and planning*. Biodiversity organization - beyond species richness for different trophic levels – considering interdependency of species and habitats (in terms of network topology defined by relative abundance proportion and environmental flow) must be considered when assessing the conservation state of a community.

Thus, the chapter aims to highlight how to quantify the *complexity of the delta ecosystem connectome* and synthesize it to improve the understanding of biota-climate feedbacks (from local to global, and vice versa, by focusing on keystone species and hydroclimatological effects in relation to ecosystem heterogeneity loss, i.e., disruption of habitat features and species proportion) and define optimal ecohydrological solutions (including spatially-explicit terraformation, biophilic plans and policy) countering the anticipated ecological collapse. Scientifically, this is novel because it extends the traditional boundaries of ecohydrology to (i) coastal marine ecosystems (emphasizing the land-ocean connections), (ii) the built environment from building to urban plans and policy, and (iii) community biodiversity vs. vegetation only. In terms of biodiversity and indicators the exploration of *novel high-resolution remote sensing* (via UAV) and *video-audio sensors* reflecting species senses i.e., *sensescapes* (including our human senses of ecosystems) is very novel and embracing the need to define robust and convenient indicators of ecological shifts. While the chapter is focused on delta ecosystems, theory, methods and models can be generally applied to any ecosystem type, which extends the scientific and practical appeal and impacts.

Shenzhen and the Pearl River Delta are great examples of ecosystems under pressure considering the rapidity of transformation, the highest population worldwide, and the huge biodiversity that natural habitats host. For example, South China accounts for 43% of all deltaic mangroves worldwide, which are critically fragile and decaying due to aggressive urban development and coastal aquaculture with cascading effects on species, connected habitats and climate. This is a particularly pressing problem in China and SE Asia (where Guangdong and Shenzhen are the northern tip) as the world's carbon lung (considering carbon sequestration of marine habitats, despite efforts have been recently dedicated to some timid restoration and environmental quality improvement). Water and biota alteration and overexploitation caused catastrophic collapse of populations in ancient times (from Egyptian to Mayas, etc.), and these ''sudden'' societal extinctions, caused by profound environmental transformation, can shift ecosystems to carbon sources from carbon sinks with impact on climate but more directly on natural resources and water-related extremes. Similar erratic transformations are occurring in the Amazon and SE-Asia ecosystems (rainforests and coastal habitats) that are actually the green and blue carbon sequestration hotspots of the world. Therefore, it is imperative to push *local protection, restoration and enhancement* of local socio-ecological communities that are already on a downward trajectory because that has implication for Earth survivability.

A Sensescape Purview for Ecosystem Decision Making Under Risk and Possibilities

Healthy ecosystems look, sound, and smell better than compromised ones. This is rather clear when we hear the symphony of a healthy vibrant forest vs. a cacophonic one. *Environmental disorganization* alters the balance of senses in species. Yet, we can use sensorial perceptions from ecosystem data – particularly audio-image one to gather *ecological disorganization* – to judge the health of ecosystems in relation to systemic environmental pressure or noise. However, many questions arise from this evidence, such as: How senses of biodiversity are related to habitats (the environmental chambers) and other factors such as disturbances that alter the symphony of ecosystems? For how long these sense-base traits are manifested and when do they lead to *irreversible collapse* including *cascading environmental extremes*? What is the degree of irregularity, magnitude and persistence of environmental pressure leading to irreversible collapse? Can we use species somatic traits and species proportions to characterize habitat fitness more precisely than using macro-environmental features only? What are the most sensitive univariate and bivariate *pattern indicators* of ecosystem shifts? What is the degree of variability of ecosystem health for equivalent habitats worldwide or nearby habitats and their socio-ecological teleconnections?

Senses (images, sounds, tastes, smells, textures, and collective behavior such as velocity and trajectory of species) spreads as waves in the environment and cause symptoms of dysbiosis such as bleaching in coral reefs or plant stress in a water-limited environment; stress that limits but also sculpts evolutionary processes leading to optimal function underpinned by organized ecological aggregation. Accurate sensors (including their location and sampling frequency) are yet needed to capture *scents of senses* and synthesize ecosystems' organization informing about *current state, closeness to shifts, environmental determinants* (diffused or localized, acute or chronic)*, and countering solutions*.

An extra element is however needed beyond senses (Wang and Convertino, 2023). *Perception* is when sensory information is selected, organized, and interpreted where models (as *perceptron*s) are used to extract salient features that (i) capture dynamics of patterns informative of processes (yet evidencing basic mechanisms) and (ii) define early and long-term decisions, at higher levels of decision making, to counter ecological risk and adaptive response, or enhance its function based on the collective organization of species and habitats (i.e., biodiversity). Perceptrons (i.e. artificial neurons in pattern-oriented machine-learning or any neuromorphic models) reflect species computation (with different level of cognition) that is the basis of collective behavior. Then, the question is how we can leverage this *''ecological computing''* through sensed information for improving ecosystems through precise interventions, plans and policy based on eco-history and feasible scenarios? What is the spatial and functional configuration of species decision trees (due to habitat/non-trophic and food-webs/tyrophic) and their perceived risks conditional to environmental stress? Are there external and beneficial *environmental stimuli* that we can manage (e.g., light and sound) to positively alter collective intelligence? How can we re-engineer collective sensing of species that has been compromised, including our co-mutual sensing with all species?

Species perceive patterns without thinking of processes and *ecosystem pathologists*/engineers should do that equivalently by minimizing undesired ecological dysbiosis (that in a computing sense can be about erroneous risk assessment). The focus should be on patterns because patterns reveal ecosystem health related to *salient processed senses* at multiple scales. Perceptions that must be optimally communicated – through visualization and other media – to strengthen collective behavior enhancing ecosystems. In this sense data are not just the dry input of models but the fundamental senses and vehicle of artistic visualization to deliver optimal information. This is an ambition rather than mere objectives, because it come with a cohesive and broader long-term vision of improving Earth ecosystems through science and applications at local scale and high resolution.

Ecological Indicators, Epitomes of Change and Cimate Opportunities

In relation to ecological research very little is done to define *baseline indicators* that can support ecosystem restoration evaluation and planning as well as define early-warning and risk thresholds of ecosystem shifts. Unfortunately, the vast majority of this work is either theoretical or grounded on pure ecological research focused on unveiling processes rather than data-based patterns and engineering controls. Models and analytics for inferring ecosystem connections and their function are certainly at the preliminary stage of development; this is an opportunity that also provides *practical applications in ecosystem engineering* for the preservation and creation of new habitats through structuring ecological corridors (ecohydrological corridors). This rewiring has immediate implication on species and nutrient fluxes regulating carbon flow and climate at large.

Considering biodiversity, the research reflects several worldwide climate policy targets that recognize the importance of coastal ecosystems for *climate change impact-reduction embracing nature conservation and restoration*. Universities and international institutes and programs such as the Paulson Institute, Microsoft AI4Earth, IUCN, UNESCO and the Di Caprio Foundation are deeply involved in *nature-centric* programs as preeminent research and ecosystem restoration efforts. Research programs focused on similar aspects are the China National Science Foundation on Double Carbon peak and Neutrality, US National Science Foundation programs on Biocomplexity, Coupled Natural Human System Dynamics, Socio-ecological Systems, Coastal SEES (Science Engineering and Education for Sustainability), Macrosystems Biology and NEON-Enabled Science (National Ecological Observatory Network) that are focused on data-intensive research of complex ecosystems where coastal ecosystems play a large role.

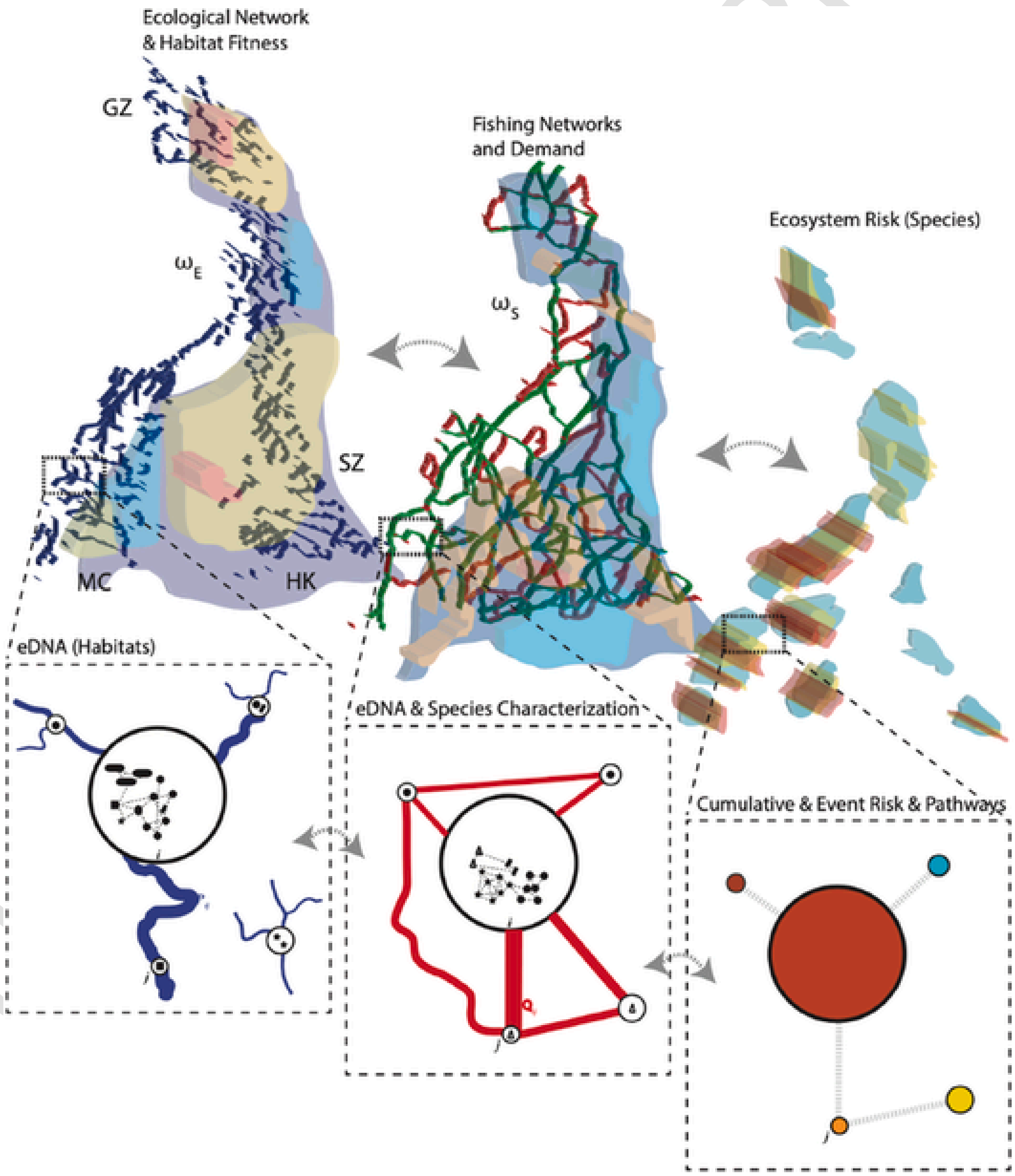
Climate cannot be restored only via black carbon reduction; other more ''colorful'' carbon, such as green and blue carbon stored in ecosystems - via balanced water and biodiversity as the fundamental determinants in nutrients' cycles - must be restored or enhanced for our own future habitats and Earth survivability.

Key Framework: Ecosystem Health as Ecological Fitness

At the moment, in both science and practice, there is a big gap between ecology and environmental sciences, environmental planning and management, and environmental engineering. In short, there is the absence of *ecosystem engineering* as a discipline and profession to synthesize eco-environmental information and translate that into actions at the ecosystem scale. This situation motivated previous efforts to define ‘‘ecosystem health’’ as a quantitative function where initially the focus was on the spread of infectious pathogens and compounds across ecosystem components (species and environment) (Johansson et al., 2019, Chan et al., 2021, Convertino et al., 2021, Servadio et al., 2021a,b; Servadio et al., 2022). However, many more efforts are needed for a *comprehensive and transdisciplinary ‘‘ecosystem health’’* approach where ecological integrity is the systemic fitness/objective (achieved through integrated eco-environmental solutions that address critical ecological ties such as land-ocean connections including rivers and infrastructure, species interactions, and people natural resource use) independently of stressors, leading to all other ecological functions (and related services) including the mitigation of impacts due to ecological stress such as climate change extremes (floods and sea-level rise), carbon evasion, and long-term effects of emerging long-lasting contaminants and pathogens (**Figs. 1** and **2**). Ecological integrity can be measured as the departure from the optimal or baseline eco-hydrological organization of species and water flow, quantified as a network topology.

Blue Carbon Ecosystems

Blue Carbon ecosystems (BC) (mangrove, seagrass beds and linked coastal/marine habitats) are fundamentally important for global climate and ecological security; for instance, coastal BC habitats have a carbon storage capacity that is at least six orders of magnitude higher than oceans (taking into account both biological and microbial carbon pumps (Galbraith and Convertino, 2021; Galbraith et al.,



2021; Wang et al., 2023, Wang and Convertino, 2023)) and accounts for ~65% of biodiversity in tropical areas. However, BC ecosystem function and services are deeply threatened by severe environmental change worldwide, causing for instance coastal wetlands to emit potent greenhouse gases due to their perturbed state. For this motivation it is imperative to investigate the poorly known feedback of climate- and anthropogenic-induced biodiversity imbalance and habitat-loss, multitrophic species collapse, and carbon sequestration decay. With the spatial and temporal quantification of these linkages, an optimal BC management portfolios (ecohydrological solutions, species-specific management, ecosystem protection areas, etc) can be implemented to counter ecosystem change (Convertino and Valverde, 2013). In light of the poorly charted BC ecological complexity (Lagerwall et al., 2012) the question about what is the optimal ecosystem architecture leading to viable ecosystem services remains. Mangroves, as BC centerpiece, with the largest carbon storage and highest terrestrial/aquatic/avian biodiversity per unit area across all ecosystems, are critically fragile and disappearing due to reclamation and climate change causing cascading effects in interconnected land-ocean habitats. This is a particularly pressing problem in China and SE Asia as the world's BC lung despite efforts have been recently dedicated to climate proofing and biodiversity preservation. South China accounts for 43% of all mangroves worldwide, which are intrinsically fragile and decaying due to aggressive urban development and coastal aquaculture with effect on species and climate. As highlighted in the Graphical Abstract, even the loss of a local fish species can have global climate consequences due to the food-web criticality of that species in maintaining prey species population that may alter BC vegetation responsible for carbon burial through photosynthesis; equivalently, habitat disruption and nitrogen/phosphorous loads cause hydrological and water quality impacts affecting species and carbon stock. Global climate factors also add up to ecosystem stress.

Climate control can be exerted via nature-based solutions and not only via reduction of emissions. Global management strategies sought to maximize carbon drawdown should consider BC ecosystems in their space-time structural and functional complexity (″ecosystem fabric″) where horizontal ecosystem fluxes (ecological flux, carbon-climate flux, and hydrogeomorphological flux) sustain optimal vertical fluxes and guarantee (or enhance) carbon stock. This highlights the centrality of the research and restoration on coastal Blue Carbon ecosystems that should focus both ‘‘abiotic’’ (i.e., hydrogeological; see **Liu *et al*., 2021**) and biotic/ecological components.

Integrated Basin Flow Model

A novel multitrophic basin approach is needed in BC research and eco-engineering that considers bio-environmental interdependencies (**Fig. 2**). For instance, BC in ocean habitats is highly affected by the preservation of more terrestrial BC habitats such as mangrove, salt-marshes and tidal flats due to their nutrient filtering that increases carbon sequestration capacity and biodiversity health in the ocean; vice versa the existence of healthy ocean habitats guarantees the existence and correct function of terrestrial BC habitats. For instance, important predatory fish in coral reefs find high-quality nursery in mangroves and these fish are extremely useful for containing populations of coastal herbivores whose excessive bioturbation can collapse mangrove/seagrass function (by releasing sequestered carbon or minimizing the carbon sequestration efficiency) and potentially determine vegetation/habitat collapse in long-term. Major gaps exist into *the mechanistic understanding and quantification of biota-environment feedback*, and in particular about the relationships between critical species interaction networks (food-webs), habitat hydro-geomorphology and carbon fluxes. Studies addressed impact of climate on some of these ecosystem services; however, very little research is dedicated on *reverse mechanisms, for instance how much biodiversity imbalance (species collective disorganization) contributes to local and global carbon-climate fluxes and habitat stability*. These gaps can be addressed by initially focusing on mangrove biodiversity that is also largely accounting for flood protection, nutrient filtering, food provision, and recreation beyond habitat maintenance and carbon cycling. Endangered, keystone, ecoengineer, and sentinel species such as herbivorous-predators (e.g., turtles-sharks), crustaceans (crabs), vegetation, and waterbirds, can be *uniquely* inferred from ecological big-data as interconnected building blocks of BC ecosystems. High-resolution studies for key tropical sites (e.g., Shenzhen, Greater Bay Area as

Fig. 1 Network representation of the proposed research framed on developed ecosystem connectome theory and models and sensescapes (i.e. sensed ecological patterns emerging from species interactions). Structural habitat networks are derived as ecohydrological networks considering the coastal portion of drainage basins (left network in the top left displaying the Greater Bay Area, with Guangzhou (GZ), Shenzhen (SZ), Hong Kong (HK), and Macao (MC) that is the largest urban agglomeration worldwide in a river delta). Ecological interdependence networks are derived from community interaction (also driven by fishery networks as highlighted in the middle top plot) and multitrophic biodiversity can be assessed through eDNA (left and central bottom plots), audio and imagery data beyond reported ecological data. Cumulative and event risk of community collapse (or key species such as bivalve, as shown by the network in the top right) is determined by the interplay of environmentally-mediated ecological species networks (whose senses are stressed by global ocean alteration, habitat disruption and biogeochemical loads) and legal and illegal fishing pressure or other navigation disturbance (Convertino and Valverde, 2018). Facilitation cascades (when species, including humans, ameliorate habitats and other species) and socio-ecological feedback can be quantified due to ecological collapse. Coastal marine ecosystems (that are ecotones or interfacial ecosystems equivalently) should be the focus within a basin framework accounting for hydrologic dynamics from lands. Figure is inspirationally drawn from **Fig. 1** (drawn by M. Convertino) in Cullen et al. (2020). Each node is a community where multiple species populations and environmental pressure can exist; w_E and w_S are spatially-explictt factors assessing the importance of preferential ecological corridors (e.g. drainage networks whose extent is larger for salt-marshes than mangroves due to their more extended area on land; see Schwarz et al. 2022) and environmental pressure (fishery networks) in predicting ecosystem risks based on altered ecological function.

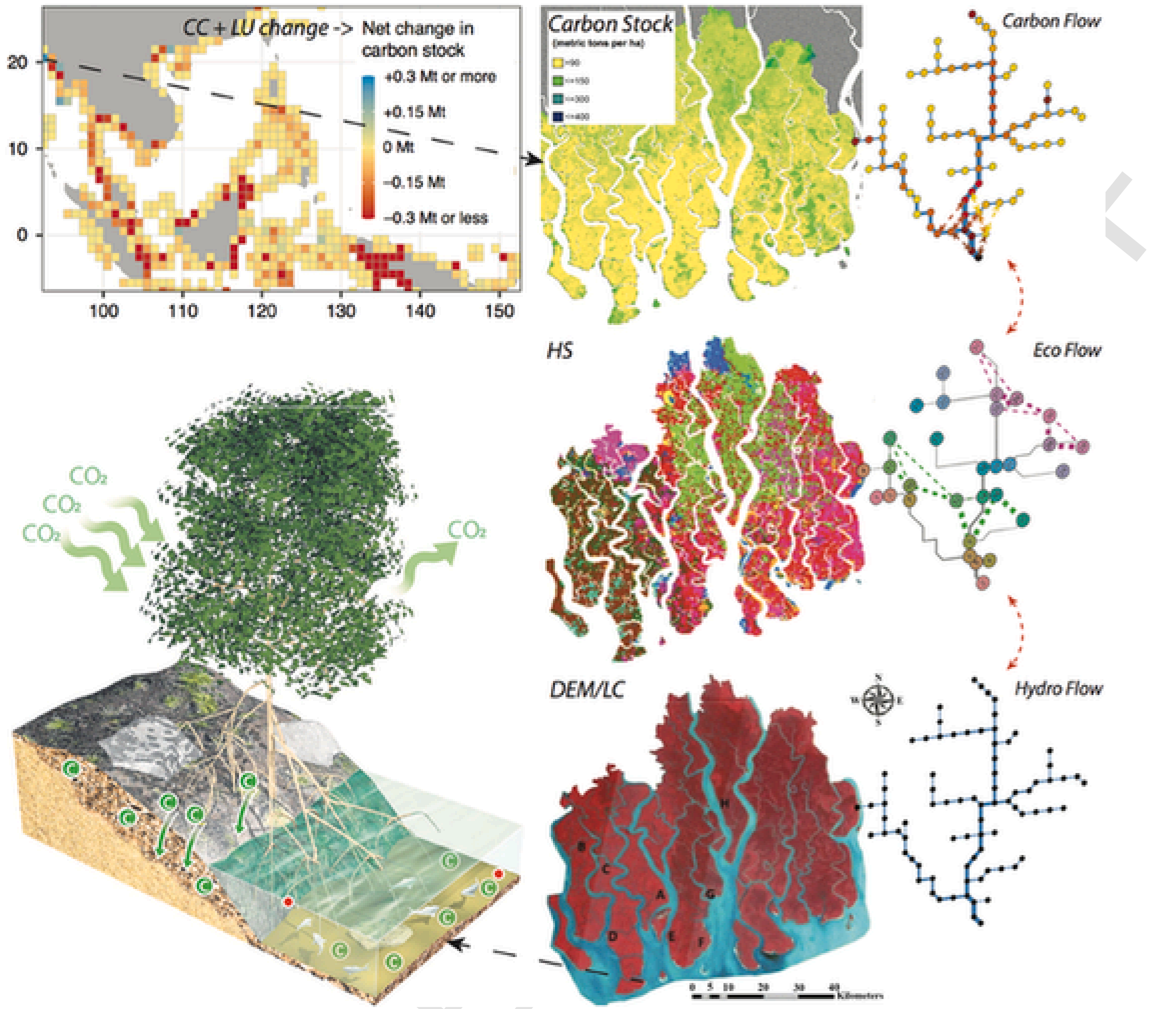


Fig. 2 Key Blue Carbon habitat restoration and biodiversity protection aim to enhance climate security and socio-ecological fitness. *Top left*: the estimated map of carbon-stock net-change in SE-Asia mangroves is shown based on 1996–2006 data; a reduction of 2% due to climate and land-use change (CC+LU) is estimated (red pixel is for net loss of carbon stock) from Richards et al. (2020); however, further resolution is necessary for quantifying loss dependent on climate, habitat fragmentation and biogeochemical pressure. *Right plots* from top to bottom: Sundarbans mangrove delta carbon stock predictions (Sanderman et al., 2018), inferred habitat suitability (HS) of plant groups, and Digital Elevation Model (DEM) (Chanda et al., 2016) from which functional networks of carbon flow, ecological flow (related to dispersal dependencies), and hydrologic flow are estimated. Land cover (LC) defines the distribution of mangroves in the delta. Network topology and directionality (the network is discretizing the main channel of the Sundarbans) is different for all displayed networks whose unknown feedback is regulating systemic ecosystem function and the dynamics of each ecosystem service (carbon stock, biodiversity, minimum runoff or environmental flow). *Bottom left*: 3D plot of mangrove structure and carbon cycling with carbon stocked above and below ground (source: The Straits Times). Carbon stock estimates are from Sanderman J, et al (2018) A global map of mangrove forest soil carbon at 30 m spatial resolution. Environmental Research Letters 13, 055002. (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/OCYUIT).

depicted in **Fig. 1**, Guangdong and SE China) can be pursued via integrated data-driven/macro-mechanistic models, considering the exceptional eco-geomorphological diversity of these areas and their development pressure.

Global/regional mapping of BC habitat shift, keystone-species multitrophic cascades and carbon-climate flux feedbacks can be innovatively predicted as complex dynamical networks dependent on climate and development/land-use trajectories (sea-level rise, extreme cyclones and ocean temperature aggravated by local biogeochemical loads) to understand their unknown linkage and inform management for valuated eco-climate security.

Future research must provide novel and quantitative discovery of local-global Gaian climate-habitat-species-carbon bidirectional feedback. This knowledge supports the formulation of optimal/Pareto BC-economy portfolios of ecosystem restoration and protection areas (for critical biodiversity hotspots/carbon sinks and ecological corridors) accounting for ecosystem non-linearity (climate-delayed effects, food-chain and habitat networks) and enhancing interdependent ecosystem services.

River network is monodirectional from upstream sites and scale-free, while carbon and ecological network are bidirectional with short- and long-range small-world topology, respectively. Red nodes for the carbon network are sink sites vs. neutral or source sites in yellow (undesired state) and across-habitat fluxes are possible; the node color of the ecological network is for different plant species group that disperse also across tidal flats and not only along drainage pathways. The core of ecosystem dynamics is on primary vegetation and associated keystone species (terrestrial, aquatic and avian) due to their criticality, socio-ecological value and eco-sentinel use. Charismatic species (e.g., the Indo-Pacific humpback dolphin and the dugong in the Greater Bay Area in China) and carbon connections (due to predator control and grazing) are great contributors and motivators of ecosystem restoration. All observed and predicted data (species abundance, carbon flow, climate features, etc.) can be transformed into networks and time series (for computationally efficient analyses) to quantify ecosystem non-linear coupling (and local-global teleconnections) and impacts due to ecological alterations driven by anthropogenic and climate stress.

Objectives for Integrated Basin Ecosystems

Specifically, objectives and scientific significance are about: i) understanding how collective environmental pressure*(hydroclimatological pressure considering temperature, rainfall, and sea-level rise adjusted by land-use change, and biogeochemical fluctuations) impact collective stability in BC habitats, multitrophic biodiversity, and carbon sequestration* (with cascading ecosystem services) as multiplex networks; (ii) inferring unknown universal and climate-/development-/habitat-specific multitrophic feedback of species and carbon fluxes/ hotspots*(interaction networks and functional relationships within and across BC habitats), bioindicators of BC potential, ecosystem shifts, and keystone species-habitat pair dynamics;* ; and, (iii) defining ecological engineering solutions restoring habitats/ecological corridors*by leveraging ecosystem engineer species with stabilizing portfolio effects on biodiversity-carbon function(i.e., fundamental ecosystem traits) and eco-hydrological restoration.* . Elements to quantify are: (1) the magnitude and features of biota for anticipating and controlling habitat loss (biogeomorphic feedback, such as how much oysters disaggregate under environmental stress); (2) how much the removal of keystone species leads to cascading biogeochemical (carbon and nitrogen primarily) and ecological collapse impacting local and global climate (systemic teleconnections); (3) the local (and fast) biogeochemical stress and infrastructure-driven fragmentation as primary factor vs. global (slow) climate change (in the form of sea-level rise, extreme heatwaves and cyclones); (4) the prediction accuracy of habitat and carbon/climate fluxes from salient biodiversity and hydrological information.

Ecosystem interaction networks and their predictability of carbon fluxes (ecosystem metabolism) can identify critical species-habitat pairs in the maintenance of carbon sequestration *critical species-habitat pairs in the maintenance of carbon sequestration* beyond their importance for multitropic cascades. Innovatively, Optimal Information Flow (OIF) can also define *critical carbon network dependencies among habitats and carbon-hydroclimatology feedback that serves to verify carbon habitat upwelling theories, overlapping with drainage pathways, and local-global climate feedback. Multispecies Conservation Values (MCVs)* (based on viability of keystone and endangered species) and estimates of carbon flux based on habitat baseline fluxes (adjusted by biota network organization) can be provided at a resolution of 90 m^2 globally or higher for selected BC hotspots (e.g., in Guangdong/Guangxi/Hainan provinces). These MCVs gives the opportunity to redefine Ecosystem Protection Areas considering ecosystem dependencies and multiple services. At the regional and global scale, maps and networks of BC habitat, biodiversity and carbon fluxes are useful for regional/transnational ecosystem management leading to potential biodiversity-carbon offsetting programs aiming to climate and ecological security facing climate change*maps and networks of BC habitat, biodiversity and carbon fluxes are useful for regional/transnational ecosystem management leading to potential biodiversity-carbon offsetting programs aiming to climate and ecological security facing climate change*. Additionally, the complexity of BC ecosystem data can leverage and test the performance of current big-data integrated machine-learning/macro-mechanistic models relevant for ecosystem science, e.g., via digitizing biodiversity (Digital Biodiversity Models combined to Digital Elevation Models) for ecological research and precise ecosystem management.

Bioterraformation: Bivalves as Epitomes of Blue Carbon Species

Biodiversity of coastal ecosystems is crucial for Earth survivability. This is particularly true for habitat-forming species such as bivalves, that are keystone for a multitude of ecosystem services. Other keystone species for different habitats can be taken as epitomes e.g., mangroves and cordgrass for mangrove forests and salt-marhses. As a result of unregulated and unreported overfishing, disease from pollution, climate change alterations in temperature, extensive coastal reclamation destroying habitats and altering hydroperiod, wild oyster reefs as well as other bivalve-formed habitats have become one of the world′s most endangered habitats. Unfortunately, this is a trend that is occurring worldwide with 85% of all natural oyster reefs that disappeared worldwide; a phenomena close to a mass extinction that is worrisomely led by ocean acidification/deoxygenation (PH decrease due to increase in carbon) due to eutrophication (loads of nutrients), temperature rise, and hydroperiod alteration (due to loss of freshwater discharge and sea-level rise). Yet, undeveloped and developing countries present *ecological risks* but also *great opportunities* due to the extent of these bivalve habitats, some of them still in pristine conditions. Among all bivalves, oysters are multi-talented coastal guardians with an impressive set of functions largely dependent on their calcareous shells, as well as ecosystem services related to their products (where seafood is one of them) (**Fig. 3**) (**Reeder-Myers *et al.*, 2022**). Their filter-feeding improves water quality and nutrient cycling, they provide safe haven for young fish and small invertebrates, re-

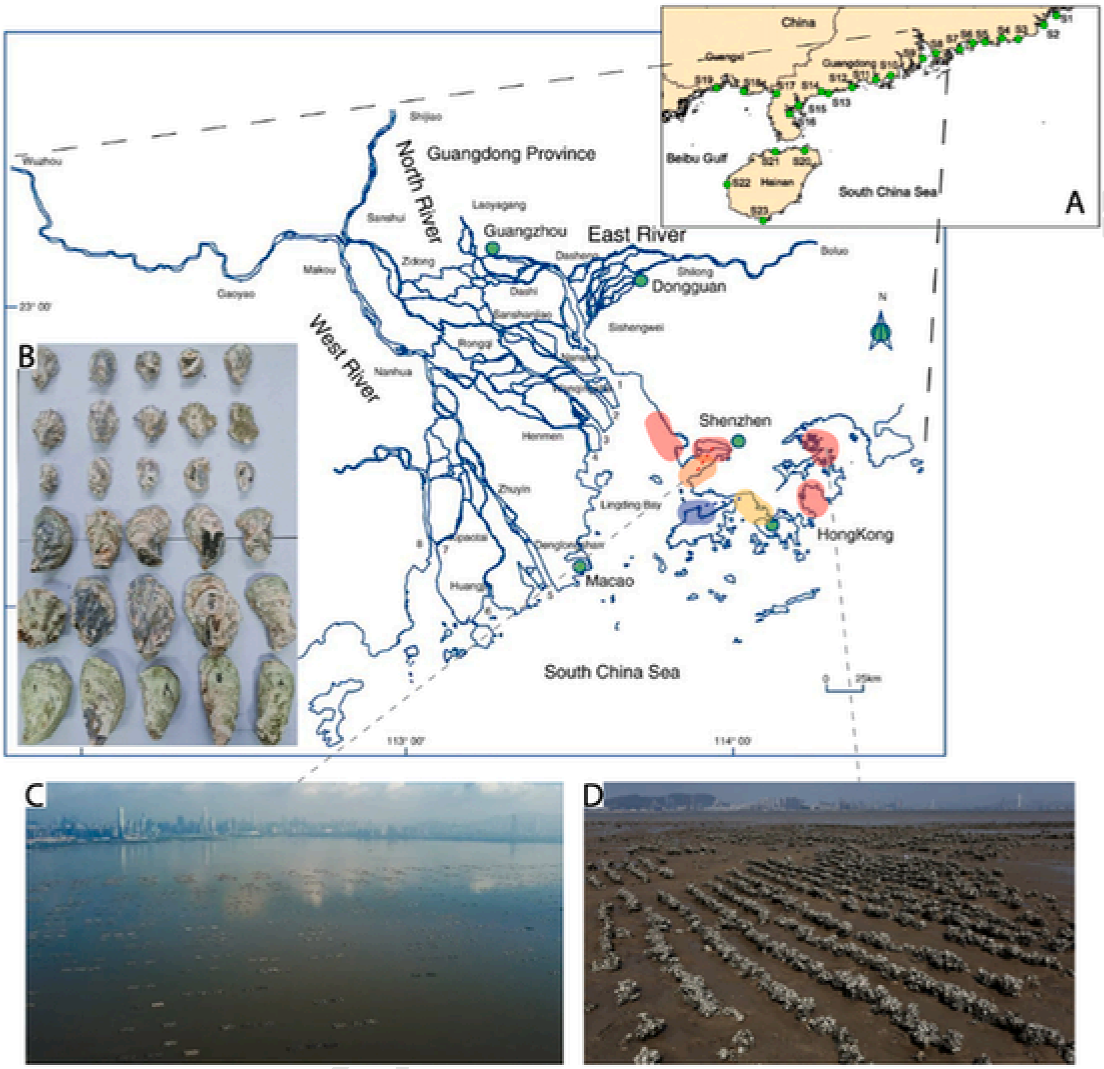


Fig. 3 Oyster distribution, diversity and habitat types. Oysters are taken as an example of keystone coastal species. (A) Guangdong and Pearl River Delta distribution and potential habitat suitability (low to high from blue to red, based on historical presence reports, current occurrence and environmental niche factors) of oyster habitats, and oyster diversity in Guangdong (B). Green points and map in (A) are from Wang et al. (2017). The PRD drainage network is extracted from Landsat satellite images considering perennial water paths. At least 4 different species are found as phylogenetically and morphologically different: line 1–3 are cultured Kumamoto oyster, line 4 are Portuguese oyster, line 5 are cultured Portuguese oysters in artificial breeding spats (C, Shenzhen Deep Bay) and line 6 are adult Portuguese oysters in natural oyster reefs (D, HK) that is the optimal ecohydrological solution. Images are sourced from The Nature Conservancy (https://www.tnc.org.hk/zh-hk/).

duce coastal erosion, and sequester large amounts of carbon. That is the reason for which these species are reputed to create truly *living shoreline* (bringing back other habitats and species and enhancing water quality) that are so important for biodiversity and socio-ecological systems. Oysters, and other bivalves, are *terraforming species* and guarantee future ecosystems where humans are included. Furthermore, their shell can be used as biomaterial in ecological engineering (for oyster substrate restoration for instance), as well as for the construction and fashion industry for instance; thus, creating a *blue circular economy* de facto.

As great examples of deltaic species, bivalves and oysters are the epitome of collective behaviorepitome of collective behavior, terraformation, and socio-ecological dependencies where all these aspects have profound implications for climate regulation though biogeochemical and hydrological cycles. Oysters, for instance, have been called the architect or engineers of coastal environments. The large ecological value of natural oyster reefs is determined by their ability to attract other species such seagrass, crabs, fish, and other bivalve like mussels considering habitats and nutrients they provide. A single oyster can filter 24–96 liters/day (1–4 liters/hour). With 750,000 oysters in one acre/year (that is average number of oysters), 18 M–72 M liters of water can be filteredwater can be filtered removing most forms of particulate matter suspended in the water column. The particulate matter oysters remove are sand, clay, silt, detritus, and phytoplankton; the latter largely affecting algal blooms. All these particulates could possibly contain harmful contaminants that originates from anthropogenic sources from rivers. Yet, instead of becoming ingested by other filter feeders that are then digested by bigger organisms (including humans), oysters can sequester these harmful pollutants, and excrete them into the sediments. Oysters and other shellfish are also climate-engineeringclimate-engineering species, abating climate change through the growth of their shell that permanently *bio-sequesters* atmospheric and ocean carbon dioxide in calcium carbonate that is stable over geologic time. Oysters, additionally have huge social implications, considering food and livelihood of coastal communities.

Preliminary evidence found that due to acidification oysters develop weaker shells, thus highlighting local-global connections. Because of this sensitivity, oysters are extremely good bioindicators of coastal ecosystem health considering habitat structure, multitrophic diversity, water quality (considering ecological standards), and consumption potential.

How much do we have before bivalve biodiversity goes extinct at the planetary scale? What are the simultaneous leading factors causing this tipping point? What are water, biodiversity and carbon implications of bivalve collapse? What is the state of other keystone species and dependent ecological communities? How divergent is water biogeochemical quality for species and humans? How can oysters minimize this water quality divergence and can they be used in water filtration plants? Can oysters and other bivalve restore impacted estuaries systemically (e.g., considering habitat degradations and pathogen presence)? Can we learn from the ecological history and engineer future ecosystems by at least guaranteeing the preservation of fundamental ecohydrological connections? What are the best species indicators of collective change? Among these indicators, useful for monitoring (Convertino et al., 2014), can we can identify optimal controls for planning, ecosystem engineering and policy solutions? Future research aims to answer all these pressing questions.

Preliminary Evidence and Hypotheses for Bivalves

Collective behavior is common across life forms. Studies were done for bacteria, plants and animals, and therefore are ubiquitous for all species across ecosystems, from biofilms to cities. However, it is still deeply uncomprehended how we can use information from collective patterns for assessing ecological health(largely underpinning ecosystem stability), and for restoring or creating habitats and biodiversity. This is also related to the misconception and misuse of species diversity as the metric related to ecosystem stability (vs. relative species abundance, i.e. RSA), and to the use of few selected environmental factors(e.g., water quality) in assessing ecological health(few causes do not determine systemic effects). A certain unappreciation exists also about the positive and direct role (biogeomorphic) of species in habitat formation– habitats that otherwise would not even be presents, such as tidal flats for bivalves – where global effects are not achieved by many isolated local actions but via preserved systemic ecological connections.

With collective behavior, ''social'' interactions among individuals propagate to affect the behavior of groups, whereas group-level responses in turn affect individual behavior. These cross-scale feedback loops between individuals, populations and their environments can provide fitness benefits, such as the efficient exploitation of uncertain resources and biological costs, such as increased competition. Although the social mechanics of collective behavior are increasingly well-studied within one species in isolation, *its role in ecosystems stability and health remains very poorly understood*. We do not know how to *engineer this collective behavior* because any eco-environmental factors are missing from existing studies. Collective behavior should be studied in a comprehensive way within a conceptual framework of *consumer–resource dynamics*, including resource-formed habitats, to demonstrate that *engineered collective behavior* (via ecological protection and enhancement) *can attenuate consumer–resource cycles and promote sustainable species* (bivalve and other species) coexistence.

Studies of collective behavior are missing the environment that is not considered explicitly -- particularly ecohydrological corridors exerting systemic controls – and other eco-environmental controls that can be used to enhance species at the individual and landscape scales (cross-scale mechanisms). A precise characterization of habitat dynamics is typically lacking, e.g., salt-marsh and tidal flat interactions, as well as multi-species feedback and how these affect individual traits and collective interactions and vice versa. The ecological portfolio analysis is really about discovering top-down and bottom-up controls that can be engineered, and their site-specificity or universalityThe ecological portfolio analysis is really about discovering top-down and bottom-up controls that can be engineered, and their site-specificity or universality. The following aims for research (or hypotheses) that are needed are formulated:

(1) *RSA and not species diversity* (for the same species across space, i.e., relative community abundance, and for different species across trophic levels) *is the basic ecological pattern underpinning aggregation of individuals and populations* (quantifiable as spatial and functional ecological networks; **Figs. 2** and **3**). Abiotic factors driven by habitat disruption (hydroperiod, salinity, temperature, and water quality), and societal demand (legal and illegal, inferred by consumption patterns detected in markets) affect biomass, species diversity and interactions (derived from RSA) affecting collective patterns. As sub-hypotheses I also argue about the primary importance of minimum water flow (balanced freshwater and saltwater affecting adjacent habitats) in defining RSA patterns versus water quality defining fluctuations of RSA.

(2) *Habitat suitability, and habitat heterogeneity loss (flow and geomorphology), is the primary top-down factor in shaping collective behavior before species fitness*, although the latter can induce local cohesion and productivity (via enhanced survival and recruitment of other individuals). Yet, *landscape-scale population assemblage and abundance* (or fitness) (**Fig. 4**) can increase individual and population fitness and predict patterns and shifts of diversity, productivity and ecosystem function such as water and nutrient cycling. As a sub-hypothesis I also argue that *habitat complexity can predict patterns of bivalve assemblage and multitrophic diversity* (vs. habitat homogeneity due to loss that leads to complete unpredictability).

(3) *Eco-morphologic traits of bivalves* and in general of any species (shape and shell patterns, including color, texture and fractal dimensions, predominantly) *are related to persistent collective behavior* and determined by long-termlong-term trend in climate and habitat

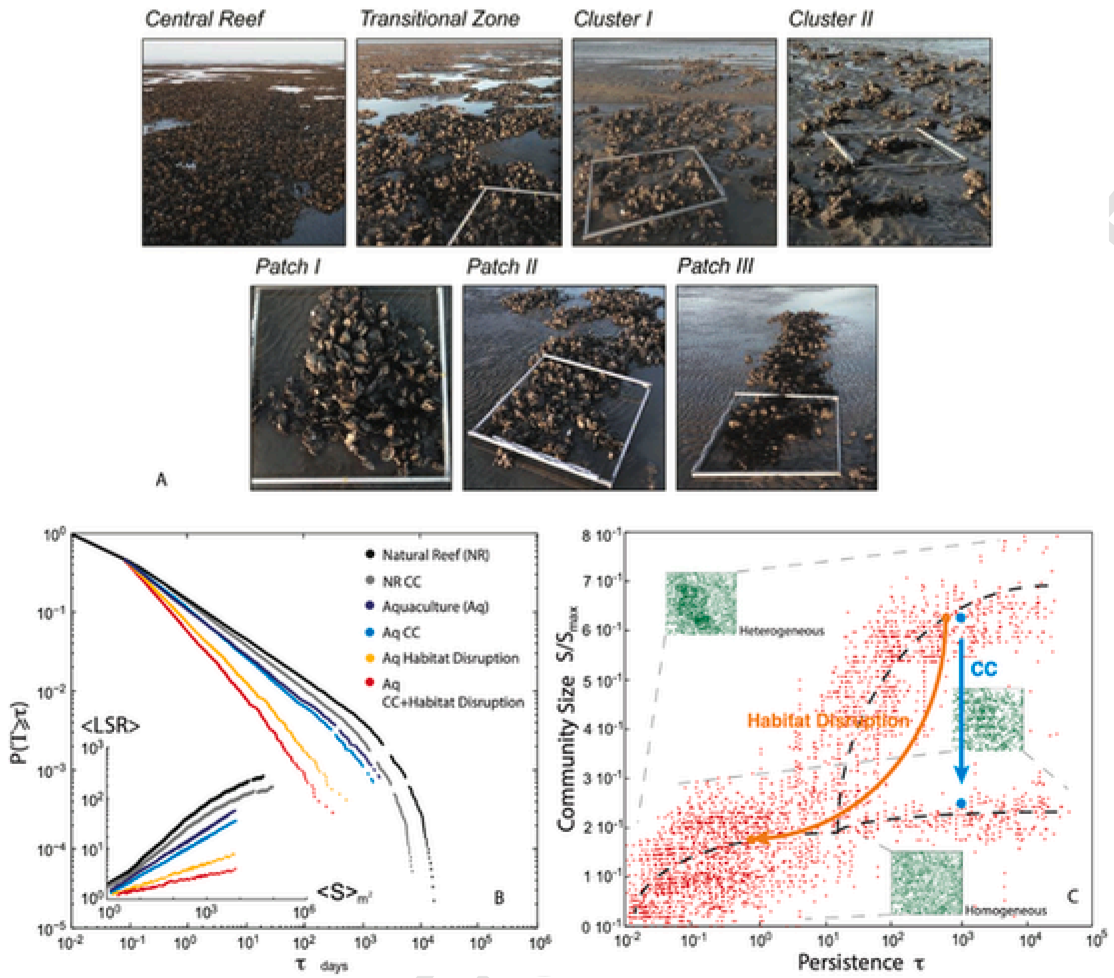


Fig. 4 Relative Species Abundance as the main determinant of community stability related to species interactions (Hypothesis 1). Oysters are taken as the epitome of keystone species. Plot A shows oyster reefs at different spatial scales highlighting large clusters and small patches: the spatial distribution and size of cluster and patches defines oyster persistence. Previous research for fish communities found that Pareto distributed interactions are broken by ocean temperature change and lead to random species interaction and community homogenization (plot B inspired by results from a neutral metacommunity model of Convertino (2011)). Plot B shows the exceedance distribution of the persistence (τ) of oyster beds in a region considering natural reefs and aquaculture habitats under current conditions, climate change and habitat disruption. The inset of plot B shows the multitrophic local species richness (LSR) in oyster reefs as a function of the reef area S, that is the species-area relationship corresponding to the exceedance distribution of oyster persistence. Plot C, inspired by results from a neutral metacommunity model of Convertino (2011),shows the non-linear relationship between oyster reef size (clusters and patches) and persistence, and how transitions occur under climate change and habitat disruption considering spatial oyster distribution as an outcome or determinant. It is hypothesized that for oyster reefs healthy states are highly diverse and unhealthy ones are majorly occupied by one or two species (like oysters and mussels only). It is also speculated that the same diversity may be found in seafood markets. Highly heterogenous reefs (with Pareto distribution of oysters) imply large community size and persistence. Aquaculture and homogenous aggregation confer instability and high sensitivity to environmental change. Oyster pictures are from Hitzegrad, J., *et al*., 2022. Oyster reef surfaces in the Central Wadden sea: Intra-reef classification and comprehensive statistical description. Frontiers in Marine Science, Section Coastal Ocean Processes. https://doi.org/10.3389/fmars.2022.808018.

features (e.g., fractal dimension of coastal habitats); in other words *the complexity of habitats is decoded into the complexity of bivalves* (for oysters in particular, e.g., topography and fractal coastline dimension are matching oyster reef microtopography and shell fractality; see **Figs. 5** and **6**) and the *landscape-scale mosaic of habitats sculpt the mosaic of bivalve forms*. Thus, these traits can be used for long-term monitoring of habitats and populations, revealing *species adaptationspecies adaptation*. *Fluctuations of eco-morphologic traits are meaningful of short-termshort-term collective behavior alterations and can inform about quality and safety of seafood* (this is mostly related to fluctuations of quickly-changing environmental factors, including societal pressure), revealing *species stress-responsespecies stress-response*. eDNA-based diversity in habitats and seafood markets can inform about potential state and legal/illegal demand of species locally.

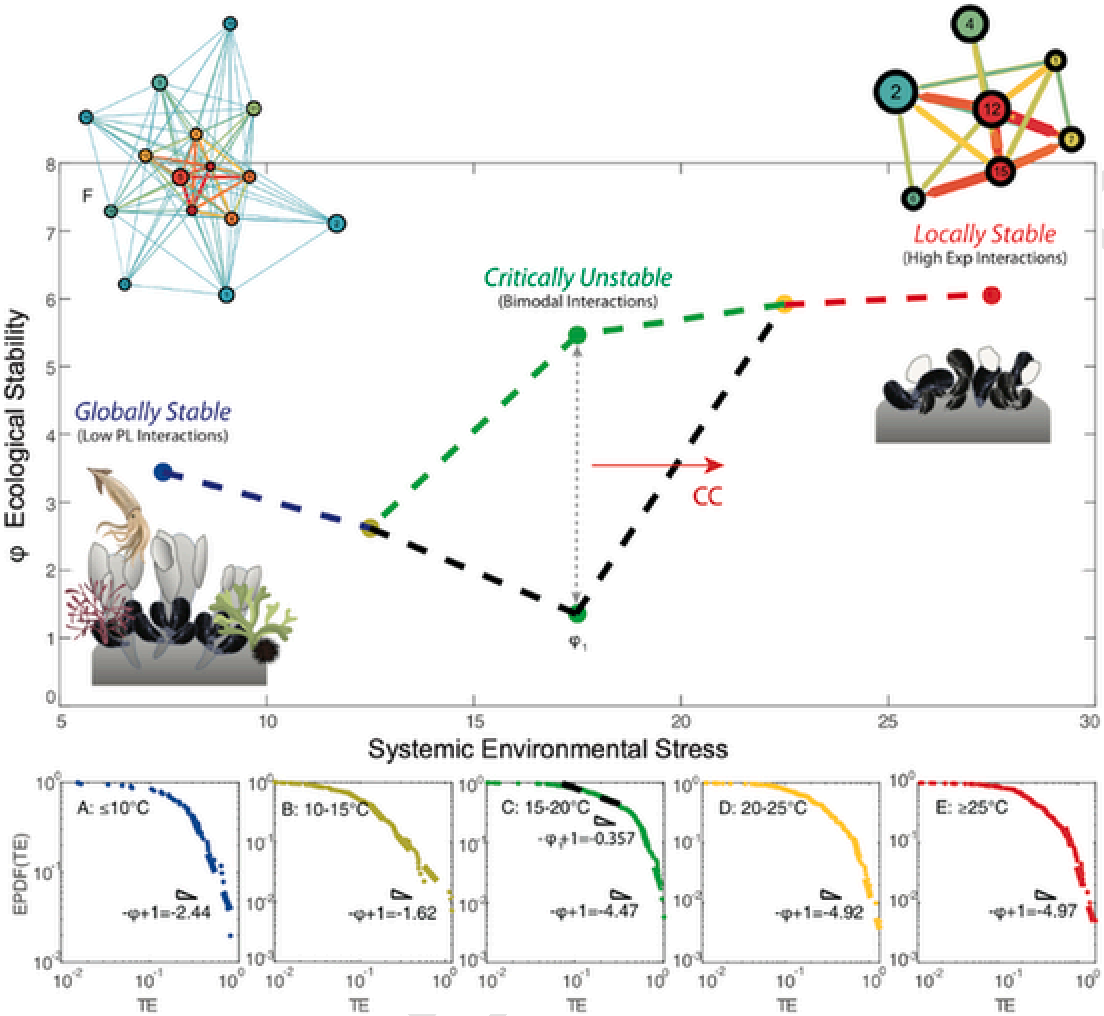


Fig. 5 Pattern of ecological stability dependent on systemic environmental stress. Oyster landscape-scale persistence and average community size (Hypotheses 2 and 3) shown in **Fig. 4** can be synthesized as Ecological Stability based on interaction of habitat patches or species on oyster reefs at multiple trophic levels. Oysters are taken as the epitome of deltaic keystone species. (Top plot, inspired by a model of Li and Convertino, 2021b for fish interaction inference) transition in ecological stability (defined by the slope of the exceedance distribution of species interactions, inferred via Transfer Entropy and displayed by the bottom plots for different ocean temperature range) can reveal habitat-specificity or ecological stress. Systemic environmental stress is majorly exerted by ocean temperature, terrestrial hydrologic flow and PH variability in different habitats (Vargas et al., 2022). Globally, ocean temperature seems the leading indicator of oyster stability. Indicators of these patterns, e.g., the slope of the power-law persistence distribution (**Fig. 4**), the multitrophic species interaction distribution (bottom plots), or the oyster patch interaction distribution can be used as indicators of ecosystem health to pinpoint conservation and restoration. Bottom plots shows a transition in the exceedance distribution from a stable power-law (for high richness in clustered oyster reefs) to a highly exponential distribution (for low-diversity disconnected oyster patches).

The historical analysis, based also on old shell samples and UAV recognition, can define unmapped current state, past shifts, risk hotspots and fragmentation, habitat-scale packing and potentially suitable habitats. Poorly quantified relationships between hydroperiod, salinity, temperature, critical biomass, multispecies coexistence, likelihood of paralytic toxin, pearl generation, consumer demand, and (potentially universal) self-organizing patterns can be innovatively unveiled. The eDNA monitoring can inform about biodiversity gradients along habitat morphology and socio-environmental stress particularly for natural and restored oyster reef, as well as fishing pressure and illicit shellfish trade in markets (e.g., banned area sourcing, yet to use traits as ‘‘conservation forensic’’ and safety indicators). The eco-morphological analysis can quantify species adaptation and response to climate-driven temperature shocks and point-source anthropogenic pollution from rivers (Convertino et al., 2018, Deere et al., 2021), and formulate trait-based risk warning for consumptions; the latter can be decoded as model features for automated species origin and quality assessment via a user-friendly App. By using oyster shells (or their pearls) as mineral ‘‘time capsules’’ I *hypothesize* that it is possible to quantify how the environment around the mollusk

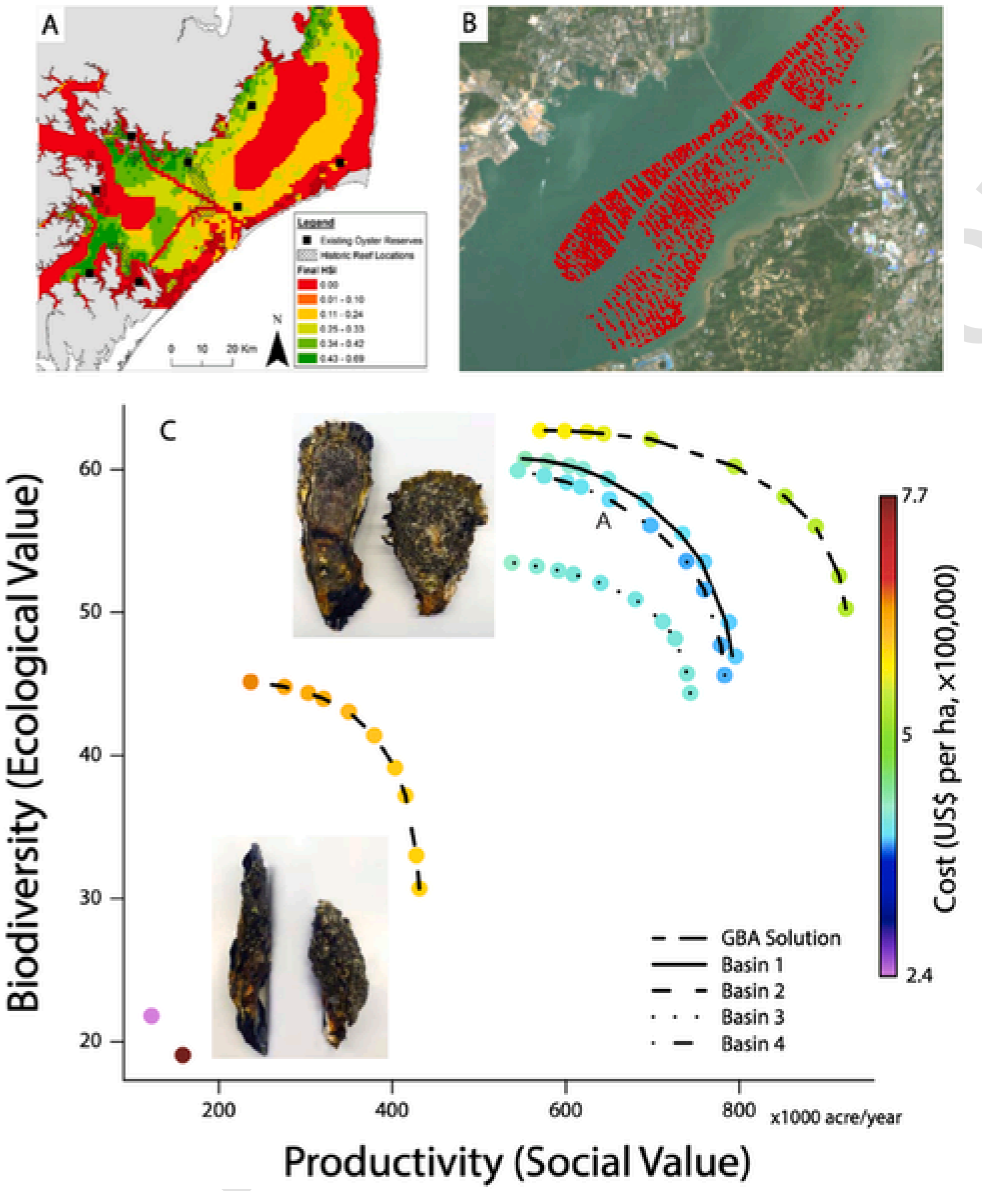


Fig. 6 Ecofolios as ecosystem ''trait'' configurations where multiple services are traded-off. Examples of oysters as keystone species (or key nature-based solutions) is shown. Plot A shows the habitat suitability of historical and current oysters that is useful for oyster reintroduction as reefs in a deltaic area (image as predicted habitat suitability in North Carolina, Pamlico River Delta (Puckett et al. 2018)), contrasted by oyster aquaculture in Hong Kong, Shenzhen Bay in the Greater Bay Area (Plot B, image from satellite Landsat images in 2019). Pareto frontiers, generated by the model of Convertino and Valverde (2013), unveils the multidimensional architecture of species considering their function-derived services imposed by habitat s and manifested by reef structure and shell morphology. Thus, Pareto frontiers are not judt management tools but diagnotic tools to assess the functioning of biodiversity.

has influenced species metabolism (and yet calcification and development) and backtrack to get a better picture of environmental change, and whether there are engineerable controls on community stability such as critical mass and organization factors. This is arguably the case for any mollusca due to their primary role in water filtering/nutrient cycling.

Plot C in Fig. 6 show Pareto frontiers of optimal nature-based solutions, corresponding to oyster reintroduction (points correspond to different spatial bivalve habitat configurations), that determine different ecosystem traits (in this case biodiversity as number of species on reefs, and productivity related to oyster potential commercial revenue) that are maximized by the portfolio multiobjective function. Points away from the Pareto frontier are suboptimal, and yet this divergence can be used to assess ecosystem health along multiple ecosystem services. Preliminary assessment of restoration cost shows that it is lower for the Pearl Delta in the Greater Bay Area vs. smaller basins (e.g., Shenzhen Bay only) due to systemic effects (e.g., higher morphologic fitness and dispersal increasing productivity and diversity due to facilitated recruitment and sediment-nutrient dynamics). Restoration that are basin-wide considering the whole drainage structure is maximizing both ecological and social productivity.

Portfolios can target enhanced restoration strategies such as the use of *eco-inspired (biophilic) tidal networks* (**Fig. 6**) improving bivalve assemblage and stability, shifting aquaculture-mariculture strategies, and integrated multispecies habitats compared to natural bivalve habitats. Ecosystem portfolios, embedding salient eco-environmental feedback, can be constrained considering feasible habitat configurations and safe thresholds of species demand for guaranteeing sustainable shellfish communities in terms of diversity and critical population abundance. Hence, the proposed portfolio can quantitatively evaluate the natural capital generated by ecological security in term of biodiversity and services such as food provision and water filtration.

Data, Information-theoretic Models and Methods

A substantial amount of biodiversity data is available for coastal and marine ecosystems worldwide although this information is largely varying in spatial and temporal resolution, and it is widely scattered among many digital platforms. In my preliminary investigation for Guangdong and the Greater Bay Area (particularly HK), data can be sourced from published literature. Environmental data can be sourced from government agencies and public repositories as well as sampled from oyster sites. eDNA sampling can be performed with state-of-the-art portable technology in coastal habitats (including historical habitats such as oyster reefs). Habitats can be surveyed at high resolution via UAV-sensed imagery and oyster collective behavior via underwater cameras acoustic sensors. The total number of sites (with focus on all coastal habitats) should be large enough to capture ecosystem variability, also through time considering major tropical cyclones to detect extreme eco-environmental changes. For species information, it is proposed to combine three of the largest biodiversity databases, i.e. Living Planet (7,340 time-series spanning 1970–2014), BioTIME (44,532 time-series spanning 1858–2017) and PREDICTS (468 studies spanning 1984–2013). The Living Planet database includes time series data of individual species' abundance for vertebrate taxa for the terrestrial, marine and freshwater realms. The BioTIME database is also a compilation of time series but of ecological assemblages for vertebrate, invertebrate and plant taxa across the marine and terrestrial realms. The PREDICTS database includes space-for-time comparison studies testing the effects of land-use change on vertebrates, invertebrates and plants and thus focuses on the terrestrial realm.

Previously developed models (MaxEnt, OIF, and PDM described below) can be contextualized and further developed considering specific needs of research objectives such as the inclusion of species traits in distribution modeling, and physical constraints on the feedback between spatial habitat- and species-networks. Ecosystem models were uniquely developed by considering *ecosystems as ''information machines''* that receive, process, store and generate information in the form of environmental and ecological space-time series spreading on networks (**Li and Convertino, 2019, 2021a,b**). This probabilistic framework is convenient because it allows to: *(i) predict ecosystems without a deep knowledge of underlying processes, inferable a-posteriori; (ii) categorize ecosystems based on their stochastic dynamics; (iii) extract salient data corresponding to critical factors and interactions among ecosystem components (species, habitat, environmental factors) for observed transitions and desired multiscale ecosystem patterns (e.g., key species distribution and environmental conditions) to predict and achieve, e.g., key species distribution and environmental conditions) to predict and achieve.*

Multinetwork Inference of Species Interactions, Habitat Connections and Fitness

Bivalve species and community networks in coastal habitats can be assessed via the Optimal Information Flow model (OIF) proposed by **Li and Convertino (2021a,b)**. The OIF model, was originally published by **Servadio and Convertino (2018)** to infer population patterns and develop *systemic risk indicators based on variable networks*. The inference of ecosystem relationships, locally and globally, based on relative species abundance and habitat change over time, is useful for developing a macro-mechanistic understanding (and models) of species co-variability, biota-control on habitats and likely effects on ecosystem services such as water filtration, hydroclimatologic impacts and potential carbon sequestration (by species and communities). *OIF innovatively reconstructs attractors of selected variables (and yet of ecosystem states)* based on their probabilistic mutual time-dependent predictability considering non-linearity (space, time and related to variable distribution), i.e. via Transfer Entropy estimated via refined algorithms on probability distribution function. Empirical functions and fitted analytics relating changes in coupled variables underpin a likely strong causality between these variables. This predictive causality can be used by Empirical Dynamical Model to forecast species abundance trajectory over space-time.

MaxEnt, uniquely modified by **Convertino *et al*. (2013a,b,c,d)** with the *inclusion of non-linear interactions of environmental variables*, is the habitat suitability (HS) model that can be used to predict species distribution and community fitness dependent on hydroclimatological (considering both ocean and freshwater flow) and biogeochemical variables; the latter penalizing species and community fitness as environmental stress on species. Eco-morphological traits of bivalve species would be considered as potential ecological features increasing or decreasing species fitness. HS constitutes the average taxonomic carrying capacity for species at each trophic level, and environment-ecology ''response functions'' can identify thresholds of critical transitions for each environmental factors (jointly acting with others) causing shifts in species distribution and community diversity. **Figs. 4** and **5** show critical shifts dictated by changes in habitat sustainability of key species (e.g., oysters) and how that affect community diversity and eco-hydro-geomorphic endpoints by consequence.

Multiscale Imagery Pattern Analysis

Multiresolution texture-based analysis developed by **Convertino *et al*. (2012)**, can be used to characterize multiscale eco-geomorphic and phenotypic patterns of remote-sensed habitats and species. Images are from satellite imagery, UAV recognition and high-resolution macroscopic imaging for shells and others. The multiresolution texture-based model based on wavelets aims to detect different species and their change (including surface area, density and clustering), as well as habitat and traits changes over space and time (**Fig. 4**). *The uniqueness of the model by* Convertino et al. (2012)*is the consideration of multiple scales and resolutions simultaneously and the linkage of texture features to species features*.

The fractal dimension is the feature that characterizes roughness of ''ecological topography'' at multiple scales (and potential departure from optimal scale-invariant network configurations): in the discussed case of habitat and species shell's geometry at the macro and ''micro'' scale. Yet, macro-, meso- and micro-topography of landscape, habitat/community and individual species can be correlated to each other (paying attention to true causality) to identify cross-scale influence or divergence over space-time. As highlighted in previous research on shorebird and bacteria populations, the *fractal dimension is an effective average measure of network topology* of species (whose dispersal occurs on these ecological networks) within a domain characterized by a certain field variability (i.e., the habitat suitability). Habitat suitability of keystone species (e.g., for oysters as show in **Fig. 6**), is a multivariate non-linear function that combines a variety of eco-environmental factors such as eco-hydro-geomorphic factors, and underpins socio-ecological productivity. The how oysters are distributed, beyond their presence, defines ecosystem function and its proximity to optimality that is the baseline of a myriad of ecosystem services from nutrient recycling to flood protection.

Ecosystem Causality Networks and Function Predictions

To predict species in the continuous space-time domain and gaining deeper insights into specific species traits, community biodiversity, environmental stress and causal habitat associationsspecific species traits, community biodiversity, environmental stress and causal habitat associations a predictive model accounting for population interactions via OIF matrices (trophic and non-trophic interactions) can be used. In this way effective risk of populations, communities and ecosystem services can be estimated in magnitude and probability rather than just divergence of species network topology from optimal configurations (**Fig. 5**). S-map (i.e., sequential locally weighted global linear map model) as Empirical Dynamical Model can predict species trajectories considering dynamical interactions over causally related species (that accounts also for environmental variability) where causality between species is estimated a-priori via OIF rather than Convergent Cross Mapping (CCM) (Sugihara et al., 2012, Ushio et al., 2018). **Li and Convertino (2021a,b)** recently proved the superiority of OIF vs. CCM in freshwater and marine ecosystems considering both predictive accuracy, realism to assess ecological associations and attributing ecological change (species and diversity change) to environmental causes. Current inference models like PCMCI (**Runge, 2019**) have been proven superior than other models (leaving aside more recent deep-learning models) to infer causal networks due to their ability to consider multivariate time series and conditional direct influence.

S-map predicts future values of species abundance from the reconstructed multivariate state-space vector (where species are interdependent by OIF inference). EDM with S-map and OIF coefficients generates time series that preserve the shape of a species attractor (based on historical ecological data) and exhibits predictive causal relationship with environmental variables (e.g., ocean temperature, salinity and others), where the unexplained variability is attributed to all other non-included factors. The key to prediction is that the Jacobian elements (i.e., interaction strengths) can be recovered at any target point ''x(t)'' (e.g., x is the abundance of any species) on the attractor using S-maps (Ushio et al., 2018), where 'S′ in the Sugihara's S-map formulation denotes the sequentially calculated interactions as the system moves along its attractor. S-maps are then locally weighted multivariate linear regressions approximating the best local linear model by giving greater weight to points on the attractor that are near the current ecosystem state. Ecosystem states reflect the conditions toward which ecosystems tends to be organized and are associated to network configurations (e.g., biodiversity is associated to certain habitat-determined interactions). Despite the local linearization of S-map, *the model is predicting non-linear phenomena due to the simultaneous consideration of all interacting species, time delays, and their non-normal distribution*, both as a 1D average and in a more computationally demanding 2D spatial formulation. The novelty of the model would be *the inclusion of species ecological features from phenotypic traits to spatial collective behavior features*, to (i) explicitly investigate multiscale determinants of species change, (ii) and make EDM+CCM a more mechanistic model with the inclusion of spatial ecological networks (this is arguably similar to the neutral metacommunity model of **Convertino *et al*. (2009)**, **Convertino (2011)**). The *species-specific risk* for specific species can be assessed considering EDM predictions that predicts abundance in space-time under environmental stress scenarios. Thus, it is possible to map species-specific and community risk hotspots and pathways: these risks can be associated to Early Warning Signals with different degrees of warning based on the severity of ecological dysbiosis that can pinpoint interventions as ecofolios addressing systemic function (Convertino and Valverde, 2013) by leveraging climate risks (Convertino et al., 2019).

Ecofolio as Potential Landscape of Future Ecosystems

The portfolio decision model developed by **Convertino *et al*. (2013a,b,c,d, 2019)** is a spatially-explicit multiobjective optimization model detecting all potential ecosystem configurations (ecofolio) considering multiple ecosystem traits as desired and potentially conflict services (e.g. biodiversity and species productivity). The *novelty of the model is about the inclusion of spatially explicit macromechanistic* *dynamics with the optimization algorithm* (MaxEnt for local habitat fitness and network-based collective dynamics for species dynamics) and *the consideration of non-normal probability distribution functions and non-linearities between ecosystem traits* (i.e., essentially considering the ecosystem state landscape defined by EDM). The latter is somewhat analogous to the use of copula functions for incorporating non-linearities in objectives in classical portfolio models. The ecofolio model can determine Pareto optimal configurations determined by habitat restoration configurations as optimal nature-based solutions that guarantee enhanced resilience of ecosystems (Convertino and Valverde, 2019). Pareto optimal configurations determined by habitat restoration configurations are optimal nature-based solutions (**Fig. 5**). The ecological novelty of this proposed ecofolio is about: (i) the primary focus on terraforming species (bivalves and other keystone species) that are salient for other species and accounting for a multitude of other environmental functions; (ii) the explict consideration of the connection with other blue carbon habitats; and (iii) monetizable species productivity as societal pressure and investment on ecosystems.

Conclusions

Societal impacts of coastal keystone species such as bivalves are immediately generated by their ecology, i.e. collective behavior, for instance assessed by considering occurrence and distribution. Oysters have impressively rapid *habitat-forming function*, environmental functions (water filtration, carbon storage, and coastal flood protection, yet they are excellent eco-filters), ecological functions (largely enhancing food-web diversity and species interactions, with incredible multispecies collective behavior similarly to coral reefs), and high social value as well as environmental pressure (e.g., oysters are both seafood and biomaterial). Thus, bivalves present large opportunities as nature-based solutions due to their high controllability in beneficial and sustainable ways. Bivalves are also crucial connectors of society and nature as well as land and ocean habitats. Beyond untangling fundamental ecological functions underlying desired patterns at multiple scales, the discussed research can formulate models and solutions to engineer ecosystems in a circular blue-economy perspective, where management of species directly produce tangible and valuable ecosystem services locally and planetarily. In other words, nature provides an insurance for ecosystem services against climate risks (Valverde and Convertino, 2019). The *ecological portfolio* model serves to implement bottom-up and top-down controls that are likely local and systemic vs. suboptimal and isolated restoration with limited systemic benefits. Dedicated *oyster sanctuaries* – i.e. oyster reefs excluded from use for harvesting and farming – can become the upskirt of marine sanctuaries acting as nursery habitats for species, including for top predators like sharks. Yet, the research on ecosystem potential and bioterraformation has the potential to tangibly link science to sustainable resource productionsustainable resource production (via both sanctuaries and enhanced farming areas) by activating the *ecology-environment nexus* (although everything is an ecological connection) in a positive way; this would be beneficial via the creation of future habitats (in many cases previously lost, like oyster reefs) where species at the core.

Educational campaigns should be developed in nature centers, and selected schools and communities to raise awareness (e.g. habitat preservation and illegal/unsafe fishing) and seek for volunteers in ecological sampling and restoration, and partners for bivalve shell use as biomaterials.

Pressing ecosystem questions are the following.

(1) At what scale *environmental heterogeneity loss* (including habitat change, particularly hydrogeomorphological and societal pressure) affects sense-dependent community and species patterns (ecosenses)?

(2) How much and with which time-delay *ecological imbalance* affects local habitat and *hydroclimatological patterns* (flow and temperature considering also teleconnections) with potential social risks (ecorisks)?

(3) Which *ecological indicators* (habitat and species traits, including Threated/Endangered/ at Risk, rare and keystone species), as well as sensor technology and location, are the most sensitive to *short- and long-term ecosystem shifts* and how do shifts appear? Are there univariate and multivariate patterns (''mandalas'') that are best for charactering *ecosystem health* and what are the major environmental causes? The dichotomy between environmental pressure and ecological health can be explored to precisely define *ecological corridors* to preserve (ecoties) ecoties and *environmental impact pathways* to control at the basin scale. Yearly maps of coastal ecosystem health (ecohealth) ecohealth can be formulated.

(4) What are the universal and site-specific salient socio-ecohydrological solutions (networks, flows, terraforming and keystone species, and behavior as ecofolios) considering future trajectories that maximize ecological organization and stability embedded into ecohealth?

(5) What is the divergence between effective and *perceived ecological risks* and what are the societal means that lead to altered behavior embracing ecological stewardship (e.g. risk communication to end plastic spillover, illegal wastewater discharge and species exploitation)?

These aims are useful for *ecosystem health assessment* (where ecological stress, leading to dysbiosis or collapse as a function of systemic environmental pressure, is predominant), conservation and restoration prioritization, evaluation of restoration and future planning, and improvement of predictive models of future ecosystem scenarios incorporating species adaptation and interactions. All these elements must be explored within drainage basins (deltas) that are the ecosystem units over which species and impacts' dynamics occurs and where the control of ecological ties is necesssary.The Digital Elevation Model resolutions (90 m^2) can be adopted as the optimal resolution trading-off ecosystem representation and computational complexity. The proposed research can lead to deeply needed ecology-informed decisions, communication strategies and visualizations (e.g., by leveraging multimedia Digital Biodiversity Models). The generated information is also impactful for improving models of local-global climate, nutrients and marine resource trajectories that guide optimal ecosystem decision making anchored on salient bioterraforming species.

Uncited References

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