Catalyzing Action Towards the Sustainability of Deltas

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Abstract
Deltaic systems are among the most dynamic and productive environments on Earth and many have a high population density. Deltas play a central role in food and water security but are increasingly facing hazards such as submergence, riverine and coastal flooding, and coastal erosion. This paper synthesizes efforts of the Belmont Forum Deltas project, an international network of interdisciplinary research collaboration with focal areas in the Mekong, the Ganges Brahmaputra, and the Amazon deltas. The inherent complexity and dearth of knowledge about deltas require disciplinary expertise to advance jointly with interdisciplinary collaboration. An overarching research framework articulates focal research areas and collaborative modules, serving as an umbrella for both crosscutting and specific research questions. These modules have allowed for common definition of goals, responsibilities, and products, but flexible and decentralized disciplinary and interdisciplinary collaborations. Self-organization within and across areas of expertise has proven effective in bringing collaborators to commit to specific efforts. Knowledge co-production workshops focusing on vulnerability and risk have successfully strengthened interactions with regional organizations. As a distributed network, challenges remain in terms of type of and level of interaction and hands-on collaborative work among research partners, including joint fieldwork, but successes far outweigh difficulties. To illustrate these points, we present a review of three research domains built upon different arrangements of disciplinary and interdisciplinary collaborations: advancing biophysical classifications of deltas, understanding deltas as coupled social-ecological systems, and analyzing and informing social and environmental vulnerabilities in delta regions.

Catalyzing Action Towards the Sustainability of Deltas

1. Deltas as sentinels of regional and global changes

Deltaic systems are among the most dynamic and productive environments on Earth, home to a human population density many-fold that of world average [1]. Important breadbaskets of the world, deltas play a central role in food and water security, and riverine and coastal vulnerability of urban and rural areas. Recent assessments suggest that during the past decade 85% of the world's deltas experienced severe flooding, a situation that could increase by 50% under current scenarios for relative sea-level rise [2; 3; 4]. Undergoing intense urban transformations, deltas are therefore not only important socio-ecological systems in virtually all regions of the world, but also coastal sentinels of global change [5; 6; 7; 8].

We describe a project that focuses on both advancing scientific knowledge and raising international awareness of the importance and vulnerability of deltas worldwide (The Belmont Forum (BF) Deltas project) [9]. The project has promoted international and regional cooperation and data sharing at the scientific and stakeholder levels. It has also provided an opportunity to initiate, mature, and reflect upon the process of establishing an international framework for interdisciplinary and stakeholder collaboration contributing to the scientific understanding of these complex systems and their changes with the goal of informing sustainability discussions more broadly. A shared research framework (Figure 1) has helped to articulate focal research areas and collaborative modules linked to specific outputs in three major deltas: the Ganges-Brahmaputra-Meghna, Mekong, and Amazon deltas.

The project framework has served as an umbrella for both overarching and specific research questions, within and across disciplinary boundaries, as well as a pathway for sustained and bidirectional exchange between researchers and stakeholders. The five modules in the framework have allowed not only for common definition of goals and responsibilities, approaches and products, but also for flexible and decentralized collaborations around issues of common interest. While sharing a common framework, self-organization has proved effective in bringing collaborators to commit to specific efforts, within the financial possibilities of the project. Our experience so far shows that the complexity of delta systems and the dearth of knowledge about how social-ecological-physical processes interact and respond to regional and global changes demand coupling of disciplinary and interdisciplinary expertise as well as collaboration with stakeholders.

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In the context of this special issue on lessons learned from interdisciplinary global change research programs, this article has a two-fold goal: to reflect on the process used by the BF-Deltas project for developing an interdisciplinary research and stakeholder collaboration and to present a review of current thinking on conceptualizing deltas as biophysical-social-ecological systems. We begin by providing a brief history of the establishment of the BF-Deltas team network. We then provide a review of three research domains where disciplinary expertise and interdisciplinary collaborations are contributing to shape outcomes: advancing biophysical classifications of deltas, conceptualizing deltas as coupled social-ecological systems, and assessing social and environmental vulnerabilities in delta regions. Each research domain is contributing to fill in key knowledge gaps. We conclude by reflecting on issues and conditions that have facilitated and/or challenged disciplinary and interdisciplinary collaboration and overview opportunities going forward.

1.1 Building an international, interdisciplinary research network dedicated to deltas

The BF-Deltas project emerged from collaborations and initiatives that begun before the Belmont Forum funding program released its first call for proposals focusing on Coastal Vulnerability. Research teams in North and South America, Europe, and Asia were actively carrying out research in the Amazon, the Mekong, and Ganges-Brahmaputra-Meghna, and other deltas. One instrumental effort was the NSF-funded Science and Technology Center, called National Center for Earth Surface Dynamics (NCED), led by Efi Foufoula-Georgiou, which was already engaging with diverse groups of stakeholders as part of research on the restoration of the Mississippi River delta after hurricane Katrina. The experience and foundational work developed by leading members of that team as well as other research efforts by project members contributed to establishing a mode of operation that has proved successful for the creation of the BF-Deltas project.

Other groups were working to mobilize attention to the concerning situation of deltas around the world. One specific effort that created the impetus for proposing the BF-Deltas project was the writing of a collaborative article calling for an International Year of Deltas (IYD) [9] and subsequently the proposal submitted to ICSU for the establishment of articulating the 'Sustainable Deltas Initiative', which became supported by ICSU in 2015 and was launched at the "Deltas in Times of Climate Change" Conference in Rotterdam. This effort helped set a common vision and research agenda where scientists working on very different aspects of deltas research could converge [9]. While the challenges faced by deltas around the world are many and vary depending on the specific stressors and their social-ecological settings, deltas also share many converging challenges, which became the driving force behind bringing together diverse teams towards a synergistic project on Deltas, These questions include: (1) How does climate change, pressure on resources and engineering/infrastructure development make people, biodiversity and ecosystems vulnerable? (2) How can this vulnerability be measured? (3) How do delta areas absorb extreme events? What are the hydrological and ecological thresholds underlying the integrity of a delta region? (4) What are the relevant local and regional biophysical and social stressors for a particular delta system. How do these interact, and how do they vary spatially and over time? (5) How can regional delta sustainability be balanced with economic growth? (6) How can one reduce future risk while attaining sustainable development?

In this context, when the call for proposals from the Belmont Forum appeared, the elements for a research project were in place around a common vision uniting a variety of research groups. In order to bring diverse research teams together to consider ways to work with regional stakeholders, the research team agreed upon a research framework that includes five main modules or work packages: a) developing an analytical framework for assessing delta vulnerability and scenarios of change (Delta-SRES), b) developing an open-access, science-based, integrative modeling framework for risk assessment and decision support (Delta-RADS), c) developing tools to support quantitative mapping of the bio-physical and socio-economic environment of deltas and consolidate bio-physical and social data within shared data repositories (Deltas-DAT), d) developing Global Delta Vulnerability Indices (Delta-GDVI), that capture current and projected scenarios for major deltas around the world and e) collaborating with regional colleagues and stakeholders to put the science, modeling, and data into action (Delta-ACT).

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Implementing this research framework has required multiple modes of collaboration within and among the Earth system, social and historical, ecological, health and engineering sciences, as well as engagement with regional stakeholders. Table 1 illustrates the diversity of perspectives bearing importance in delta research. It has required analysis of observational, experimental, and numerically modeled deltas to understand how physical forcings (e.g., climate, rivers, ocean waves, vegetation, sediment composition) affect the structure of delta channel networks. It has also required the development of a conceptual framework to examine deltas as coupled social-ecological systems. The project has included analysis of large and small-scale biophysical observations, socio-economic data from household surveys, censuses, and demographic assessments, and knowledge co-production workshops with regional partners and institutions. During the first three years of the project, the research group has progressively developed common terminology, conceptual tools, and considered new questions. While responsibilities were assigned depending on the expertise of each research team, a great deal of new collaborations and self-organization emerged. Below, we review three areas of research collaboration contributing to advancing both basic research and problem-oriented analysis of deltaic systems.

2. Deltas as laboratories for collaborations: Examples in three research domains

2.1. Understanding delta as biophysical systems: advancing quantitative delta classification

As the intersection of landmasses, river basins, and large bodies of water, deltas are naturally very dynamic. They grow, sink, and change courses, shaping land and aquatic ecosystems, posing challenges for human settlements and navigation. Humans attempt to stabilize delta dynamics by various means, [10], many of them involving coastal engineering, channeling and land reclamation, as exemplified by the Dutch Delta works [11]. Upstream damming often alters crucial sediment supply to the delta [12; 1], and disrupts nutrient export and composition [13].

One of the key questions identified at the onset of the BF-Deltas Project was that of understanding deltas as complex physical-social-ecological systems. This understanding requires new forms of interpretation and classification of deltas commensurable with the diversity of conditions and changes of deltas worldwide. The BF-Deltas project is contributing to international efforts to advance quantitative-based approaches for delta classification, a topic that has a rich history.

The 1960s and 1970s witnessed an increasing number of delta studies worldwide, informed by an expanding availability of satellite imagery. New proposals for classifying deltas emerged largely based on a measure of the influence of river discharge relative to ocean waves and currents [14; 15]. Delta morphology, far from being universal, exhibits a large variability depending on the physical processes acting on the delta, e.g., external forcing [16; 15] and sediment composition [17]. Fisher et al. (1969) [14], for instance, distinguished between 'high-constructive' river deltas in settings of strong fluvial influence and weak wave and current activity, and 'high-destructional' deltas, associated with wave and current removal of a significant part of the fluvial load. The most commonly used classification for deltas is that of Galloway (1975) [15] who proposed a categorization of deltas in terms of three end-point members: river-, wave- or tide-dominated, that he grouped into a ternary diagram. This seminal classification became widely adopted as it allows for individual river mouths to be positioned in a classificatory diagram based on the qualitative analysis of the perceived influence of river flow, waves and tides. More recently, Hori and Saito (2008) [18] proposed some quantitative indices based on tidal range, wave height and suspended sediment load to distinguish between wave-influenced, mixed tide-wave-influenced, and tide-influenced deltas, based on the explicit assumption that all deltas are strongly influenced by fluvial discharge and sediment load that determine delta growth.

The complexity of river deltas and their self-organizing patterns of distributary channel networks split and rejoin to deliver water, sediment, and nutrients from the apex to the coastal zone. These characteristics make them more difficult to study than their tributary counterparts, i.e., the river basin networks, which collect fluxes to a single outlet. In addition, delta networks are highly dynamic and sensitive to local human activities, upstream basin alterations, land subsidence, sea level rise, and extreme climatic events [6]. A quantitative study of the patterns (*e.g.*, shoreline, channel network structure, island distribution) carved in deltaic surfaces by the different physical and anthropogenic processes is difficult but offers the potential for advancing our understanding of deltas as complex systems, allowing for a quantitative comparison of deltas to replace the still qualitative diagrams of Galloway (1975) [15] (and also [19]), and helping thus to draw connections between the dominant physical processes and the delta morphology they imprint on the landscape.

Building upon multiple efforts to advance the qualitative classification of deltas [20; 21; 22; 23; 24; 25 26; among others], we highlight here an effort by members of the BF-Deltas project to introduce a rigorous mathematical framework for studying deltas using graph theory [25]. In this framework, delta channel networks are represented as directed graphs, with junctions as nodes and channels as links, and it was shown that via simple algebraic operations on the 'adjacency matrix' (a sparse matrix that contains all the information about network connectivity), several topologic and dynamic properties of deltas can be computed, as well as vulnerability maps constructed depicting the places of the network where disturbances would most significantly affect the shoreline fluxes.

This framework allowed the research team to develop a suite of metrics that capture the topologic (connectivity structure of channel pathways) and dynamic (exchange of fluxes among delta apex-to-outlet sub-networks) complexity of deltas [26]. This Topo-Dynamic perspective of delta networks sets the foundation for quantitative and comparative classifications of deltas.

Figure 2 illustrates the application of this approach to seven deltas around the world. It is observed that the relatively young, river-dominated Wax Lake and Mossy deltas, for example, exhibit low topologic complexity (mostly simple bifurcating structure with a small number of loops) but high dynamic complexity (significant *leakage* of fluxes from each subnetwork to its neighboring subnetworks draining to different outlets). This is opposite, for example, to the more mature (and exposed to wave energy and permafrost) Yukon delta, which has high topologic complexity but low dynamic complexity.

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These topo-dynamic relationships provide the opportunity to quantitatively relate the complex delta patterns to the processes that created them, but they need to be further studied in a controlled environment where the exact physics behind the emerging patterns are known. This is only possible in a controlled laboratory setting [27; 28; 29] or via numerical simulations [30; 31; 32; 33; 34). Recent work using Delft3D-simulated river dominated deltas with varying size distribution of incoming sediment, demonstrated that sediment composition plays a significant role on delta shape and dynamics with coarser incoming sediment tending to create more complex topologically (increased number of pathways) but simpler dynamically (reduced flux exchange between subneworks that join the apex to the shoreline outlets) (see figure 2). By comparing and contrasting field deltas with simulated deltas of known physics and morphodynamics, a more refined classification as well as detection of geologic and anthropogenic constrains on deltas, is possible [35].

The example of quantitative delta classification discussed above shows the importance of interdisciplinary collaboration within the natural sciences, involving geologists, hydrologists, engineers, mathematicians and modelers recognizing the importance of and contributing to advancing previous efforts in order to understand and classify the diversity of deltas around the world. From such a collaboration a complex system perspective is evolving, bringing more attention to the potential role of ecological and anthropogenic processes and the need to examine deltas as coupled social-ecological systems, as discussed below.

2.2. Understanding deltas as social–ecological systems: conceptualization and application

The interconnected nature of deltas and the types of problems which these regions face, ranging from elevated risks of natural hazards and disasters to increasing pollution, call for analytical frameworks that integrate and are relevant to different knowledge domains and to the broader public. Furthermore, at the nexus of land and water systems, operating at multiple scales of interdependence, deltas pose specific challenges to environmental governance and sustainability. A useful definition of a social-ecological system for application in deltas studies is provided by Glaser et al. (2012) [40], which highlights the interdisciplinary nature of research on social-ecological systems such as deltas: "*A social-ecological system consists of a bio-geophysical unit and its associated social actors and institutions. Social-ecological systems are complex and adaptive and delimited by spatial or functional boundaries surrounding particular ecosystems and their problem context*." However, for historical, environmental, and political reasons most delta regions tend to present a high degree of mismatch between governance arrangements and biophysical, social, and economic boundaries.

In this context, one of the focal areas of the BF-Deltas project has involved the design of a problem-oriented conceptual framework to analyze delta regions as coupled social-ecological systems (Deltas-SRES) [see 36 for detailed explanation]. This framework is coupled with a geospatial data system (Deltas-DAT) and expands upon terminology, definitions, and components presented in various other conceptual frameworks, particularly the Institutional Analysis and Development Framework, or IAD, [37; 38] and the Ostrom Social-Ecological Systems (SES) framework [39]. Figure 3, adapted from Brondizio, et al. [36], shows the two main components of the framework: (a) defining boundaries and interdependencies associated with a given problem and (b) defining and outlining the components of the collective action situation associated with the problem.

Two underlying assumptions have informed the development of the Deltas-SES framework for the BF-Deltas project. First, we propose that the definition of analytical boundaries of a given delta region should be flexible, defined by the type of problem at hand. That is, boundary definition should be preceded by interdisciplinary examination of a given problem, so that interconnections operating at different time and spatial scales can be considered. Second, many, if not all, of the problems experienced in delta regions exhibit characteristics of collective action dilemmas of common pool resources (CPRs), that is, the actors involved compete and negotiate appropriation and provisioning of resources at different sales. Most problems in delta regions can thus be analyzed as nested or multi-level collective action situations [36].

The two main components of the framework and operationalization steps are presented in Figure 3 [see 36 for detailed explanation]. The *first step* aims at defining the focal problem to be diagnosed and examined, which can be place-specific or cross-scale. This step necessarily involves an interdisciplinary research group and depending on the nature of the problem it should also involve relevant stakeholders. This step can help initiate a process of co-design and co-production of research and diagnostic efforts [41]. The *second step* includes identifying types of telecoupling to capture salient interactions between local and distal processes. These types of interactions can include those that are socio-demographic, economic, ecological, material, and climate-hydrological. The *third step* involves defining SES boundaries using, as needed, five different dimensions: socio-economic, governance, ecosystems/resource use, topographic-hydrological, and oceanic-climate systems. Steps *two and three* should be done in an integrated fashion, so discussions about the nature of the problem help to define the potential SES boundaries required to understanding it.

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This interactive approach to problem and boundary definition should evolve along with the understanding of the factors, places, and stakeholders involved. It should also contribute to generate new research and policy questions relevant to catalyzing efforts around potential solutions to the problem. The *fourth* step aims at defining the type of collective action dilemma or problem that can be analyzed as one or multiple ‘action situations’. An action situation, derived from the IAD framework, refers to defining a conceptual unit for analysis [38]. A focal action situation can be defined at a given level, but always influenced by action situations operating at other levels. At each level, an action situation takes into account social actors and interest groups, their worldviews, positions, the influence of formal and informal rules, and levels of access to information, all influencing types of interactions and outcomes. The *fifth step* focuses on defining and characterizing the contextual factors (endogenous and exogenous to the system) influencing an action situation and related outcomes and interactions.

This framework has been used to give a new definition of the Amazon delta that combines biophysical, hydrological, and social-political dimensions [36]. Section 2.3.3 below presents an example of the application of the framework to the modeling and analysis of socio-economic vulnerability to flooding in urban areas of the Amazon delta. The framework is currently being used to help diagnose a growing collective-action problem related to the impacts of urban growth and pollution on small-scale fishing resources in the Amazon delta. Accelerated and poorly planned urban expansion and industrialization are contributing significant pollution of local ecosystems. Until recently, management of fish-shrimp stocks was primarily a collective action problem among fishers who competed for these resources [42]. Increasingly, however, fishers are confronted with problems that involve industries, urban expansion and pollution, and other impacts from upstream sources. The precarious and accelerated growth of urban centers, and resulting habitat changes and pollution discharges, are affecting the quantity and quality of fish and shrimp stocks and the pattern of fishing grounds downstream. Industrial pollution spills and high loads of organic pollution and solid waste are increasingly compromising the quality and quantity of fish stocks as well as human health.

A detailed discussion of the Deltas-SES framework and associated data system is presented elsewhere [36]. The SES framework is intended to be dynamic and flexible, able integrate advances (e.g., new data layers, models) from different knowledge domains.

2.3. Understanding delta vulnerability through modeling and participatory approaches

Densely populated and increasingly urbanized deltas are often at risk to environmental hazards such as extreme floods, droughts, hurricanes, storm surges, relative sea-level rise and salinity intrusion. A basic understanding of the dynamics, and climate-human feedback systems [43] is necessary to inform policies that may help to reduce social and environmental risks to hazards. While there is a large number of vulnerability assessments available for coastal regions in general and delta environments in particular, there are as yet no unified social-ecological frameworks and corresponding multi-disciplinary indicators that are both available and applicable to diverse delta contexts [see 36; 44]. Table 2 provides a comparison of selected vulnerability assessments used in deltas. Sharing complementary analytical frameworks and data systems, scientists involved in the BF-Deltas project are contributing three complementary approaches to advance delta vulnerability assessments worldwide.

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2.3.1 Comparative assessment of relative risk to flooding for 48 deltas globally

The vulnerability of delta communities to flooding events can be considered as a component within a larger risk framework. Tessler et al. [5] developed estimates of flood risk in terms of the expected loss caused by flood events. Risk is high in deltas where extreme flood events are more likely to occur (high hazards), where more people live in low-lying areas exposed to flooding (high exposure), and where social vulnerability to flooding is high and greater flood exposure is more likely to cause harm (high vulnerability). The same group [5] used empirically defined indicators to locate 48 global deltas within the risk space defined by these three components, supporting a comparative assessment of relative levels of risk. The indicator-based risk framework can be used effectively in large-scale inter-delta comparative studies, especially as a complement to higher-resolution studies at the local scale [45, 26]. Deriving indicators from cross-disciplinary data can be a major challenge, though GIS tools have helped to provide common frameworks for geographical data. A collaborative approach has been important to allow integration of geophysical remote sensing and modeling data with social indicators of vulnerability to address different components of coastal risk. This approach requires quantifying social effects of flooding, such as health, the scope of such effects and how they play out across social groups and time, as illustrated below.

2.3.2 Global Delta Vulnerability Index (GDVI) – a modular approach to sub-delta scale SES vulnerability to multiple hazards

Collaborating across disciplinary lines, researchers in the BF-Deltas project are developing a Global Delta Vulnerability Index (GDVI) aiming at providing a social-ecological system centered assessment approach for delta vulnerability globally. The GDVI includes: 1) a multi-hazard vulnerability assessment method encompassing social and ecosystem susceptibility, social adaptive and coping capacities as well as ecosystem robustness [44]; 2) a set of multidimensional indicators developed from a combination of a detailed literature review and regional expert consultations and knowledge co-production workshops in focal deltas; and, 3) an "indicator library" allowing for a flexible indicator selection depending on the environment and data availability. While desk-based studies have been important, regional expert consultations helped to characterize sub-delta areas prone to different types of hazards and the stakeholder groups developed a list of vulnerability indicators relevant to both the social and ecological part of the SES. The indicators developed in the BF-Deltas project are relevant for hazards typically occurring in deltas and are organized in a modular way to be responsive to the specific social, economic and environmental contexts of different deltas globally. In this sense, the GDVI has been useful in identifying deltas with high vulnerability to multiple hazards, such as flooding, storm surges, cyclones, salinity intrusion, and drought. An empirical application integrating the Deltas-SES framework (Section 2.2) and a version of the GDVI applied to urban areas in the Amazon delta is briefly presented below.

2.3.3 Socio-economic vulnerability to flooding in urban areas of the Amazon delta

Flood episodes are both daily and seasonal in the Amazon delta varying in influence across a gradient of elevation with direct impact on social conditions and daily life [36; 46; 47]. Floods are also the main natural hazard that when interacting with poorly maintained or non-existent sanitation and drainage infrastructure pose the greatest threat to the majority of urban population, predominantly low-income households, in the Amazon delta. Building upon the frameworks presented above, a conceptual model describing levels of socio-economic vulnerability to flooding events in the urban areas of the Amazon delta was developed. The model included types of biophysical hazards, conditions of social exposure, access to infrastructure, and susceptibility to flooding, and their feedbacks. Using disaggregated geospatially-referenced social, economic, infrastructural, hydrological, and topographic data the model supported a detailed assessment of intra-urban vulnerability to flooding for 41 of the 50 municipalities of the delta region [48]. Urban vulnerability was described as a result of the exposure to a particular risk, sensitivity and adaptation potential of an area and population, particularly in terms of the availability of services across sectors of urban areas and how effective and capable their local governments are to provide the basic infrastructure and responses to events. The appropriate indicators were selected based on: (1) relevance to flood risk assessment; (2) applicability; (3) data available at census sectors scale, in all cases paying particular attention to the population at risk. These indicators were confirmed and expanded following a consultation workshop, as described above, held in the city of Belem in collaboration with 30 participants representing 15 institutions. Moving from the municipal to the census sector level, our analysis and models indicated that 60 to 90% of the urban population in the region, living in precarious social conditions, are facing moderate to high risk of flooding and sewage spills, and associated health risks [see 49 for detailed discussion].

3. Concluding remarks: lessons learned and opportunities ahead

The sustainability challenges we are currently facing require new approaches to research, transcending disciplines and continents. This type of collaboration also requires new funding mechanisms that complement traditional funding sources from national agencies that tend to support individual researchers or research. The Belmont Forum established an international framework for global cooperation, including national mechanisms for accountability and reporting. This program allowed for the emergence of international research teams working under the familiar auspices of their own funding agencies but within a global team perspective. The challenge of understanding how physical, ecological, and social forces interact within delta systems and how these might change under climate and human actions motivated our team to come together and submit a proposal to the first Belmont Forum call.

The BF-Deltas project has aimed at promoting cross-disciplinary and complementary research to advance understanding of the social-ecological-physical dynamics of fast changing deltas and their societal implications. As the discussed examples illustrate, different forms of disciplinary and interdisciplinary collaborations have emerged to tackle specific problems. This approach has worked well for a large and internationally distributed research network. Sharing a common research framework and promoting self-organization have contributed to catalyzing productive forms of disciplinary and interdisciplinary collaboration, and engagement with regional partners and stakeholders. Looking forward, the next challenge for the BF-Deltas research network is to find appropriate mechanisms to continue its mature and effective collaboration and take it to the next level of an integrated implementation of computational models for delta classification, conceptual framework for analyzing deltas as social-ecological systems, and the analysis of social and environmental vulnerability in delta regions towards sustainable management and decision support..

A number of lessons are emerging as the project concludes three years of collaborative research.

First, we recognize that complex research problems such as those present in delta regions require disciplinary expertise and interdisciplinary collaboration to work in tandem to fill in specific knowledge gaps; one cannot preclude the other. *Second*, we recognize that large-scale international and multi-disciplinary projects such as the BF-Deltas project depend on agreed upon definitions of goals and responsibilities, approaches and products. A research network also requires an agreed set of concepts and terminology (and recognizing that these are themselves evolving), and willingness to frame new questions together. Achieving this goal takes time and requires openness and appreciation of different disciplinary strengths and limitations. *Third*, flexible and decentralized collaboration within the research network has encouraged self-organization of collaborators around topics of common interest, without a preconceived expectation (and thus potential frustration) that all components should be unavoidably inclusive. *Fourth*, common research sites have allowed collaborators from multiple areas of expertise to focus on concrete regional problems of relevance to regional populations and policy. Regional workshops have proved valuable and essential to advance knowledge and to enhance collaboration with regional partners and stakeholders. Achieving this goal also takes time, requires meaningful collaboration with regional institutions, and depends on specific budget lines. Finally, leveraging funds from other initiatives proved important, but also limiting. Significant upfront ‘overhead’ (time and funds) was invested to organize a new interdisciplinary and international research network. Funds were limited to support graduate students and post-doctoral researchers. Additional funding would have allowed more training of graduate students and post-doctoral scholars, more intensive exchange activities between research groups, and more engagement activities with stakeholders

There are advantages and disadvantages of grounding a project on a distributed international network. Relying on multiple forms of sharing research outputs – working papers and research articles, conference panels and presentations, webinars as well as in person and virtual meetings -- have proven largely effective to keep information flowing and engaging a large and diverse research network. On the other hand, while virtual communication and meetings have been effective, it has limited more in-depth discussions of specific issues and the kind of cross-disciplinary learning that happens when one works side-by-side. Virtual connections imposes some limitations on the type of interactions, usually limiting attention to topics that demand more commitment to learn about and engage in each other’s area of expertise.

Looking forward, the project should also include collaborative fieldwork. Fieldwork offers a unique opportunity to bring together research partners to experience the process of and the difficulties involved in collecting data, evaluating different forms of evidence, and interacting with local populations and stakeholders.

Deltas are emblematic sentinels of global change and at the forefront of the challenges facing local, regional, and global sustainability. The social, ecological, and physical complexities of delta systems offer opportunities for disciplinary expertise to advance while at the same time challenging disciplinary silos. Deltas are inherently laboratories for interdisciplinary collaborations and stakeholder engagement. For instance, the progress towards the achievement of the recently endorsed Sustainable Development Goals [SDGs] and accompanying targets can only be effectively assessed using integrated and collaborative approaches that account for interactions across social, ecological, and physical systems [49; 50]. The challenges of implementing and assessing the SDGs in deltaic systems represent a problem of great analytical complexity to which the BF-Deltas team has contributed towards [51; 52]. Collaborative efforts on this front will contribute to advance science and science-policy interfaces of relevance to many other areas and predicaments of global change.

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Figure and Table captions

Figure 1: The BF-Deltas Project Research Framework

Figure 2: 2D TopoDynamic Space. Combining both the Topological (Number of alternative paths, N_{ap}) and Dynamic (Leakage Index, *LI*) complexity, each delta is positioned uniquely in the TopoDynamic space. Seven field deltas (Niger, Parana, Yukon, Irrawaddy, Colville, Wax Lake and Mossy) and six numerical deltas with different median grain size are displayed. From the numerical deltas we can conclude that fine grained, cohesive deltas have low topologic complexity and high dynamic complexity. For field deltas, it is observed a transition to high topologic complexity and low dynamic complexity as well. The dots correspond to the medians of both parameters, i.e., Number of alternative paths and Leakage Index, while the vertical and horizontal lines span the corresponding 25th up to the 75th percentiles. [For details see Tejedor et al. 2015c]

Figure 3: The Deltas-SES Framework: a Problem-Oriented Framework for Analyzing Deltas as coupled social-ecological systems. Adapted from Brondizio et al. [36]; see the latter for a detailed explanation of the Deltas-SES framework.

Table 1: Examples of disciplinary domains and interdisciplinary collaborations involved in the BF Deltas project

Table 2. Comparison of the vulnerability assessments used in DELTAS

Figure 1

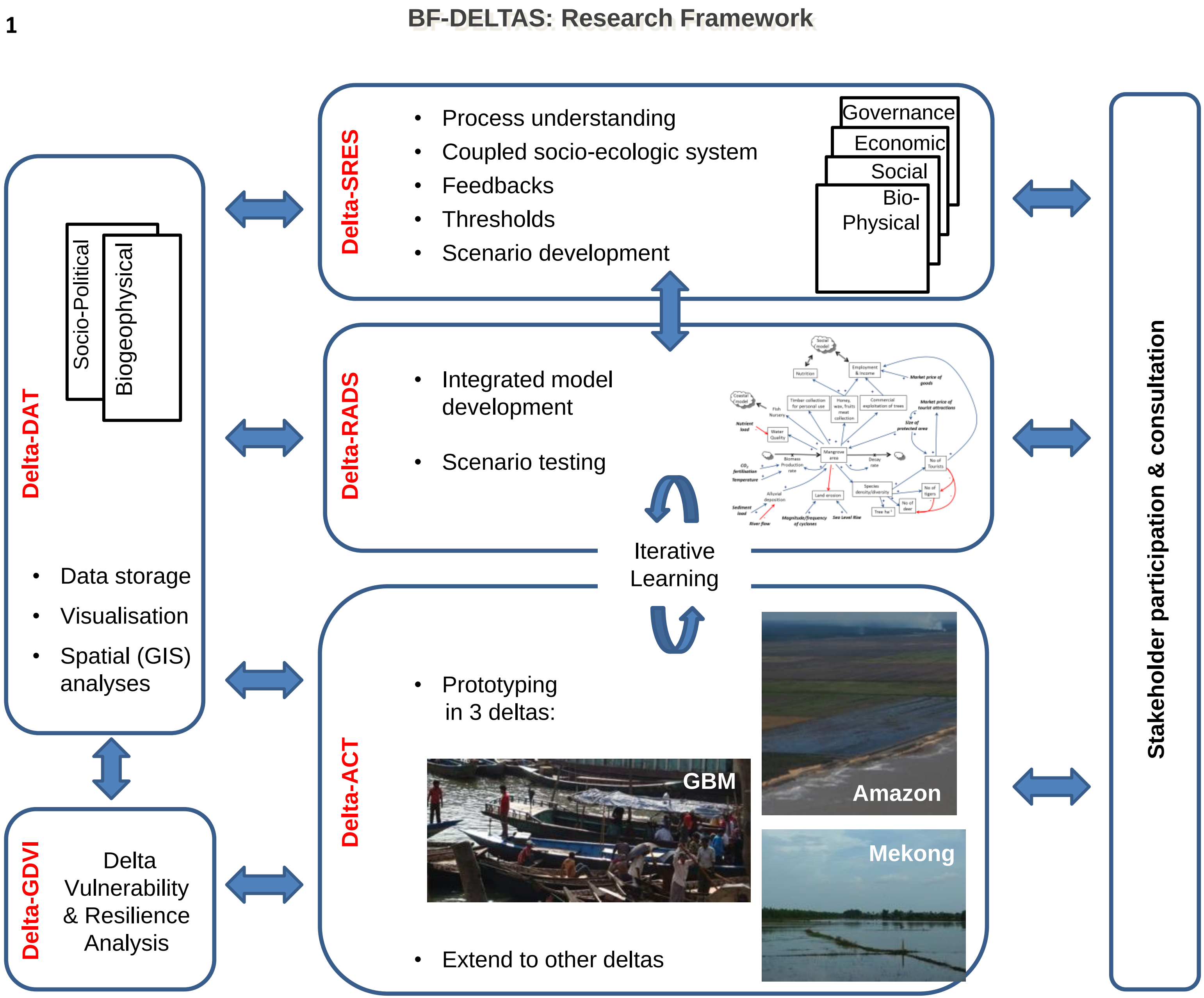
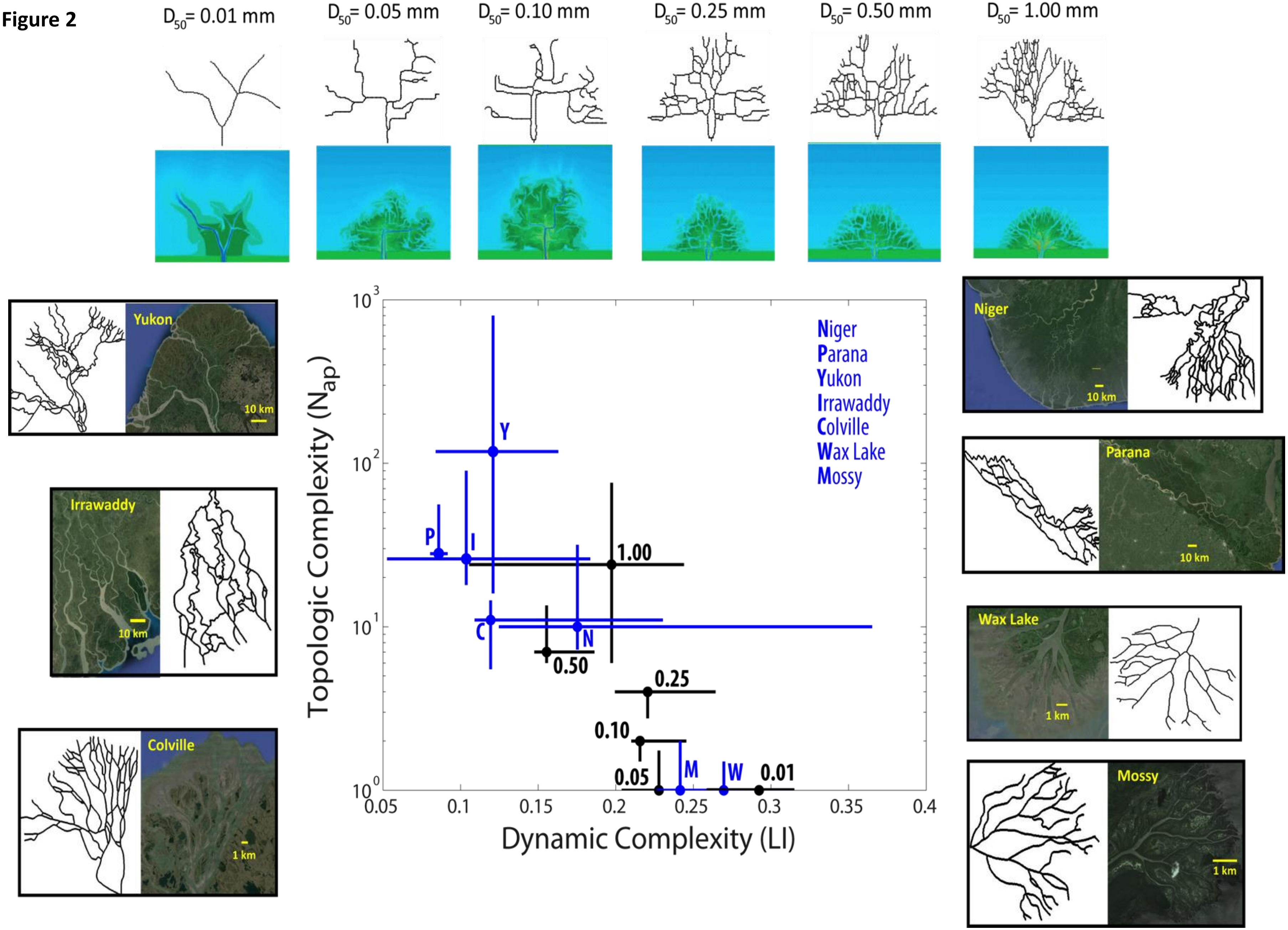

BF-DELTAS: Research Framework
Delta-SRES
Process understanding
Coupled socio-ecologic system
Feedbacks
Thresholds
Scenario development
Governance
Economic
Social
Bio-
Physical
Delta-DAT
Socio-Political
Biogeophysical
Data storage
Visualisation
Spatial (GIS) analyses
Delta-RADS
Integrated model development
Scenario testing
Iterative Learning
Delta-ACT
Prototyping in 3 deltas:
GBM
Amazon
Mekong
Extend to other deltas
Delta-GDVI
Delta Vulnerability & Resilience Analysis
Stakeholder participation & consultation

Figure 2



D_{50}= 0.01 mm
D_{50}= 0.05 mm
D_{50}= 0.10 mm
D_{50}= 0.25 mm
D_{50}= 0.50 mm
D_{50}= 1.00 mm
Yukon
10 km
Irrawaddy
10 km
Colville
1 km
Niger
10 km
Parana
10 km
Wax Lake
1 km
Mossy
1 km
Topologic Complexity (N_{ap})
Dynamic Complexity (LI)
Niger
Parana
Yukon
Irrawaddy
Colville
Wax Lake
Mossy
Y
P
I
C
N
M
W
1.00
0.50
0.25
0.10
0.05
0.01
10^3
10^2
10^1
10^0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

Figure 3

Problem-Oriented Framework for Analyzing Deltas as SES

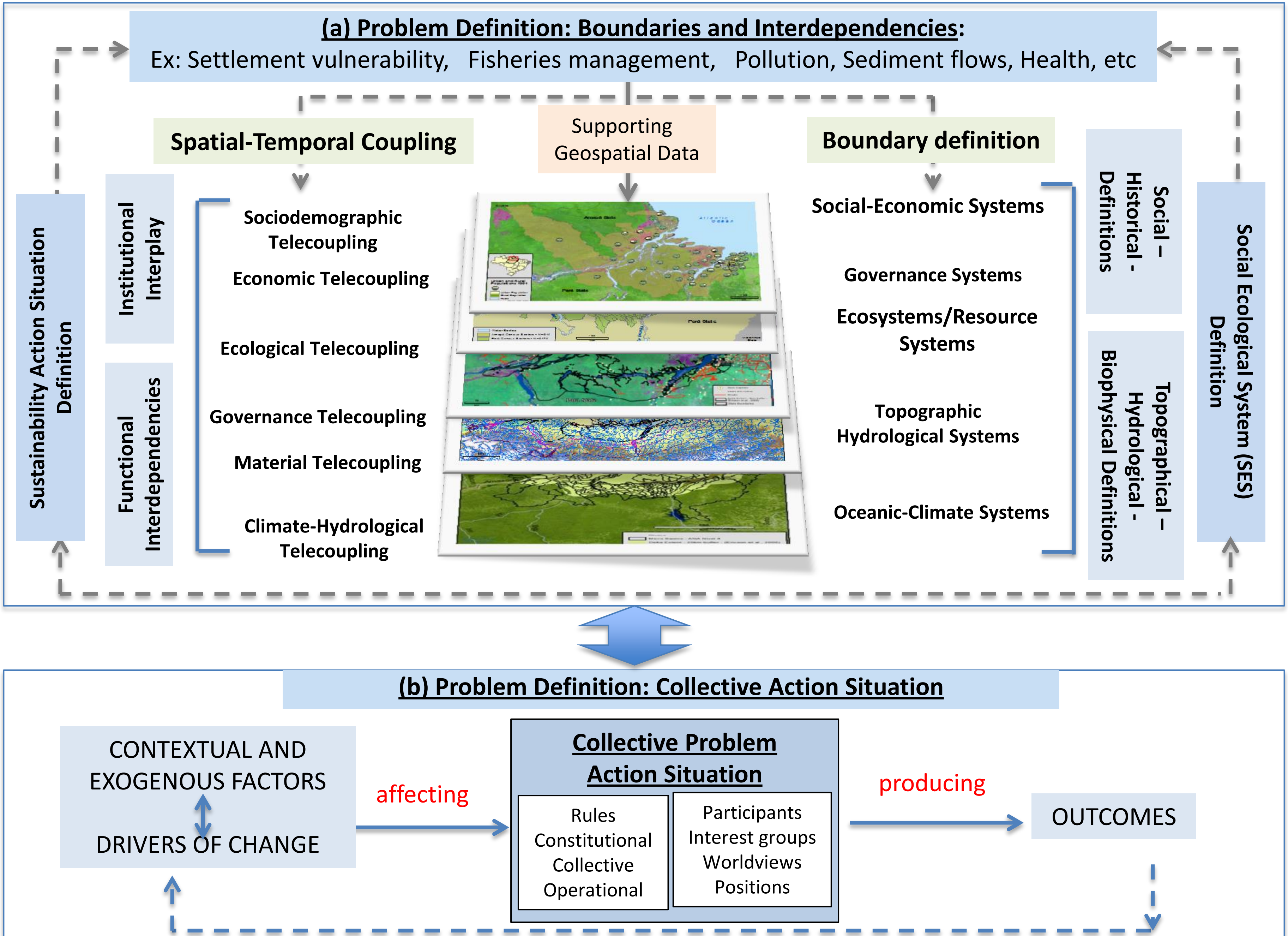


Table 1

Knowledge domain	Knowledge branch	Examples of knowledge contribution
Earth System Sciences	Climate science	Sea-level rise, trends in meteorology and hydrology
	Meteorology	Storm surge, river floods
	Hydrology	Water cycle and damming, saltwater intrusion, sediment transport
	Geology & Physical geography	Sediment deposition, erosion
	Oceanography	Sea-level rise, tides, storm surge flooding
Engineering	River basin engineering	Dam construction, River works
	Coastal engineering	Port construction, dredging coastal works
	Urban infrastructure	Drainage and land reclamation
Environmental sciences	Terrestrial Ecology	Vegetation mosaics, habitats
	Limnology	Freshwater-floodplain gradients; water chemistry; fish ecology
	Forest ecology	Land cover variation and mosaics
	Marine biology	Coastal ecosystem dynamics
	Land use & Landscape ecology	Land use change and landscape management
	Environmental chemistry	Interaction aquatic and terrestrial environments
Social sciences and Humanities	Anthropology, Archeology	Coastal populations history of settlements, social organization, economic activities, landscape management, adaptation
	Sociology	Social context, political and administrative changes, and resource control and management
	Human Geography	Urbanization in the delta-zone, vulnerability mapping
	Economics	Poverty dynamics in delta areas. economic sectors, stakeholder mapping, risk and insurance losses, ecological valuations
	Political science	Governance, trans-border issues, international relations
	Demography	Population dynamics, fertility, mortality, migration
	Development studies	Human welfare, societal resilience, socio-economic inequalities, sustainable development
	History	Long-term changes; colonization, occupation and settlement history
	Social statistics	Measuring and quantifying wellbeing, health and resilience in delta regions and their links to environmental factors
Health sciences	Epidemiology	Water-borne diseases; infectious diseases
	Nutritional sciences	Nutrition and food safety and security
	Toxicology	Health impacts of air and soil pollution

Table 2

Vulnerability assessments in DELTAS	Scale	Vulnerability of …	Vulnerability components	Hazard	Indicator selection strategy
Comparative assessment of relative risk to flooding for 48 deltas globally [5]	Global	Social system	Economic (aggregate and per-capita GDP); Governance (World Governance Indicators)	Flooding	Evidence in the literature for a direct or indirect relationship with one of the three risk components; indicators were limited to those available at the global scale
Global Delta Vulnerability Index - a modular approach to sub-delta scale SES vulnerability to multiple hazards [44]	Global	Social-ecological system	Social and ecosystem susceptibility, social adaptive & coping capacities and ecosystem robustness	Multi-hazard	Review of published coastal/delta vulnerability studies and stakeholder consultations in the three deltas; indicators available at global, delta or sub-delta scale
Socio-economic vulnerability in urban areas of the Amazon Delta [48]	Amazon	Social system	Social exposure, sensitivity and the level of adaptation of an area or population	Flooding	Relevance with flood risk assessment, applicability, and data available at census sectors scale