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SPECIAL FEATURE: ORIGINAL ARTICLE

Sustainable Deltas: Livelihoods, Ecosystem Services, and Policy Implications

A conceptual framework for analyzing deltas as coupled social–ecological systems: an example from the Amazon River Delta

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Abstract At the nexus of watersheds, land, coastal areas, oceans, and human settlements, river delta regions pose specific challenges to environmental governance and sustainability. Using the Amazon Estuary-Delta region (AD) as our focus, we reflect on the challenges created by the high degree of functional interdependencies shaping social–ecological dynamics of delta regions. The article introduces the initial design of a conceptual framework to analyze delta regions as coupled social–ecological systems (SES). The first part of the framework is used to define a delta SES according to a problem and/or collective action dilemma. Five components can be used to define a delta SES: social–economic systems, governance systems, ecosystems-resource systems, topographic-hydrological systems, and oceanic-climate systems. These components are used in association with six types of telecoupling conditions: socio-demographic, economic, governance, ecological, material, and climatic-hydrological. The second part of the framework presents a strategy for the analysis of collective action problems in delta regions, from sub-delta/local to delta to basin levels. This framework is intended to support both case studies and comparative analysis. The article provides illustrative applications of the framework to the AD. First, we apply the framework to define and characterize the AD as coupled SES. We then utilize the framework to diagnose an example of collective action problem related to the impacts of urban growth, and urban and industrial pollution on small-scale fishing resources. We argue that the functional interdependencies characteristic of delta regions require new approaches to understand, diagnose, and evaluate the current and future impacts of social–ecological changes and potential solutions to the sustainability dilemmas of delta regions.

Keywords Deltas · Social–ecological systems · Amazon · Telecoupling · Governance · Sustainability

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Introduction

At the nexus of watersheds, land, coastal areas, oceans, and human settlements, delta regions pose specific challenges to environmental governance and sustainability. The flow within deltas of water, nutrients and sediments, pollutants as well as people and resources creates complex social and physical interactions operating at different scales and marked by pulses and time lags. These include rainfall patterns, river discharge (liquid and solid), ecological processes, flood cycles and tides, waves, and changes in settlements and human activities responding to these biophysical variations and to dynamic local and global economies.

This article presents an integrated problem-oriented conceptual framework for (a) defining estuary-delta regions as coupled, multi-level social–ecological systems (SES) and (b) analyzing collective action situations related to specific problems posed by complex interactions and mismatches of governance, biophysical, social and economic boundaries characteristic of estuary and deltas. Of the two main parts of the conceptual framework, the first concerns definitions and scope, while the second deals with actions and responses. In the paper, we lay out the conceptual framework with an accompanying literature review of other conceptual frameworks applied to delta regions worldwide. Basic definitions to key concepts are provided.

The Amazon Estuary-Delta (AD) region is used to illustrate the application of this framework as it is a microcosm of such complexity. At the ocean interface of the largest watershed in the world, draining approximately 40 % of South America, the AD is both the largest estuary and delta on Earth with an overarching influence of over 1500 km of the South American coast between Brazil and Venezuela. For 500 years, the AD has been a hub for regional and global economic chains but entering a new phase of urban and industrial expansion (and pollution), expansion of transportation and communication infrastructures, pressure on land and aquatic resources, upstream engineering projects, proposed new ports and offshore oil platforms (RAISG 2013; GeoAmazonia 2009; Pinedo-Vasquez et al. 2011). These changes are interacting with shifting rainfall and sea-level patterns that, together, are introducing new types of vulnerabilities, as well as opportunities. Thus, the AD provides a good example of application of this framework for diagnosing complex collective action problems in estuaries and deltas.

First, the framework is applied to define boundaries and to characterize the AD as coupled SES. We then utilize the framework to diagnose [illustratively] a collective action problem related to the impacts of urban growth and pollution on local fisheries in the AD. These applications illustrate how to take into account the intersections between topography, hydrology, political-administrative units (i.e., states, municipalities, and census sectors), and other dimensions when defining the analytical boundaries of a delta to analyze different types of problems and goals. They also illustrate how deltas are characterized by 'functional interdependencies' between biophysical and social processes operating in different parts of the broader basin and coastal region where they are situated. We conclude the paper by reflecting briefly on the potential of the proposed conceptual framework to diagnose collective action problems and to inform scenarios and planning addressing sustainability challenges in delta regions.

Analyzing delta regions as coupled social–ecological systems (SES) and as sustainability action situations

Delta regions are marked by high degrees of interdependence between physical, ecological, and social systems operating at various scales and subjected to different types of spatial and temporal lags (Foufoula-Georgiou et al. 2011). As such, we argue that defining the analytical boundaries of delta regions should vary according to the problem at hand. There are numerous definitions, approaches, and correlated terms for social–ecological systems, herein SES (see for instance, Berkes and Folke 1998; Young et al. 2006; Binder et al. 2013)[1], all of which emphasize that people and environment are interdependent and cannot be treated as separated systems. For the purpose of this article, Glaser et al. (2012:4) offer a useful definition suited to delta systems: "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." Furthermore, sustainability issues in delta regions exhibit characteristics of collective action problems of common pool resources (CPRs) wherein the actors involved compete and negotiate for resources at different scales. In other words, there is a high cost of excluding users from the system and a high degree of rivalry between users (i.e., users subtract resources from each other) (Ostrom 1990, 2005; Brondizio et al. 2009). As such, most problems in delta regions can be analyzed as nested or multi-level collective action situations, representing the dilemmas of a 'sustainability action situation'.

To situate the proposed framework within the deltas literature, we carried out a review of conceptual frameworks applied to delta regions worldwide (Table 1). Binder et al. (2013) provide a review of several existing frameworks for analyzing SES from global scales (Schellnhuber et al. 2005) to regional and local scales (de Groot et al. 2002; Scholz and Binder 2003; Burns 1999; Turner et al. 2003). These frameworks have been widely applied for analyzing delta systems. For example, the Driver, Pressure, State, Impact, Response (DPSIR) Framework (Eurostat 1999) is generally used in delta systems to identify interactions between components of human–environmental systems and describe the cause–effect processes in a functional chain of explanation [e.g., Yagtze Delta (Yuan et al. 2014), Po Delta (Pirrone et al. 2005), Several Deltas - Deltares (Bucx et al. 2010)]. The Sustainable Livelihood Approach (Ashley and Carney 1999; Scoones 1998) has

[1] Binder et al. (2013) offers a useful comparison of ten socioecological systems frameworks.

Table 1 Comparison of conceptual frameworks, including social–ecological systems frameworks applied to delta regions and studies

Systems type	Framework	Purpose	References of based framework	Examples of application in deltas worldwide	Applications
SES DELTAS	This study	Provides a common language for case comparison for organizing the many variables relevant to the analysis of DELTAS as SES into a multitier hierarchy that can be unfolded when needed, and for facilitating the selection of variables in a case study	This study based on Ostrom (2007, 2009) and others	Amazon Delta	For analyze collective action problems in socio-ecological deltas; conceptualization of the social system including both micro and macro, and also the interaction and feedback loops between them (includes all hierarchical levels) Provides guidance for the definition of boundaries and selection of variables to study
SES	Driver, pressure, state, impact, response (DPSIR)	Develops an improved understanding of, indicators for, and appropriate responses to impacts of human activities on the environment along the causal chain-drivers-pressure-state-impact-responses	Eurostat (1999)	Yangtze Delta (Yuan et al. 2014); Po Delta (Pirrone et al. 2005); Several Deltas-Deltares (Bucx 2010)	Measures the state of environment over time social scale: decision makers, conceptualize the social system only at macro level. Conceptualizes the ecological system from an anthropogenic perspective: the ecological system is seen as a provider of services that increases human well-being (see Binder et al. 2013) Can be applied to different scales. Provides guidance for the selection of variables and analytical
SES	Sustainable livelihood approach (SLA)	Analyzes which combination of livelihood assets enables livelihood strategies with sustainable outcomes	Ashley and Carney (1999) and Scoones (1998)	Mekong Delta (Smith et al. 2013); Mahakam Delta (Bosma et al. 2012)	Conceptualizes the social system considering the macro to micro-relationships. Conceptualizes the ecological system from an anthropogenic perspective: the ecological system is seen as a provider of services that increases human well-being (see Binder et al. 2013). Local and regional scales

Table 1 continued

Systems type	Framework	Purpose	References of based framework	Examples of application in deltas worldwide	Applications
SES	Vulnerability Framework (TVUL)-Turner	Analyzes who and what are vulnerable to multiple environmental and human changes, and what can be done to reduce these vulnerabilities	Turner et al. (2003)	Chinese coastal cities (Su et al. 2015; Mansur et al. 2016)	Conceptualizes the social system considering the macro to micro-relationships. Conceptualizes the ecological system from an anthropogenic perspective: the ecological system is seen as a provider of services that increases human well-being (see Binder et al. 2013). Local scale
SES DELTAS	Vulnerability Frameworks and risk analysis for deltas SES	Review of vulnerability analysis framework including steps of development of the Delta-Global delta vulnerability indices (GDVI) capturing current and projected physical–social–economic status of deltas worldwide	Sebesvari et al. (2016)	Mekong, the Ganges–Brahmaputra-Meghna and the Amazon	Vulnerability analysis for comparison. Encompasses social and ecosystem exposure, social and ecosystem susceptibility, social adaptive and coping capacities as well as ecosystem robustness. Can be applied to different scales. Review paper. Provide conceptual framework, suggest indicators to measure vulnerability
SES DELTA	Vulnerability and risk analysis for deltas SES (specific for flood risk analysis)	Quantified changing flood risk due to extreme events using composed indicators of integrated set of global environmental, geophysical, and social indicators in deltas. 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	Tessler et al. (2015)	48 Deltas worldwide	Indicator-based risk ramework for specific hazard (flood hazard). Combine three domains with no integration with stakeholders. 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

Table 1 continued

Systems type	Framework	Purpose	References of based framework	Examples of application in deltas worldwide	Applications
SES coastal systems	Vulnerability and risk analysis for deltas SES: coastal adaptation framework	Provides holistic and step by step (multistage) processes to develop sustainable coastal adaptation policy including seven integrated steps of coastal adaptation planning process for practitioners. The framework provides detailed explanation as to what step, what process and why the process has to be followed to achieve sustainable adaption (Boateng 2010)	Boateng (2010)	Red River Delta and Mekong Delta (Boateng 2012)	Focused on the physical factors (costal areas and climate change) in assessing vulnerability. Local scale Provides useful analytical guidance
SES DELTA (Site specific study)	Vulnerability and risk analysis for deltas: community-based multi-hazard framework (including the SMUG and FEMA model)	Scientific models (SMUG & FEMA) are used to enable evidence-based decision making of a vulnerable community; risk and vulnerability assessment include local knowledge	Islam et al. (2013)	Ganges–Brahmaputra Delta	For multi-hazards risk and vulnerability assessments. (1) SMUG model (qualitative): a tool to deliver a simple analysis to prioritize hazards based on four indicators (2) FEMA model (quantitative): evaluation and scoring system based on four criteria. Local scale
SES DELTAS (Site specific study)	Vulnerability and risk analysis for deltas: Environmental assessment framework	A conceptual framework based on the environmental assessment framework designed by the Institute of Development Studies to study the nature and extent of impacts by commercial salt water shrimp farming on local ecosystems and rural livelihood patterns in southwest Bangladesh	Vulnerability analysis based on IDS Framework (Institute of Development Studies) and Sustainable livelihoods framework (Scoones 1998)	Ganges–Brahmaputra Delta (Swapan and Gavin 2011)	Vulnerability context, livelihood assets, strategies for economically sustainable and environmental friendly livelihoods. Regional scale
SES DELTAS (Specific pressures)	A delta model framework of livelihood and poverty changes of farmers under climate and environmental change	A model to simulate the livelihood and poverty changes of farmers in coastal Bangladesh under climate and environmental change	Lázár et al. (2015)	Ganges–Brahmaputra–Meghna	The model captures both macro- and micro-scale environmental and climate processes and link these to the welfare of households or individuals at the local scale Provides guidance for application in other agricultural deltas

Table 1 continued

Systems type	Framework	Purpose	References of based framework	Examples of application in deltas worldwide	Applications
SES DELTAS (Specific pressures)	Graph-theoretic approach for studying connectivity and steady state transport on deltaic surfaces	Provides a formal quantitative framework for studying delta channel network connectivity and transport dynamics based on spectral graph theory	Tejedor et al. (2015a, b	Wax Lake delta, Niger delta (Tejedor et al. 2015a) and Niger, Parana, Yukon, Irrawaddy, Colville, Wax Lake, Mossy (Tejedor et al. 2015b)	Explores delta connectivity and flux dynamics (Tejedor et al. 2015a); Presents graph theory and entropy-based metrics to quantify two components of a delta's complexity: (1) Topologic, imposed by the network connectivity and (2) Dynamic, dictated by the flux partitioning and distribution (Tejedor et al. 2015b) Can be applied for deltas at different scales Provides guidance for systematic vulnerability analysis and defines a suite of metrics illustrated by case study applications

been applied to analyze the potential impacts of social and environmental pressures on community-level adaptation to these changes [e.g., Mekong Delta (Smith et al. 2013); Mahakam Delta (Bosma et al. 2012)]. Finally, the vulnerability framework (Turner et al. 2003) has been adapted and contributed to integrating factors and processes affecting the vulnerability of populations in delta or sub-delta systems [e.g., Chinese coastal cities (Su et al. 2015); Amazon delta cities (Mansur et al. 2016)]. In addition to SES-related frameworks, several other frameworks have been developed and applied to the analysis of environmental and social vulnerability and risk assessments at the level of entire deltas (e.g., Boateng 2012; Tessler et al. 2015; Sebesvari et al. 2016), at site level studies for vulnerability assessments (Swapan and Gavin 2011; Islam et al. 2013), and at the level of specific types of pressures (e.g., Lázár et al. 2015; Tejedor et al. 2015a, b).

The framework presented (Fig. 1) here builds upon a combination of SES frameworks, including several mentioned above. It also builds upon conceptual frameworks focusing on institutional and governance analysis. In particular, we use as a foundation the terminology, concepts, and components presented in Ostrom's general SES framework (2007, 2009). The Ostrom's SES framework itself expands on previous efforts to diagnose collective action problems, in particular the Institutional Analysis and Development Framework, or IAD (Ostrom 1990; Mcginnis 2011; Ballesteros and Brondizio 2013) developed at Indiana University's Ostrom Workshop (Aligica and Boettk 2009; Poteete et al. 2010; Cole 2014). The Ostrom's SES/IAD frameworks accommodate multiple levels of institutional analysis, approaching the interaction between levels by identifying conceptual analytical units defined as *action arena and action situation* (Ostrom 2011). The framework presented here is also informed by concepts developed by Young et al. (2002, 2006) (i.e., institutional fit and interplay, functional interdependence), Epstein et al. (2015) (i.e., institutional fit), Turner et al. (2003) (i.e., vulnerability analysis), Pahl-Wostl et al. (2010) (i.e., water management-MTF), and Liu et al. (2013) (i.e., telecoupling).

The integrated and problem-oriented framework presented here includes explicit attention to biophysical, social, and ecological connectivity in delta systems and offers a geospatial and multi-temporal approach that, when combined, can be used to:

– Define the boundaries of delta social–ecological systems.
– Define nested action situations in social–ecological systems (or define sustainability action situations).

Figure 1 illustrates the two main parts of the framework and provides steps, inspired by Lelie (2015) use of the

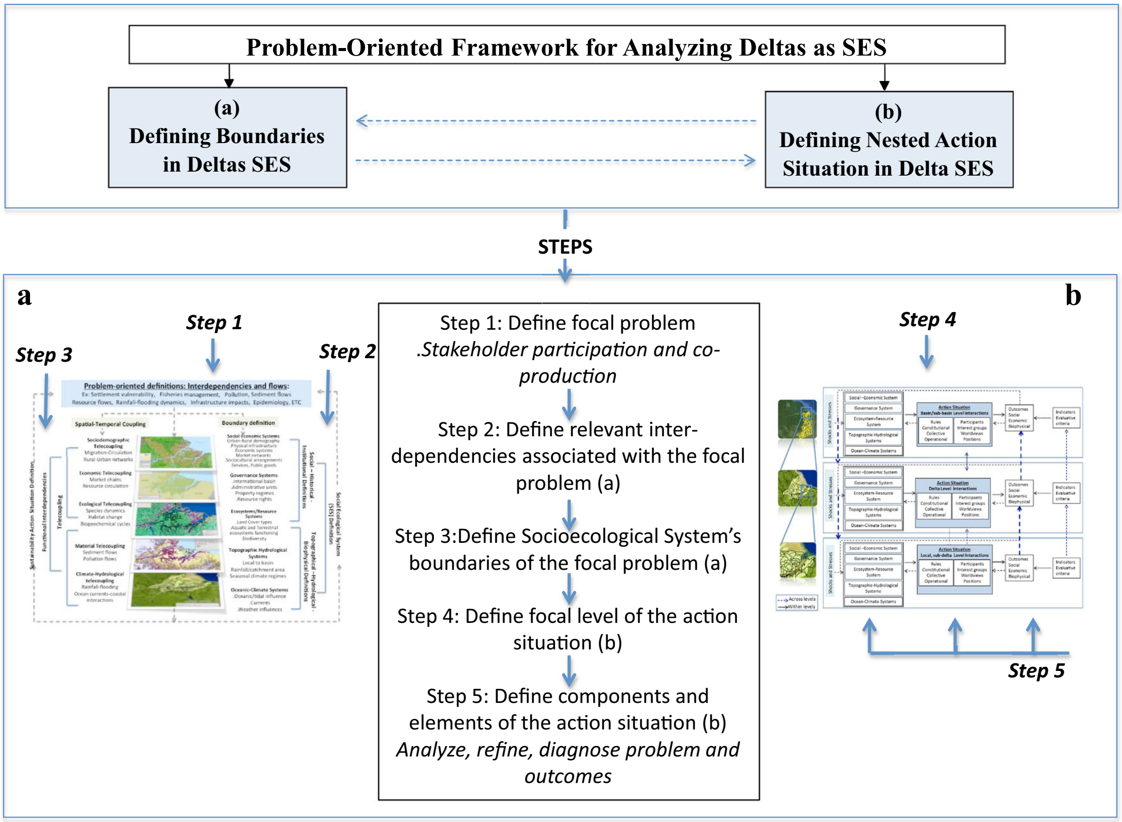


Fig. 1 A problem-oriented framework for defining and analyzing Deltas as coupled social–ecological system (SES): **a** defining spatial–temporal boundaries and **b** nested sustainability action situations

Ostrom's SES framework, for operationalizing the analysis of research and/or collective action problems. As shown in Fig. 1, five general steps are suggested to guide the analysis of delta regions as SES. Each part of the framework and their respective components are described in more detail in the following. The framework is supported by a geospatial data platform—the Amazon Delta-DAT—that allows integration and analysis of data from different domains (see Textbox 2).

The *first step* aims at defining the focal problem to be diagnosed and examined, which can be place-specific or cross-scale. This step should involve an interdisciplinary research group and depending on the nature of the problem it should also involve relevant stakeholders. This step can help to initiate a process of co-design and co-production of research and diagnostic efforts (Tengö et al. 2014). The *second* (types of telecoupling and interdependencies) *and third* (boundary definition) *steps* should be done in an integrated fashion aiming at recognizing the nature of the problem and the potential SES boundaries required to understand it. As illustrated in Fig. 2, for step 2 five types of telecoupling can be used, as relevant to the problem, to define the most salient kinds of local and distal interactions underlying a social–ecological problem: socio-demographic, economic, ecological, material, and climate-hydrological. For step 3, five dimensions can be used, as relevant to the problem, to define SES boundaries: socio-economic, governance, ecosystems/resource use, topo-graphic-hydrological, and oceanic-climate systems.

This interactive approach to problem and boundary definition should evolve along with the understanding of the factors, places, and stakeholders involved. Most importantly, it should generate research and policy questions to help define and characterize the relevant 'sustainability action situations' to be analyzed.

The *fourth* step defines the focal action situation for analysis, i.e., a given question or problem to be examined. As illustrated in Fig. 3, 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 includes an action arena with social actors and interest groups, their worldviews, positions, the influence of formal and informal rules, and levels of access to information, all influencing a given action situation. An action situation at a specific level can be influenced and influence a related action situation at a level above or below. The *fifth step* should focus on defining the contextual inputs influencing an action situation and related outcomes and interactions. The contextual

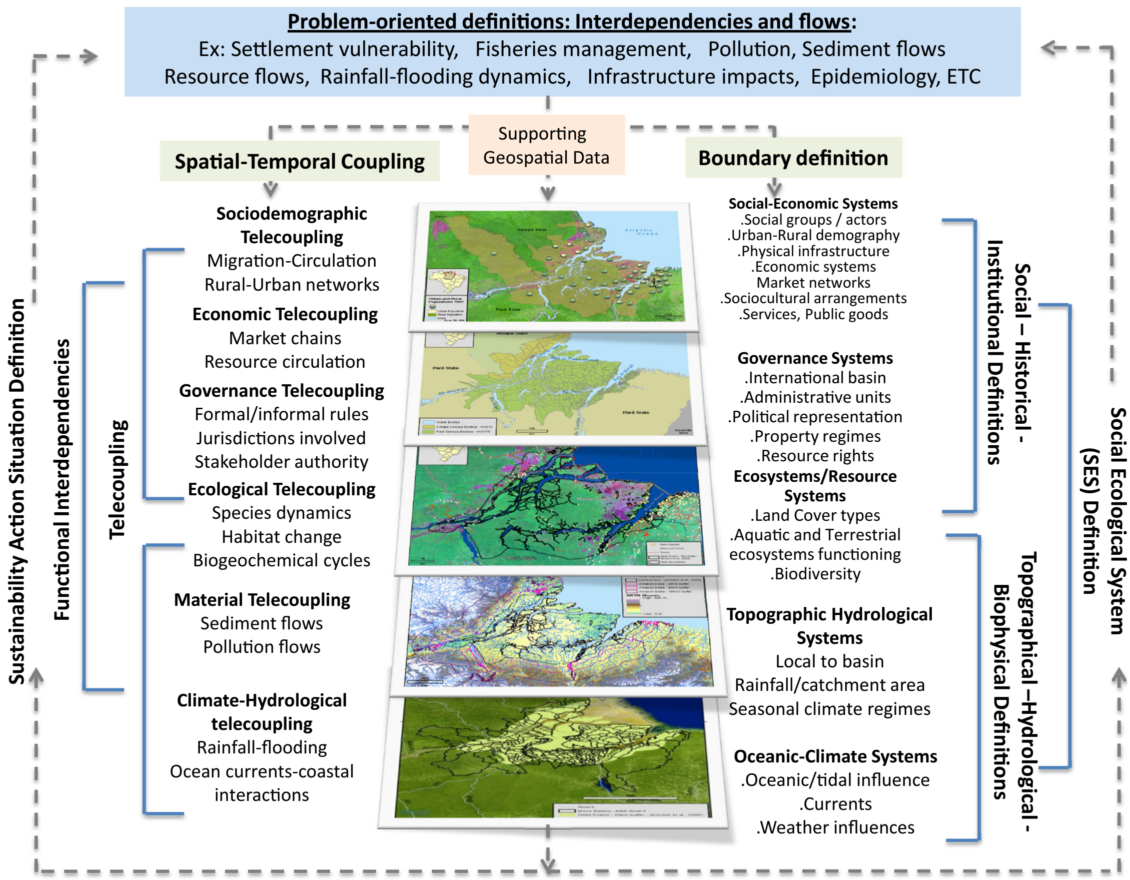


Fig. 2 Defining a Delta as a coupled social–ecological system (SES): boundaries and interconnections/telecoupling dimensions. Examples from the Amazon delta using the Delta-DAT system

elements are the same as those used to define the boundaries and interdependencies associated with the focal problem (a): socio-economic, governance, ecosystems/resource use, topographic-hydrological, and oceanic-climate systems. Furthermore, as with the IAD, the action situation is influenced by different types of formal and informal rules (Mcginnis 2011). An action situation is marked by patterns of interactions between social actors within and between themselves and the resource units they utilize, which generate social, economic, and biophysical outcomes. As with the IAD, the framework presupposes that collective action problems are dynamic and evolving, where new institutional alternatives and actions to deal with a given problem are created, influencing the system as a whole. These outcomes should be evaluated according to selected evaluative criteria including efficiency and sustainability in resource use, distributional equity, social legitimacy, level of participation, accountability, fiscal equivalency, adaptability and resilience to shocks (Mcginnis 2011; Ostrom 2011).

In the next section, we illustrate the application of this integrated framework to define the Amazon Delta as an SES and to diagnose a problem common to many deltas around the world.

Illustrative applications: defining the Amazon Delta as a SES and diagnosing problems

Defining the core SES of the Amazon Delta

To our knowledge, to date there has not been a definition of the Amazon delta as a SES. Thus, our first goal is to define the core SES of the Amazon delta based on the intersection of the physical limits created by topographical, hydrological, and oceanic influences and the corresponding social and political-administrative units directly influenced by and influencing these limits. As explained below, this definition includes the area affected by flooding and tidal pulses according to topographic gradients of the region.

Under the auspices of the Belmont Forum Deltas project [*Catalyzing action towards sustainability of deltaic systems with an integrated modeling framework for risk assessment*],

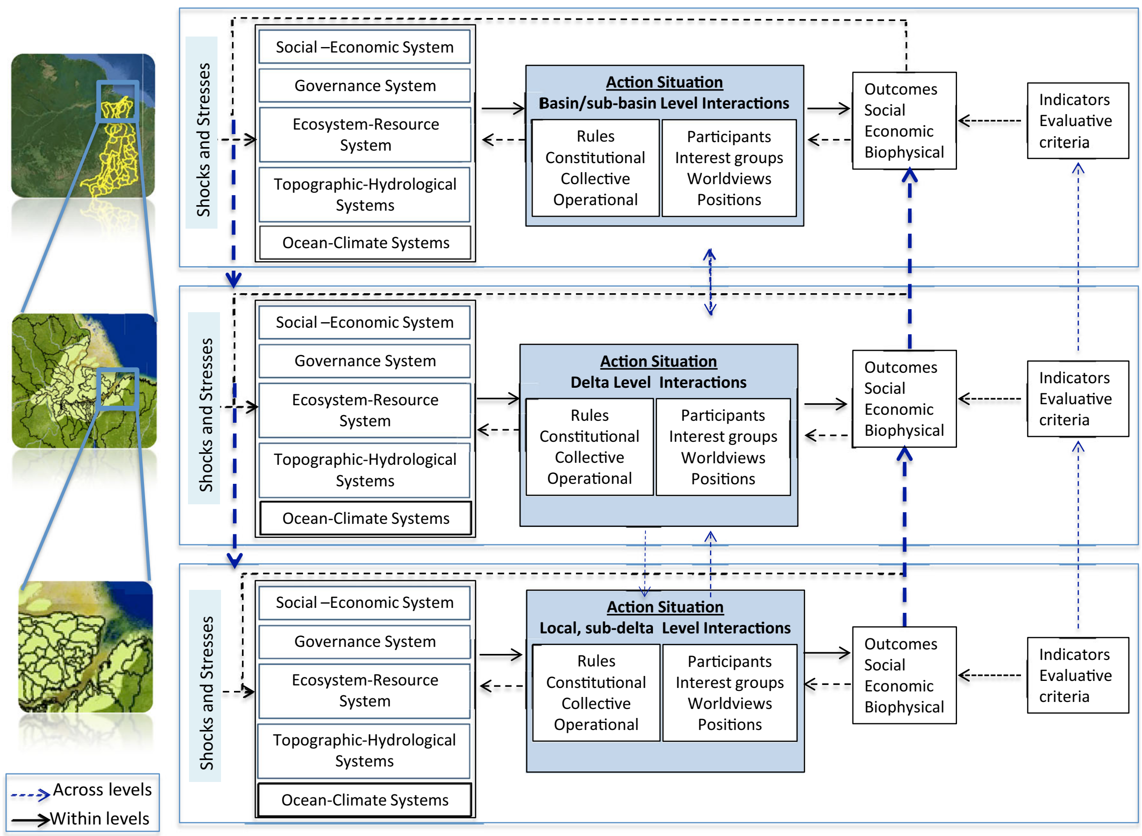


Fig. 3 Defining a Delta as a coupled social–ecological system (SES): multi-level collective action situations [adapted from the IAD framework]

a multidimensional geospatial database (Amazon Delta-DAT) has been developed for the AD (see Textbox 2). Delta-DAT allows us to define the SES boundaries of the AD according to different types of problems. As a baseline in this paper, we propose a definition for the core SES of the AD. To define the physical limits of the core SES, we adapted criteria from Ericson et al. (2006) in which the presence of deltaic soils, topography (based on the GTOPO30 dataset), position, and upstream limits of distributary channels can be used to define the Amazon delta[2]. As illustrated in Fig. 4, these limits were used to define the states and municipalities, and associated census sectors, in direct connection to the AD. We call this definition the core SES of the Amazon estuary delta. It involves two states, 50 municipalities, and 6000+ census sectors. This definition of the core SES of the Amazon delta can be expanded through the definition of progressively larger and associated watersheds or reduced by delimiting subregions within the AD.

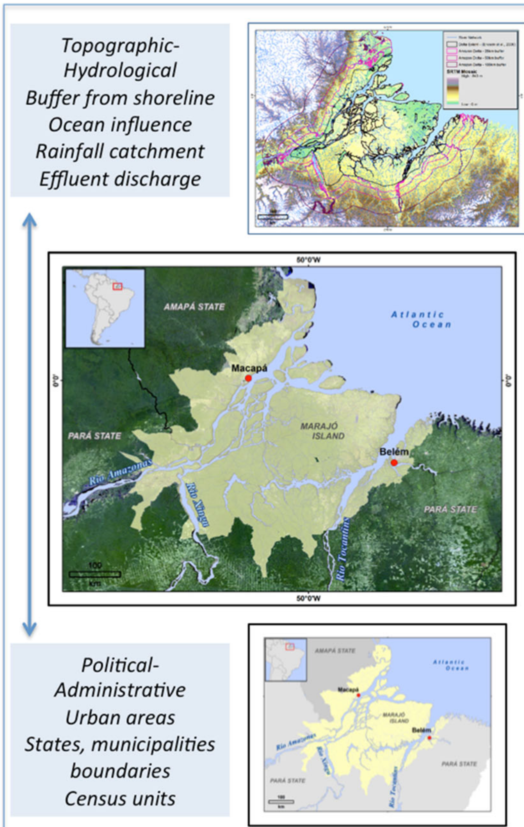
The Amazon Delta-DAT includes the Brazilian National Water Agency (ANA) Ottocodified Hydrographic Base (BHO), which supports the national system for the management of water resources. The BHO is generated from the digital mapping of the country's hydrography and organized so as to generate hydrologically consistent information. An essential feature of this representation is its topological consistency, i.e., correct representation of the hydrological flow of rivers, connected by passages and flow direction[3]. Below, we provide a brief description of the biophysical and social dimensions that interact in defining the core SES of the Amazon delta.

Topographical-hydrological-biophysical characteristics of the AD region

"The natural gateway of the Amazonian basin" as once described by Goeldi (1889), the Amazon estuary-delta has, at its center, the world's largest fluvial island (~50,000 km^2), Marajó Island, with its western part

[2] Zach Tessler at The City University of New York further modified this definition by buffering the original extent by 5 and 25 km and then clipping to a land/water mask product (based on the MOD4W dataset).

[3] For the delimitation of watersheds, ANA refers to the first level of Ottobacias encoding. Ottobacias are contributing areas of the river network stretches coded according to the Otto Pfafstetter method for watershed rating. At the end of the 1980s, the Brazilian engineer Otto Pfafstetter developed a numerical method for coding watersheds, considering as main input areas of direct contribution of each stretch of the river system. Watersheds correspond to aggregation of areas of river contribution, known as Ottobacias, at level 1.



Socio-Economic Indicators		
Number of municipalities	50	This study
Population of delta census sectors (millions)	4.3	IBGE 2014
Area of delta census sectors (km^2)	160,662	IBGE 2010 Ericson et al. 2006
Population density of delta census sectors (pop/km^2)	19.3	IBGE 2010, IBGE 2014
Urbanization (% of urban population)	78.9	IBGE 2010
Urban sectors considered at flood risk or unplanned settlements (%)	40	Mansur et al. 2016
Urban population considered at flood risk or in unplanned settlements (millions)	1.2	Mansur et al. 2016
Biophysical Indicators		
Mean Tree Cover (%)	93.7	Hansen et al. 2013
Mangrove cover (10^3 km^2)	2	Giri et al. 2010
Saline water intrusion (km)	Unknown	Archer and Greb 2012 França et al. 2012
Project area loss by 2050 (ESLR) (%)	2.45	Ericson et al. 2006
Relative sea level rise ($mm\ yr^{-2}$)	Unknown	Syvitski et al. 2009
Sediment reduction (%)	0	Syvitski et al. 2010
Average discharge (m^3/s)	198,676	Syvitski and Saito 2007

Fig. 4 Defining the 'core SES' of the Amazon delta and sub-delta definition of north and south channels and respective catchment basins

covered by forests and its eastern portion covered by seasonally flooded grasslands. The AD represents an assortment of Amazonian landscapes with vast upland and floodplain forests, mangroves, and extensive savannas transformed by a history of occupation dating back thousands of years.

The AD has a 300-km wide funnel-shaped estuarine mouth comprising two major channels, the North and South Channels, and numerous smaller interconnected channels bound to the south by Marajó Island. The North Channel drains the bulk of the Amazon basin with vast influence on the northern coast of South America. The South Channel is mostly formed from the watersheds of the Tocantins-Araguaia River and the Pará River, with only a fraction of its volume discharged from the Amazon River through transversal channels behind Marajó Island.

The AD combines the hydrological and morphological attributes of both a river estuary and a delta but in rather unique ways at the global scale (Anthony et al. 2014) (see also Textbox 3). The massive mud discharge of the river leads to rapid and sustained fluid-mud concentration and trapping associated with fresh water–salt water interaction that takes place on the shelf (Geyer et al. 2004). Thus, the estuarine turbidity maximum (ETM), the main zone of large-scale river mud trapping in estuaries resulting from interactions between fresh river water and seawater, occurs well outside the mouth of the AD. The AD does not, therefore, correspond to a classic estuary inasmuch as its ETM is located on the inner shelf rather than being confined within the river mouth. Since the liquid discharge is large, much of the mud is thus expulsed onto the shelf where it is trapped within the ETM where it builds up a subaqueous delta. The uppermost portion of the Holocene subaqueous delta built by the AD now forms the shoreline. Under the present sea-level conditions, the sediment trapping efficiency on the coast and shelf of the Amazon is close to 100 %, such that sediments currently supplied by the river do not reach the Amazon deep-sea fan (Hinderer 2012).

About 15-20 % of the mud supplied through the AD forms large coastal banks that migrate, under the influence of waves and currents, along the South American coast to the Orinoco delta in Venezuela. This mud bank regime has generated a unique progradational system stretching alongshore for 1600 km between the Amazon and the Paria Peninsula in Venezuela, and wherein the influence of the AD constitutes a dominant driver of the geology, ecology and economy of the coastal belt of the Guianas (Amapá region of Brazil, French Guiana, Suriname, Guyana, and Venezuela).

The macro-megatidal context of the AD involves large spatial variability in tidal ranges. This, combined with differential exposure to ocean waves, entails complex interactions between geomorphology and hydrology, with significant social and ecological implications. This complexity is reflected in the variability of sedimentation, shoaling, and channel and island morphologies, as well as in the distribution of muddy versus sandy coasts, all of which contribute to the large topographic, hydrological and ecological diversity of the AD. Such diversity has direct influence on settlement patterns, social–ecological arrangements, and economic activities.

The relatively rare sandy deposits on the muddy AD coast are important economically, socially, and ecologically because they provide locations a few metres in elevation above the muddy plain for human settlements and coastal routes linking the Guianas. The rare perennial sandy beaches on this part of the South American coast provide recreation outlets for the coastal populations and are especially fundamental to the ecology of protected marine turtles.

Socio-demographic, and political administrative characteristics

The Amazon delta is one of the most ancient areas of occupation in the Amazon with human settlements dating back 3000 years and including complex chiefdoms and mound-building cultures preceding the arrival of Europeans. Archeological data indicate large-scale agriculture strategies, high population density and social complexity of great significance (Roosevelt 1991; Schaan 2009). As the gateway to the Amazon, the region became the center of the Spanish and Portuguese colonial expansion. Missions and forts were built early on.

As defined here (Fig. 4), the core SES of the Amazon delta involves forty-one municipalities in the state of Pará and nine municipalities in the state of Amapá. During the colonial period, the region was subjected to intense missionary occupation. Immense land grants were distributed to designated families and religious missions creating a scenario of land concentration, which persist today particularly in Marajó Island. By the eighteenth Century, the region was the source of many agricultural and forest export products, followed by a large cattle ranching culture that, to date, defines the economy and social systems of the eastern portion of Marajó Island and other parts of the AD. Economic activities boomed during the rubber period (~1850–1910) followed by a period of economic decline, marked by numerous mini-booms in forest products until the beginning of the açai palm fruit economy during the 1980s (Vogt et al. 2015; Pinedo-Vasquez et al. 2001).

Today, açaí palm fruit production and export represent by far the most important economic product of the region, alongside a variety of agriculture and forest products, and fisheries (Brondizio 2008). Industries, including large-scale mining processing plants, are largely concentrated in areas accessible from the cities of Belém and Macapá. As elsewhere in the Amazon, most municipalities in the region have strong natural resource economies, but fragile and weak transformative industries and taxation basis, depending strongly on federal subsidies, and employment based predominantly in the informal sector (Costa and Brondizio 2009). The majority of formal employment is based on the public sector. In spite of its long history and wealth of resources, the Amazon delta is among the poorest regions of Brazil (Brondizio 2011).

About half of the municipalities today were created before 1940. Cities in the region are predominantly small, with 70 % of them having a population of less than 50,000 inhabitants. However, the regional urban population is significantly concentrated (56 %) in the two state capitals, Belém (Pará) and Macapá (Amapá) (Szabo et al. 2016; Costa and Brondizio 2011). Most of the regional population has been living in urban areas since the 1960. Furthermore, from 1970 to 2010 the urban population in the region has increased by around 300 %, particularly between 1990 and 2000 (IBGE 2010). Today, the region has approximately 79 % of its population living in urban areas, compared to 69 % for the Amazon region as a whole. This is a result of better transportation and communication as well as changing expectations of rural families in terms of better access to services and opportunities (Steward 2007). Research has shown that rural and urban households are closely interconnected in the AD, allowing families to benefit from access to natural resources and agricultural products in rural areas and to find better chances of employment and access to education, health, and public services in urban areas (Eloy et al. 2014; Brondizio et al. 2013; Padoch et al. 2008). The accelerated pattern of urban growth observed in the region has come without provisioning of basic sanitation infrastructure as well as precarious water and garbage collection (see Mansur et al. 2016). Pollution and sewage discharge represent a major public health and environmental problem in urban and rural areas throughout the region. In what follows, we illustrate the application of the framework to provide a brief example of diagnosis of this problem.

Illustrative example: initial diagnosis of the impact of urban growth and pollution on small-scale fisheries

As an illustrative example of how the framework can be applied, below we follow the steps presented in Fig. 1 to describe and provide an initial diagnosis of a collective action problem involving the impact of urban growth and pollution on small-scale fisheries.

Step one: the focal problem

During the last decade, riverine fishers occupying the floodplains of AD have been noting changes in both flooding patterns and changes in quantity and quality of the fish stock and extent and location of fishing grounds. Following Castello et al. (2013) call for coupling the analysis of land and freshwater systems in the Amazon, we take this situation to illustrate the application of the framework to characterize and analyze the collective action problem related to the impact of urban growth and pollution on local fishing in the southern channel of the AD.

Based on the framework presented above, our *first step* is to define the focal problem not as isolated problem, but as a problem that connects multiple places and people. Different categories of problems should be considered (see Textbox 4) so that one can start to identify the nature and geographical scope of the problem, proximate and distant drivers of change, and relevant stakeholders. For instance, fishing resources in the AD are influenced by upstream factors such as rainfall-flooding patterns, fish migration patterns, as well as habitat destruction, pollution from mining operations and urban and industrial sources, and pressures from resource users working with different fishing technologies. This requires the analyst to consider the relative role of different factors and stakeholders affecting the availability of fish resources at the local and regional levels. A participatory approach is mostly recommended, if not required, at this stage. As part of the latter, it is also important to explicitly define the types of evaluative criteria to be used for the analysis and diagnosis of the problem. Evaluative criteria should include social, biophysical and ecological indicators and parameters relevant to different stakeholders. This is followed by *step two* (defining telecoupling and interconnections) and *step three* (defining boundaries), which we briefly present as follows.

Step two: defining telecoupling and interconnections driving the problem

The timing and location of fishing and shrimping activities as well as floodplain agriculture of riverine populations in the AD are closely linked to changes in the height, duration, frequency and currents of floodwaters. These in turn vary with daily tidal cycles, lunar phases and seasonality of upstream rainfall (Vogt et al. 2016). There is a lag between the time when rainfall begins to increase in the wet season (and decrease in the dry season), in the upstream basins feeding the AD, and changes in average river level (rises and falls) and current strengths in the AD (Fig. 5). That is, causes of variation in flood conditions are not only linked to local rainfall and tides but upstream rainfall that cannot be directly sensed by local residents (Vogt et al. 2016). For the purpose of this example, we can see these linkages by examining the southern channel of the AD, which is strongly influenced by climate, ecological, and social processes taking place upstream along the Tocantins watershed.

Depending on the place of residence of fishers and communities along the floodplains of the southern channel, one may receive different levels of pollution from upstream rivers. The majority of cities and towns in the AD have insufficient sewage infrastructures to service their populations, resulting in a high degree of organic pollution discharged into local rivers and channels. For instance, from 2000 to 2010, in almost all municipalities of the region the number of households connected to a public sewage system and treatment has remained around 10 % and in some cases inexistent. While this figure is higher for the City of Belém, with more than 1,300,000 inhabitants (not counting the connected metropolitan area which combined has 2.5 million inhabitants), the majority of wastewater remains untreated (Mansur et al. 2016). As the majority of riverine residents depend on river water for daily activities, increasing pollution loads have implications not only for fishing, but also human health.

Loss of floodplain habitat for housing, artificial levees and other infrastructure has reduced food availability for frugivore species at the bottom of the food chain, which may have cascading impacts on the entire fish food chain. In addition to pollution from urban sewage, industrial and mining spills are not uncommon around cities such as Belém and Barcarena, such as the case of kaolin spills. The amount of solid waste flowing from upstream has also increased dramatically in this region. Local riverine

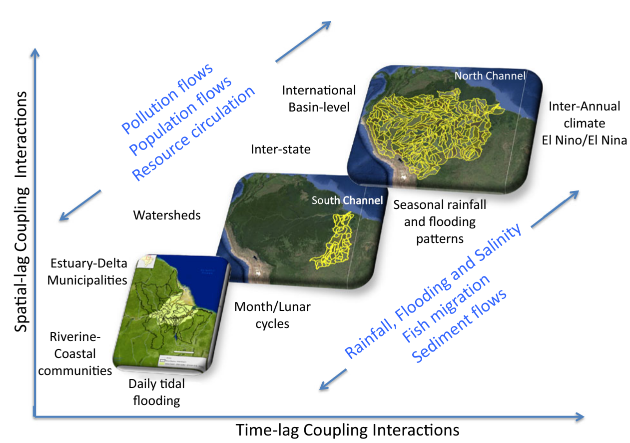


Fig. 5 Spatial and temporal lags influencing the Amazon Delta Social–Ecological System (SES)

residents are increasingly noticing the impact of plastic waste and oil fuel on riverine ecosystems. Furthermore, competition for fishing resources has also increased, which along with changes in technology (types of fishing gears and fishing boats) have put significant pressures on the stocks of commercial fish and shrimp. Reduction of habitat, increases in pollution, and fishing pressures reduce distribution and quantity of the fish resource available for local consumption. Increasing demand from national and international markets continues to push fish price up, making it inaccessible to a large segment of low-income residents. Fishing, including shrimp fishing, is an important part of the subsistence and market economies of the region. As productive fishing grounds become scarce near urban areas, fishers increasingly pay higher transportation costs to provide for urban markets. Pollution and habitat loss result in the need to fish in more distant grounds and to use ice to keep fish fresh on the way to market, increasing the costs of production. The changes in water quality are linked to rapid and precarious urban expansion occurring both in urban areas throughout the AD as well as upstream along the Tocantins River. The framework is intended to allow the research group to consider these different types telecoupling and interdependencies and to define the boundaries of the SES of interest and the specific variables and causal relationships influencing the problem at a given level, i.e., a given unit of analysis of an action situation.

Step 3: Definition of boundaries of [sustainability] action situations

Thus, the telecoupling of local fishing activities to upstream processes (urban growth, pollution, resource use) creates a collective action problem involving different stakeholders and physical-ecological processes. This situation goes beyond those traditionally studied local fisheries organized at the community level, usually based on informal institutions and direct interactions with the local ecosystem and fishing grounds. The type of situation emerging in the AD, therefore, requires the definition of boundaries (*step 3*) that allow connecting a local action situation, for instance in a local community, to the larger catchment area, in this case cities along the watershed of the Tocantins river, and related municipalities and communities (Fig. 6). Given the potential complexity of the problem, the geographical definition of the study area (or

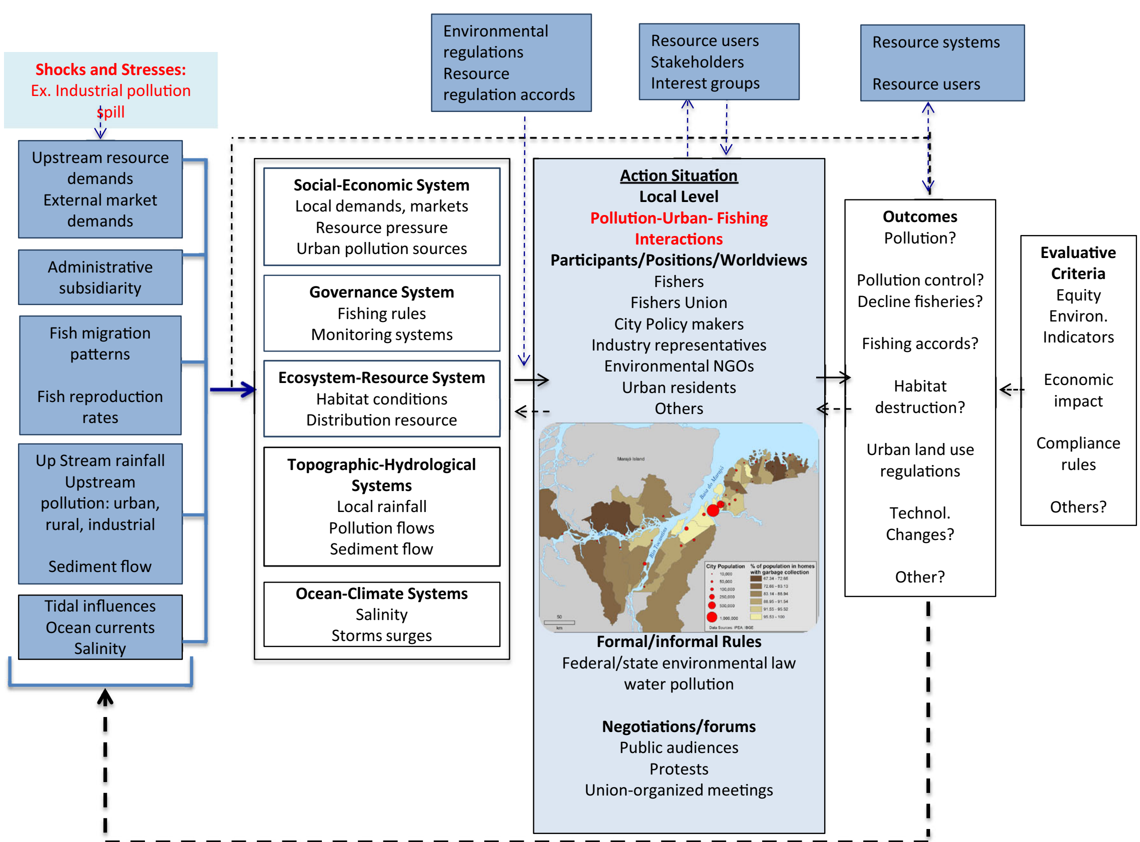


Fig. 6 An illustrative application of the framework to map out the impact of urban growth and pollution on smallscale fisheries in riparian areas and mangroves of the AD

management area) requires prioritization of questions and objectives. The framework (b) illustrates the possibility of connecting three levels of analysis (see Fig. 3), but these decisions depend on the problem and questions at hand. For instance, the main source of the pollution problem for a riverine community may be a mining processing plant upstream (which is actually a common case in the region). In this case, defining the geographical boundaries of the analysis to capture this connectivity (telecoupling) requires mapping out the stream network connecting the mining processing plan to the community downstream, and the land area along the selected hydrology network. The definition of the land area could involve both ecological limits (e.g., floodplain area) as well as a delimitation based on districts and municipalities and/or census sectors. The latter allows for disaggregated analysis using social, demographic, infrastructure, and economic data. The goal of this step, then, is to define the unit of analysis of the problems, their respective geographical boundaries, and their interrelationships.

Step 4: Characterize the components and nature of action situations

Once the problem is initially characterized in terms of interacting factors and social–ecological boundaries, one can start to analyze the components and nature of this sustainability action situation at a given level, as described in *step 4*. Figure 6 illustrates the characterization of the problem in the southern channel of the AD. As discussed above, this action situation is influenced by factors occurring at local (fishing grounds) and larger scales (watershed of the south channel). These include pressure on resources locally as well as upstream pollution from specific cities, habitat destruction around cities, events of industrial pollution, as well as rainfall and flooding levels affecting the seasonal migration of specific fish species. In the case of the southern channel, the Tucurui Dam has also impacted water and sediment discharge affecting the AD. The amount of solid waste flowing from upstream has also increased dramatically in this region. Local riverine residents are increasingly noticing the impact of plastic waste on riverine ecosystems and pollution in the water they use for drinking and bath. The intention here is not to analyze the problem in detail, but to show the use of the framework to systematically consider the different categories of factors affecting the problem, potential causal relationships, the different set of actors involved, the influence from proximate and distant causes, potential outcomes and their feedbacks, and potential evaluative criteria. The small figure inserted into Fig. 6 shows the amount of untreated sewage for cities along the southern channel of the AD.

Step 5: Analyzing and refining research questions, diagnosis of causal processes and outcomes

Once an initial social–ecological characterization of the problem is outlined, the framework allows a research team to pose questions and to test different theories about interactions between different factors and the conditions that mediate these interactions and their outcomes (*step 5*). This illustrative sustainability action situation is influenced by factors occurring at local and larger scales, involving among others pressures on upstream fisheries, habitat destruction around cities, events of upstream pollution and industrial spills, and factors affecting seasonal migration of specific fish species. Based on the analysis of empirically studied outcomes, one may start to diagnose, for instance, which groups of factors and actors may be more relevant within different impact chains affecting the problem in a given location. One can consider how different categories of problems, as illustrated in Textbox 4, are inter-related, and what variables are important to study them in more detail.

One can also evaluate the types and functioning of formal and informal rules and norms affecting different components of the problem (e.g., land use change, pressure on resources, pollution regulation). For instance, among fishers, several fishing accords have emerged from agreements made within fishing unions and/or imposed by federal and state environmental regulating agencies. While these changes in rules can be effective in limiting the pressure on fishing resources at a local level (e.g., halting fishing activities during reproductive seasons, restrictions on fishing gear, fishing ground entry rights), they do not address urban sources of pollution and habitat destruction or industrial pollution spills occurring upstream that impact those fishing grounds. Therefore, analyzing this sustainability action situation requires attention not only to the local collective action problems among direct users of a common pool resource (e.g., population size, asymmetrical power relations, diversifying livelihood choices) or those local economies (e.g., change in demand or harvest sizes) but also processes and participants operating at different levels. In this case, it should also include factors influencing urban and industrial land uses upstream that directly or indirectly affect ecological conditions downstream.

This analytical exercise opens the possibility of positing different types of questions of relevance to sustainability action, such as what types of formal and informal rules are influencing urban land change and planning; who participates in urban planning and how are they chosen; who is occupying new urban spaces and why; what are the costs of effluent reduction technologies and how it relates to municipal economies; among many others. In spite of the growing severity of the cross-scale problem presented here, most actions and discussions of sustainability in the region have not involved collaborations between fishers, city planners, and other involved groups. While fishing accords have been crafted, including changing fishing rules and monitoring of fishing technologies, pollution problems, including significant industrial spills, have not been addressed in spite of their growing prevalence. The framework, thus, helps to characterize the complexity of the situation while considering social, physical, and ecological causal factors operating at different scales, and their outcomes and consequences at different levels.

Concluding remarks

Within the context of global deltas, the Amazon delta is considered among the most preserved and resilient to social and environmental change (Syvitski et al. 2009). Social processes and biophysical forces operating from local to global levels, however, increasingly challenge the long-term sustainability of the region. Regional changes in infrastructure, urban growth and pollution, and growing demand for resources are putting pressures on local ecosystems and livelihoods. Little is known, for instance, about the potential interactions and impacts of changing rainfall patterns, climate change, and sea-level rise on the Amazon and other delta regions of the world.

Delta regions are microcosms of global sustainability problems wherein distal and local stakeholders and ecosystems interact, implicitly or explicitly, to shape outcomes. In this article, we have presented the initial outline of an integrated conceptual framework to help define delta SES according to different problems and to diagnose the components of complex sustainability dilemmas and their interdependencies. While using examples from the Amazon, we believe that this framework is largely applicable to other deltas and estuary regions. The framework builds upon literature in SES and sustainability drawing from a variety of disciplines and regions of the world. We have tried to maintain terminology widely used in SES analysis while bringing together concepts from the social and biophysical sciences that emphasize multi-level processes and social–ecological interdependencies characteristics of delta regions.

This framework is intended to support both case studies and comparative analysis. It can be applied in a single delta to diagnose the causal processes of a particular sustainability action problem, as illustrated in Sect. 3, or for comparative studies between deltas. One could, for instance, examine how cross-scale processes of a similar sustainability problem may vary between cases, or why similar cross-scale causal processes have different outcomes across deltas. The proposed framework and its components are intended to serve as a guide, offering consistent terminology and a flexible structural configuration to be adapted to different problems and regions. We hope it will contribute to the development of new approaches to understand, diagnose, and evaluate social–ecological problems and potential solutions to the sustainability dilemmas of deltaic regions.

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Textbox 1: Defining key terms

Institutional fit is used to describe the congruence or compatibility between the social and ecological systems, i.e., whether a form of collective action at a local level matches the larger ecological system within which it is subsumed (Young 2002; Epstein et al. 2015).

Institutional interplay designates interactions (and tensions) between governance arrangements operating within and/or across scales (Young 2002, 2006).

Functional Interdependence refers to the way human actions or biophysical processes taking place in one setting can produce impacts in areas and systems that are far removed from the site of such actions and/or processes. Functional interdependencies can involve both biophysical and socioeconomic linkages (Young et al. 2006; Brondizio et al. 2009).

Collective action is used here to mean the cooperation among two or more individuals to try to achieve outcomes that none of these individuals could achieve on their own. As such, collective action involves different types of cooperation and conflicts among individuals and/or groups of individuals to solve collective problems and choices at different levels. Collective action is difficult in proportion to the scale of the problem as well as to the size and heterogeneity of the group of actors: the larger and more diverse the group, the higher the differences in objectives, the higher the transaction cost of information exchange and collaboration, the harder it is to act collectively.

Governance refers to a social function centered on steering human groups toward mutually beneficial outcomes and away from mutually harmful outcomes.

Telecoupling refers to both to the interconnection between social and natural systems and to the distant causes of local phenomena. Liu et al. (2013, 2015) telecoupling framework includes five main components: *systems, agents, flow, causes, and effects.*

External forcing refers to "…to a forcing agent outside the climate system causing a change in the climate system. Volcanic eruptions, solar variations and anthropogenic changes in the composition of the atmosphere and land use change are external forcings." (IPCC 2013:1454).

Textbox 2: The Amazon Delta-DAT

The Amazon Delta-DAT is a Geographic Information System created as part of the Belmont Forum Deltas project. The Amazon Delta-DAT geospatial data platform includes on the one hand socioeconomic data sets, such as different political and administrative units, historical census data (including social, demographic, and economic indicators), land use change, urban infrastructure and services and, on the other hand, biophysical data such as remotely sensed datasets, topographic data, watershed information, historical rainfall patterns, tidal records, and land cover change.

Outputs in the form of statistical analyses and map products are also archived within Delta-DAT. The geospatial methodology is based on change detection techniques, providing a basis for monitoring the distribution, extent and direction of changes in the land cover as associated with different types of property regimes (e.g., common, governmental, private, open access), contextual factors (e.g., access, location), and/or other units of analysis such as watersheds, census sectors, municipalities, communities, different types of reserves and protected areas and so forth. To consolidate and make data readily available to the larger BF-Deltas team, the authors worked in cooperation with colleagues at the City University of New York, under the leadership of Zach Tessler. Through this collaboration, the Delta-DAT geospatial database is now served by open source data management software known as The Integrated Rule-Oriented Data System (iRODS). iRODS allows for metadata generation, automated workflows, secure collaboration and data virtualization providing a middleware between several physical data storage systems and the user interface. iRODS is currently running on a server at City College of New York.

Textbox 3: Geology, hydrology, and climate of the Amazon estuary-delta

The AED is located on a rifted passive tectonic margin and is the terminus of a drainage basin of 6.1×10^6 km^2 (Organization of American States 2005). The AED experiences a hot, humid tropical climate (Koppen Af) with temperatures averaging between 25 and 27 °C. Shifts in the Intertropical Convergence Zone (ITCZ) from around 14°N in August to 2°S in March–April condition the east to northeast trade winds and rainfall patterns. These trade winds are mainly active from January to May. Rainfall is in the range of 2500–3000 mm and is concentrated in a rainy season also lasting from January to May. Rainfall and river discharge are significantly influenced by ENSO oscillations. A recent estimate of the mean annual water discharge of the river at Óbidos, 900 km upstream of the mouth, has been set at 173,000 m^3 s^{-1} (Martinez et al. 2009), that is about 20 % of the world's fluvial liquid water discharge. The water discharge peak of over 220,000 m^{3}s^{-1} occurs in May–June and the low discharge of 100,000 m^{3}s^{-1} in November–December. These variations engender significant changes in water level within the AED, which, when combined with the strong tidal effects of this system, constitute a source of important spatial–temporal hydrological variability (see Fig. 5). The Amazon also discharges the highest total sediment load to the global oceans, although the specific sediment yield of 190 t km^2 a^{-1} corresponds to the world's average (Milliman and Farnsworth 2011). Recent estimates of sediment discharge at Óbidos range from 754 to 1000×10^6 t a^1 (Martinez et al. 2009; Wittmann et al. 2011). About 90 % of this sediment load is silt and clay (Milliman and Meade 1983), reflecting intense tropical weathering of materials of dominantly Andean origin (Guyot et al. 2007). Martinez et al. (2009) have shown that the liquid water discharge is relatively regular whereas sediment discharge showed more significant inter-annual variability. The rest of the load consists of sand.

The large continental shelf built-up by sediment supply by the AED over geological time leads to significant tidal amplification at the mouth of the river, thus generating large tides that favor important water level changes within the funnel-shaped mouth. In the Northern channel, this tidal influence is felt up to the town of Óbidos. Tides are associated with a flood-dominated asymmetry that leads to the formation of bores (*pororoca*) in some Northern channels. Ocean surface stress by the trade winds generates strong westward along-shelf flow of the North Brazil Current. The trade winds are also the dominant generators of waves impinging on the AED coast, which come from an east to northeast direction (Gratiot et al. 2007). Trade-wind waves have significant periods (T_s) of 6–8 s, and significant offshore heights (H_s) of 1–2 m. The AED coast is also affected by longer period (>8 s) swell waves generated by North Atlantic depressions in autumn and winter and by Central Atlantic cyclones in summer and autumn.

Textbox 4: Categories of collective action problems adapted from Mcginnis (2011)

Appropriation problem: relates to motivating individuals to forego excessive consumption of a subtractable resource, i.e., whether one group of users benefits more than another.

Provisioning problem (or public good problem): relates to the motivation of individuals to contribute to the resource system and infrastructure, i.e., to avoid a 'free riding' problem.

Assignment problem: the location of one group may be more beneficial than for others and differential access to resource use.

Technological externality problem: differential access to technology creates uneven rates of use and benefits between users that have similar rights to resources; it can also create environmental and social externalities affecting different segments of the population.

Rent dissipation problem: one group of users seeks high rates of short-term use and return than other users with similar rights to resources.

Cross-scale mismatches problems: Fit between the institutional boundaries of governance and the ecological boundaries of the resource system is intended to manage; and interplay between two neighboring governance systems that may be competing for the same resources.

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