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SPECIAL FEATURE: ORIGINAL ARTICLE

Sustainable Deltas: Livelihoods, Ecosystem Services, and Policy Implications

Local ecological knowledge and incremental adaptation to changing flood patterns in the Amazon delta

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Abstract The need for understanding the factors that trigger human responses to climate change has opened inquiries on the role of indigenous and local ecological knowledge (ILK) in facilitating or constraining social adaptation processes. Answers to the question of how ILK is helping or limiting smallholders to cope with increasing disturbances to the local hydro-climatic regime remain very limited in adaptation and mitigation studies and interventions. Herein, we discuss a case study on ILK as a resource used by expert farmer-fishers (locally known as *Caboclos*) to cope with the increasing threats on their livelihoods and environments generated by changing flood patterns in the Amazon delta region. While expert farmer-fishers are increasingly exposed to shocks and stresses, their ILK plays a key role in mitigating impacts and in strengthening their adaptive responses that are leading to a process of incremental adaptation (PIA). We argue that ILK is the most valuable resource used by expert farmer-fishers to adapt the spatial configuration and composition of their land-/resource-use systems (agrodiversity) and their produced and managed resources (agrobiodiversity) at landscape, community and household levels. We based our findings on ILK on data recorded for over the last 30 years using detailed ethnographic methodologies and multitemporal landscape mapping. We found that the ILK of expert farmer-fishers and their "tradition of change" have facilitated the PIA to intensify a particular production system to

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optimize production across a broad range of flood conditions and at the same time to manage or conserve forests to produce resources and services.

Keywords Indigenous and local knowledge · Resilience · Adaptation · Amazon delta · Sustainability · Multifunctional landscapes

Introduction

Findings presented in the IPCC AR4 report suggest that the surface area of flooding in deltas will increase by 50 % by 2100 (Syvitski et al. 2009). This increase is projected to be caused by both natural factors from a changing climate as sea-level rise and shifts in basin-level rainfall patterns (Mcleod et al. 2010; Day et al. 2011) and non-climatic factors as change in sediment loads from dams and discharge levels from rivers due to land-use changes in basins feeding them, for example (Syvitski 2008; Ipcc 2014). Indigenous and local ecological knowledge (ILK) plays a key role in sociocultural responses that underpin the process of incremental adaptation (PIA) to disturbances to local hydro-climatic regimes in delta regions. In this paper, we present the ILK that expert farmer-fishers in the Amazon delta apply to adapt their land–resource use and management systems in order to secure food, land and income to changing flood patterns and market demands to forest and agroforestry over the past 30 years. We document and analyze ways that expert farmer-fishers are building resilience and reducing vulnerability of social–ecological systems (SESs) in the Amazon delta to challenges from the perceived changes in flooding patterns as well as the opportunities from high prices and demands for the *açai* palm fruit in local to global markets. The important contribution ILK can make toward building sustainability of deltas is recognized in both the IPCC AR5 (Ford et al. 2012; Ipcc 2014) and the United Nations Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) assessments (Díaz et al. 2015a, b; Larigauderie and Mooney 2010; Tengö et al. 2014), yet these knowledge systems remain largely understudied and undocumented.

Local populations in the Amazon delta are noting both gradual and sudden changes in tidal regimes not explained or anticipated by lunar and solar phases, affecting fish and floodplain production dynamics on which their livelihoods and food security are highly dependent. Since a seminal work of Chambers and Conway (1992), several studies utilized the concept of sustainable livelihoods to evaluate how traditional populations cope with and recover from external pressures or shocks. Diversity and flexibility as tools for traditional populations to adapt to enhance food, land and income security to external shocks as global markets or extreme tidal events has increased in recent years (Denevan 1983; Berkeset al. 1998, Pinedo-Vasquez et al. 2002; Vogt et al. 2015). Using participatory approaches, this paper seeks to document knowledge of expert farmer-fishers of how to enhance the resilience and adaptive capacity of their socioecological systems to both gradual and less predictable tidal regime changes underway in the Amazon delta. Rather than assessing relative vulnerability or capacity to adapt to changes in the tidal regime underway, we will more directly document how select experts are building resilience of local social–ecological systems to both gradual tidal regime changes and less predictable sudden tidal events, to complement more quantitative data on variations in local climate also being collected.

The definition of traditional ecological knowledge (we use ILK that is used today in IPCC and IPBES assessments) we will adopt in this paper is that of "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes et al. 2000). ILK has been more widely utilized in natural resource management, conservation and development planning (Redford and Padoch 1992; Kusters and Belcher 2004; Berkes 2008) than in mitigation and adaptation studies. However, today there is more widespread agreement that ILK, including its use for management of functional diversity (Diaz et al. 2011) for providing resources and services through extreme events (Spangenberg et al. 2014), should be incorporated into climate impact and adaptation assessments, as local (traditional and indigenous) populations are relatively more vulnerable to impacts of climate change, and they have a wealth of knowledge of how local ecosystems respond to environmental change (Salick and Ross 2009; Turner and Clifton 2009; Green and Raygorodetsky 2010; Agrawal and Perrin 2009; Ford et al. 2011). In the IPCC fourth assessment report (AR4), ILK is argued to be "an invaluable basis for developing adaptation and natural resource management strategies in response to environmental and other forms of change" (Raygorodetsky 2011) and should be taken a more prominent role in future reporting. Traditional populations in many places of the world have adjusted social–ecological systems to changing external forces for generations and no doubt have important contributions in mitigation and adaptation.

As a way forward to use ILK in climate change adaptation studies, Berkes (2009) argues it is important to look at ILK as a process more than static content. That is, ILK of environmental change is dynamic and evolves by adaptive processes (Berkes 1999, 2009; Nelson et al.

2007), as trial-and-error of resource productivity across environmental contexts and different technologies. In the last decade, studies of adaptation to environmental change utilizing ILK have placed much emphasis on adaptive learning (Gunderson and Holling 2002; Folke et al. 2002; Olsson et al. 2004) cultural traditions of change that facilitate resource-use adaptation (Pinedo-Vasquez et al. 2002) and flexibility of land-use decisions (Vogt et al. 2015; Brondízio 2008), among others.

ILK of the upland–floodplain–aquatic dynamic in response to changes in flood regime dynamics is a tool to enhance resilience to extreme flood events (locally known as *lançantes*) and other anomalies produced in the local hydro-ecological regimens. We argue that they build resilience in the delta SESs by generating, innovating and integrating knowledge of a range of forest, agroforestry agriculture and fishing production. These management and conservation systems are conducted at different locations on the landscape at different times depending on requirements of environmental contexts, and they are flexible to switch between the built options in the short term (Pinedo-Vasquez et al. 2002; Vogt et al. 2015). Pursuing ILK of climate impacts on these complex SESs is costly and time-consuming to acquire, yet a powerful tool to link broad- and meso-scale studies of climate variability to local sociocultural adaptation processes for more locally relevant interventions and early warning tools.

The "Results" section of this article is divided into three sections. In the first section, we present expert farmer-fisher knowledge of managing landscape patterns to adapt to perceived long-term changes in timing, frequency and duration of *lançantes* and a comparison of floodplain micro-topographic zones between in situ measurements and field interviews with expert farmer-fishers. This comparison provides quantitative measures for locally defined elevation categories. In the second section, we present expert farmer-fisher knowledge of managing shorelines of secondary rivers where communities are located to (a) reduce erosion and (b) maintain habitat, places to feed and rest, for subsistence shrimp and fish during *lançantes*. In the third section, we present expert farmer-fisher knowledge of management of individual species at the household level as (a) trees whose roots regulate depth of primary streams (*igarapés*) to allow fishing and shrimping at either extremely low or high river level in secondary rivers and main channels, (b) performance of fruits and crops across micro-topographic zones during *lançantes*, (c) fruits that produce more and for longer duration in years of more frequent flooding and that are consumed by subsistence and commercial aquatic species and (d) aquatic species present when extreme high tidal floods are driven by sea level and when driven by upstream river level.

How ILK is being used by local experts to build resilience to changes in local hydrological regimes in deltas and estuaries, driven by both natural and non-climatic factors, is largely missing in sustainability studies of deltas and estuaries, though its importance is highlighted in the *Impacts, Adaptations and Vulnerability* section of the recent IPCC report. Deltas and estuaries are also known to be rich in resources that often have high economic value, and the IPBES program also explicitly calls for including ILK in assessments of biodiversity and related policy generation. We argue that the ILK accumulated over generations by local farmer-fishers of the Amazon delta in response to both the challenges of changing flood patterns and the opportunities of market booms is valuable for both designing and implementing mitigation and adaptation programs aimed at enhancing sustainability of deltas to secure income, food and land of local populations into the future.

Study area

The Amazon delta as taken in this study is the area below the island of Gurupa and rivers more greatly affected by diurnal tidal floods that can vary between 1 and 4.4 m (Fig. 1). It is an area five times bigger than Costa Rica and larger than the state of Acre. It includes upland forests (locally known as *matas da terra firme*) and one of the largest floodplains that are known as *várzea* floodplain that is composed by extensive riparian vegetation (locally known as *matas da várzea*), swamp savannas and inundated grasslands (locally known as *campo aladagos*) and networks of interconnected streams (locally known as *igarapés*) (Pinedo-Vasquez et al. 2011). It is estimated that more than five million smallholder people are residents of the estuarine municipalities of the states of Amapá, Pará and Tocantins (IBGE 2010). Belém, the second largest city in the Brazilian Amazon with an estimated population of more than 1.5 million, is located in the Amazon estuarine region (IBGE 2010). While smallholders have actively participated in economic booms, they were and continue to be engaged in fishing, hunting, logging, agriculture and temporary labor to make a living in the dynamic and changing environments and landscapes of the Amazon delta.

Methodology

We applied a suite of ethnographic methodologies including semistructured interviews, transect walks on floodplain during *lançantes* (extreme high tidal floods), *aguas vivas* (spring tides) and *aguas mortas* (neap tides), surveys and

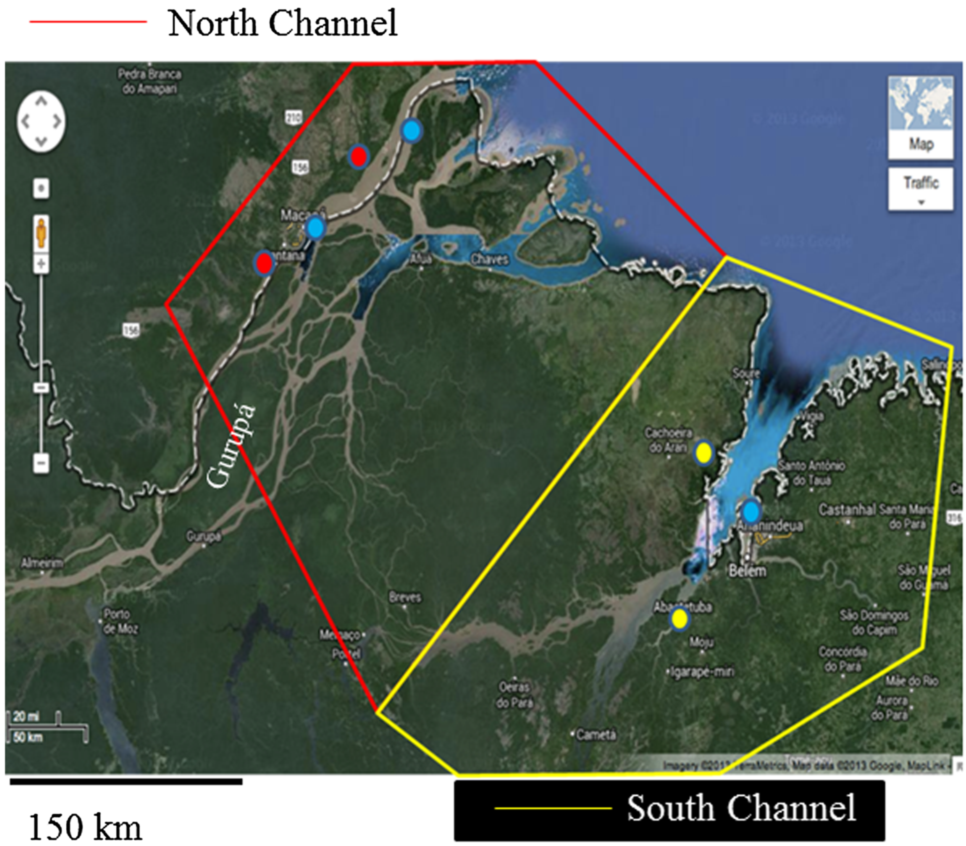

Fig. 1 Study area

historical flood pattern reconstructions all with expert floodplain farmers of the Amazon delta. These were conducted since the 1980s and more intensely and at times of specific tides between 2011 and 2015. Multitemporal landscape maps were often used in the interviews as a way to validate historical land-use patterns on the landscapes captured in key informant interviews.

Indigenous and local knowledge of how to adapt to sea-level rise and climate change is not a collective resource that all delta residents possess, but is held by expert farmer-fishers. Experts are recognized by other riverine farmer-fishers and sought after for advice on challenges and opportunities produced by hydro-climatic events. In this way, they were too identified for collaboration in projects. We identified experts as those community members known for their capacity to solve problems related to extreme flood events, popularity and openness to other community members and richness of produce (annual and perennial crops) and conserved and managed resources (shrimp, fish, game, timber and non-timber forest products) on their holdings. Experts are few but may be old or young, new or old residents, and women or men. Experts can be found in each community and are known to share knowledge when sought after. There are other constraints and supports beyond ILK to *Caboclo's* flexibility to adapt to hydro-climatic changes that are discussed further in Vogt et al. (2015). In both channels, sets of expert farmers in different communities have been followed for over 25 years.

Rulers were placed in rivers and daily maximum and minimum heights measured daily for 2 years. Transects were walked from the ruler measuring the elevation of the floodplain at 10-m intervals in relation to the ruler. The micro-topographic zones were classified by expert farmers as they were mapped, as well as land-use histories, annual crop and fruit trees managed on each zone under different flood conditions. Archival information on *lançantes* and other extreme events were collected from rulers in local rivers in 1980s, mid-1990s and for 2 years in this current project, from tidal gauges placed in each of the North and South channels (see Fig. 1) in this project and archival studies of extreme events documented in local newspapers conducted at the National Institute of Space Research (INPE) in Brazil to validate the oral history information on hydro-climatic events collected from expert farmers and long-time residents. Figure 2 shows the conceptual framework used to guide the analysis of role of ILE in aiding in the assessment of risk from external pressures and shocks and the incremental adaptations to those signals.

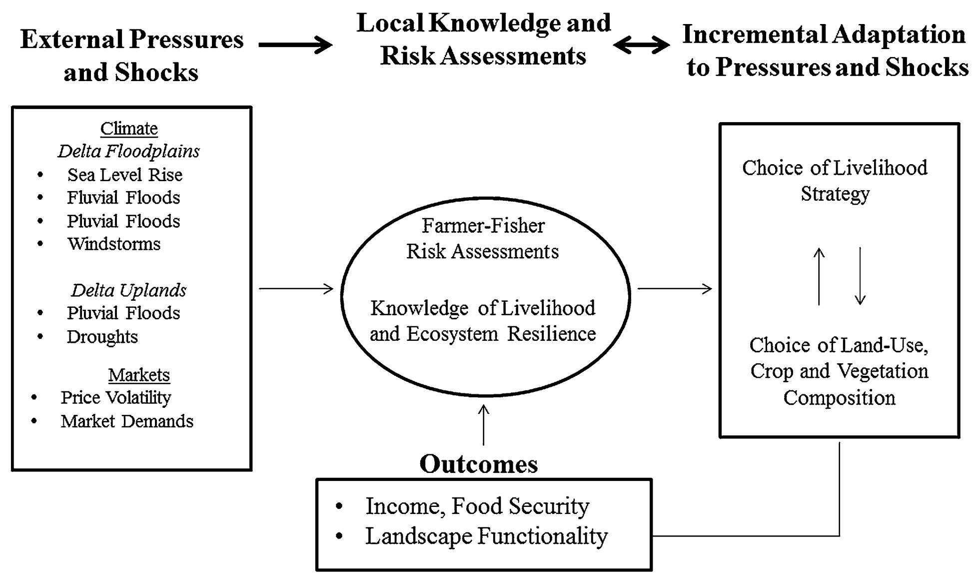

Fig. 2 Conceptual framework

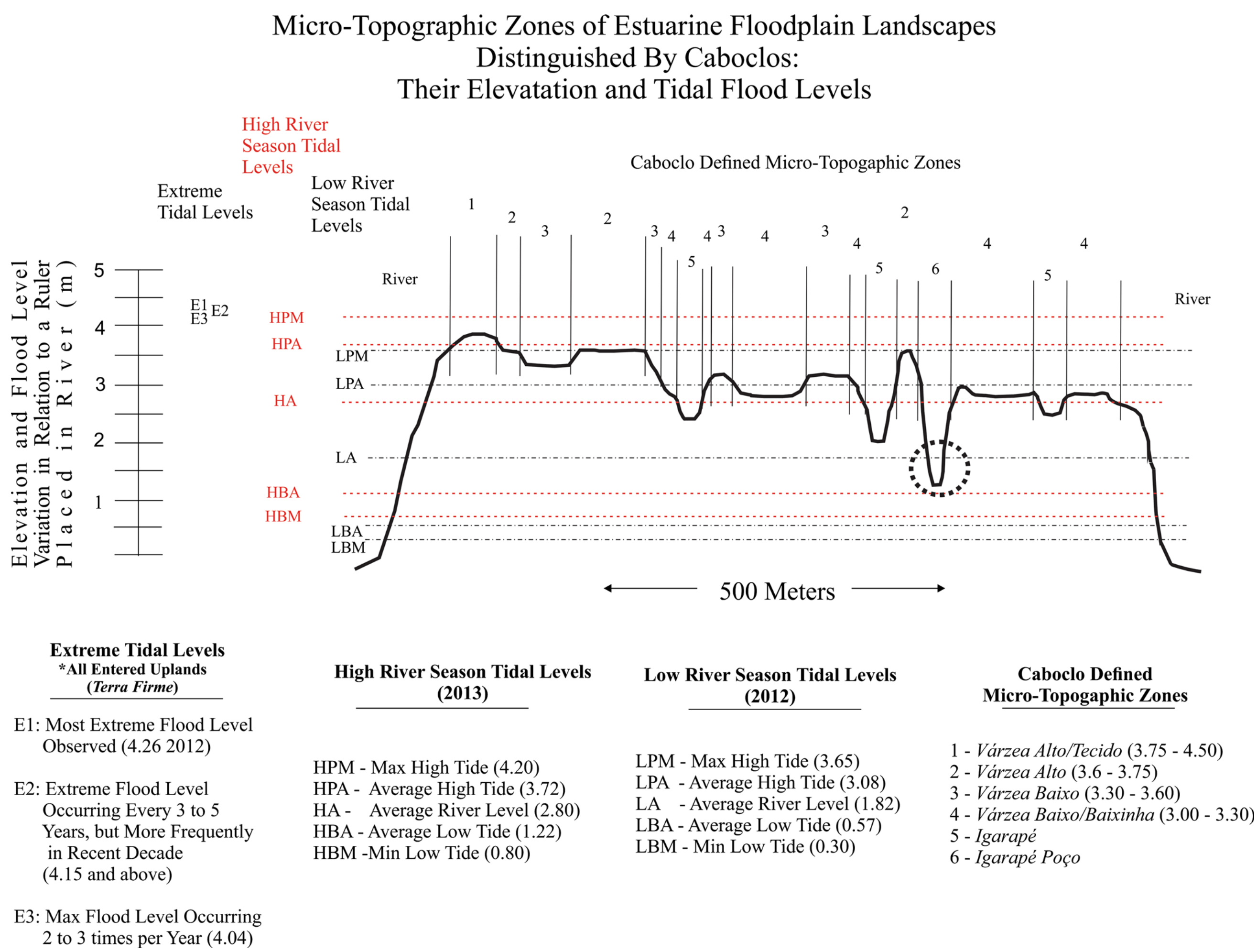

Fig. 3 Micro-topographic zones of estuarine floodplain landscapes. Distinguished by Caboclos: their elevation and tidal flood levels

Results

Indigenous and local ecological knowledge to adapt landscapes to *Lançantes* and other changes in flood patterns

From long-term interactions with the estuarine floodplains under different flood conditions, the estuarine farmer-fishers have developed a nuanced classification for different phases of floods through the lunar and solar calendars. These names reflect that the frequency and duration of different zones of the soil catena are inundated and the type and quantity of fish and shrimp present in the floodplain habitat (Fig. 3). Expert farmer-fishers identify two *lançantes* (flood tides) and two *vazantes* (ebb tides) per day. *Aguas vivas* (spring tides with relatively high amplitude and strength) occur during *lua cheia* (full moon) and *lua escuro* (new moon). *Aguas mortas* (neap tides with relatively low amplitude and strength) occur during *lua minguante* (neap tide of waning moon) and *lua crescente* (neap tide of waxing moon). Extreme tidal flood events are often referred to as a *grande lançante.*

The river level and the amplitude of tidal flood vary broadly between *aguas de inverno* (high-water-level season broadly occurring between February and April) and *aguas de verão* (lower-water-level season broadly occurring between July and November), where there is approximately 1 meter difference in average river level (Fig. 3).

Expert farmer-fishers classify micro-topographic zones of the delta floodplains according to the frequency and duration of zones flooded and types of land uses, annual crops and trees that can be managed on them. These include *praia de lama* (mud flats) or *várzea baixa baixinha* at the edge of rivers or *igarapés* (streams), *várzea baixa* (low floodplain), *várzea altavárzea alta* (high floodplain) and *restinga* or *tecido* (river levee) (Fig. 3). Though sparse in extent in the delta, there is also a *Beira Marituba* that is found at some transition zones between floodplains and uplands, an area that only floods during the highest flood levels of the year. This zone is highly irregular in elevation over short distances, containing nearly all other micro-topographic zones over short distances. Variations in elevations of each zone vary from approximately 15–30 cm. The *restinga/tecido* has a broader range of approximately 75 cm (Fig. 2).

An important difference in elevation is the frequency and duration in which *várzea altavárzea alta* is inundated. During *aguas de inverno*, the *várzea altavárzea alta* is inundated in nearly all high tides, either *aguas vivas* or *aguas mortas*. However, during *aguas de verão*, this zone is only inundated 2–6 times across 1–3 days during highest or extreme tides (*lançantes*) of *aguas vivas* and the river begins to subside again (Fig. 3).

Local ecological knowledge to adapt landscapes to changing flood patterns

Expert farmer-fishers have perceived increases in the frequency and duration of flooding of *várzea alta* during *aguas de verão* in recent years. In recent years, *aguas de verão* are higher and with greater amplitude, with *várzea alta* now often flooding 4–8 times across 2–4 days rather than 2–6 times across 1–3 days. When the frequency of flooding was 6 or less times and only during *aguas vivas*, expert farmer-fishers would plant *roça da várzea* (small mixed crop floodplain fields) that could include more annual crops that are less tolerant to daily flooding. In recent decades, they have increased intensity of *açai* agroforestry and expanded it from *várzea baixa* to *várzea alta* as it performs well in micro-topographic zones of high-frequency flooding and under extreme tidal flood events (Fig. 4).

Expert farmer-fishers have also perceived an increase in the duration of river level of *aguas de inverno* over recent decades. In the past, 35 years ago, the river level would consistently begin to decline at the end of April, beginning the approximate 2-month transition in river height from that of *aguas de inverno* to the level of *aguas de verão* (Fig. 4). Expert farmer-fishers have perceived that in the last decade, the river level does not begin to decline until June or even July, with nearly daily flooding of the *várzea alta* often continuing until July. Annual crops were often planted in the *várzea alta* during this transition season (see Table 1a for a list of annual crops historically planted in *várzea alta*). Expert farmer-fishers report that in many dry seasons of recent years, the frequency of extreme tidal floods has been too high to plant many of these crops. Table 1a shows crops no longer planted in floodplain but in *tecidos* or *terra firme*. Some *roça de várzea* crops are more flood tolerant and are still managed in the floodplain (Table 1a). Again, the landscape adaptation to the increased duration of *lançante* is to expand the more flood-tolerant açai agroforestry and forest fallow land use enriched with more flood-tolerant species from *várzea baixa* to *várzea alta* (Fig. 3).

Roças are now primarily planted in uplands, and the seeds of *açai* from floodplain agroforestry are used as soil cover to maintain higher levels of soil moisture during the dry season. There are increases in the number of forest, forest fallow and forest fragments on landscapes replacing agriculture in *roças* of either upland or floodplain and cattle ranching on *campo alagada.*

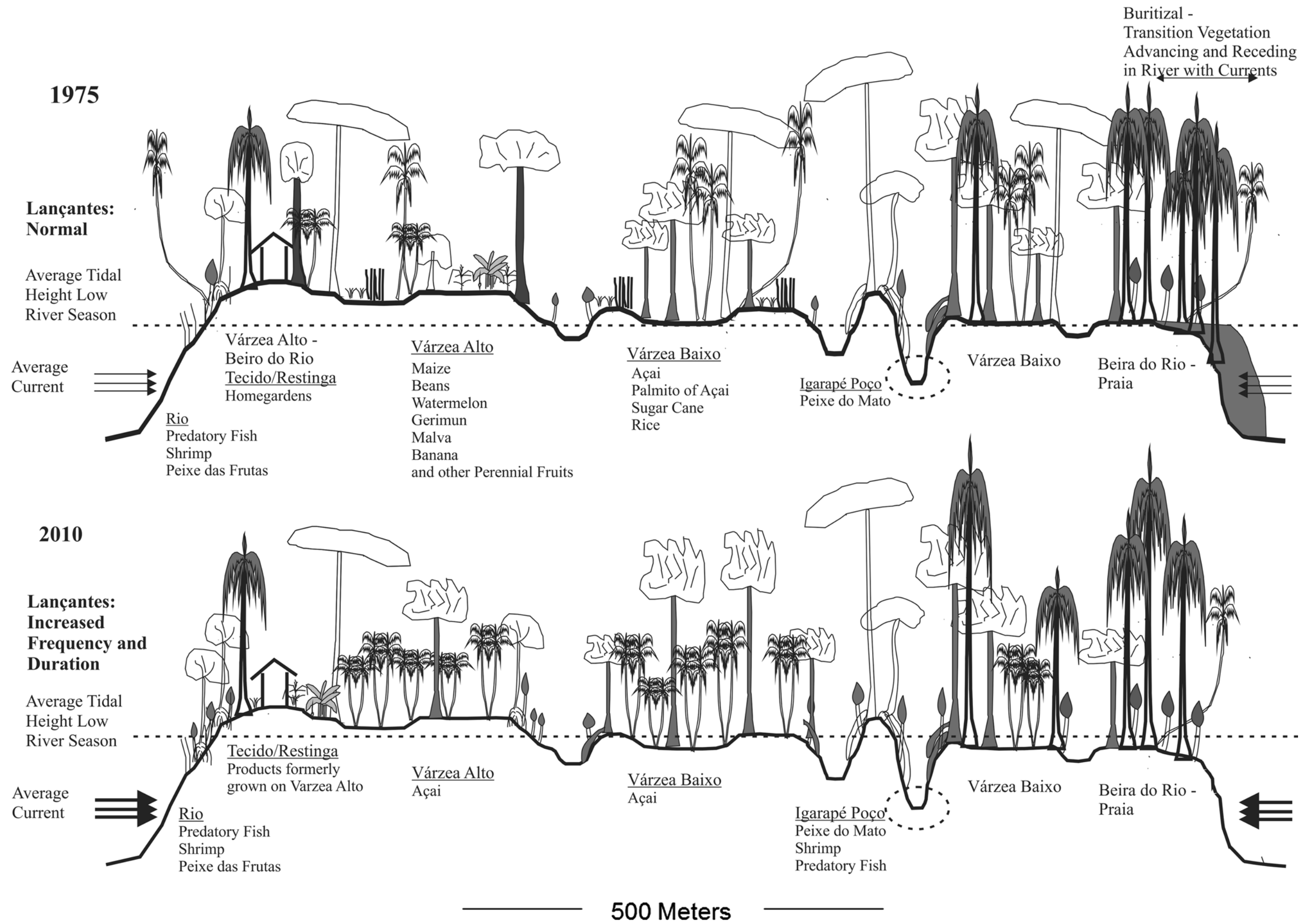

Fig. 4 Landscape-level responses

Local ecological knowledge to adapt community shorelines to *Lançantes* and lateral erosion

Typical rural communities in the Amazon delta are located on forested floodplains along secondary channels (*pequeno rio*) of the AD. Secondary channels always contain sufficient water for navigation by both larger motorized boats and canoes, even during low tides. These are fed by primary channels (*igarapés*) that drain the forested floodplains and that are not navigable by large motorized boats and parts of them (except for the *poços*) often dry during low tides. Homes are constructed on shorelines at intervals and 10–100 s of meters. The individual holdings extend into the floodplain forest and contain *igarapés* that fill during high tides and dry during low tides of the secondary rivers. Expert farmer-fishers manage shorelines of secondary channels where communities are located to (a) reduce erosion and (b) maintain habitat for subsistence and commercial aquatic species to feed and rest during *lançantes* (Fig. 5). Erosion management often occurs at the individual or household level, but it is a collective action problem as erosion in front of one household had external effects on other members of the community living in that micro-basin. Due to this, solutions by community leaders, experts and extension agents are often sought at the community level.

In recent decades, expert farmer-fishers of several communities across the delta are reporting increases in rates of shoreline erosion in secondary channels driven by increases in the strength of lateral currents. Rates of erosion are particularly high where shoreline vegetation is removed, particularly by large cattle ranchers. Removal of shoreline vegetation also reduces the extent of habitat and places of refuge for the fish and shrimp used for both commercial and subsistence ends. Expert farmer-fishers manage vegetation on secondary channels and streams to reduce erosion and provide place of refuge for fish and shrimp during *lançantes*. Expert farmer-fishers have identified and selected tree and shrub species that are more resistant to extreme floods.

Species that help reduce erosion from lateral currents include *Aninga* (*Montrichardia arborscens*) and *Aturiá* (*Machaerium lunatum*) (Table 1b). Tree species that help secure shorelines but perceived to provide habitat for

Table 1 Practices, actions and strategies used by expert farmer-fishers to reduce vulnerability and increase resilience to environmental shocks produced by sea-level rise and climate variability

a. Nine of the most common crops that were and are planted by farmer-fishers

Common and scientific name	Were on *Várzea Baixa*	Were on *Várzea Alta*	Are in levees/uplands
Corn (*Zea mays* L.)		×	×
Cassava (*Manihot sculenta*)		×	×
Sugarcane (*Saccharun officinarum*)	×		
Watermelon (*Citrulus* sp.)		×	×
Beans (*Phaseolus* sp.)		×	×
Sweet potatoes (*Ipomoea* sp.)		×	×
Squash (*Cucurbita moschata*)		×	×
Banana (*Musa* sp.)		×	×
Rice (*Oriza sativa*)	×		

b. Fourteen of the most common forest species managed to control current and lateral erosion and to provide resting and feeding grounds for fish, shrimp and game species

Common and scientific name	Current and erosion	Habitat
Açai (*Euterpe oleracea Mart.*)	×	×
Buriti (*Mauritia flexuosa* L.f)	×	×
Macacaúba *Platymiscium filipes Benth.*	×	
Ingá (*Inga* sp.)	×	×
Andiroba (*Carapa guianensis Aubl.*)	×	
Assacú (*Hura crepitans* L.)	×	
Pracaxi (*Pentaclethra macroloba Willd*)	×	
Pracúuba (*Mora paraensis Ducke*)	×	×
Pau mulato (*Callycophyllum spruceanum*)	×	
Arumá (*Vitex* sp.)		×
Taperabá (*Spondias nombin* L.)	×	×
Flecha (*Digitaria* sp.)		×
Taboa (*Bombusa* sp.)		×

shrimp and fish include *Pracuuba* (*Mora paraensis*), *Virola* (*Virola surinamensis*), *Andiroba* (*Carapa guianensis*) and *Jaranduba* (*Zygia ampla*). Some secondary channels and streams contain stands of buriti (Mauritia flexuosa) and wetlands of *taboa* (*Cyperus giganteus*) on the edges of *praia* (mudflats) (Table 2). These are forms of transition vegetation on the edge of floodplain forests whose extents are continuously expanding into and contracting away from the river with changes in lateral erosion strength reducing mudflats and sediment deposits expanding them (Fig. 5). Expert farmer-fishers maintain these buriti stands to reduce the dynamism of the floodplain by enriched planting and managing *açai* within the understory. *Taboa* wetlands are maintained for the production of artisanal products and reed mats. Both also provide habitat for *peixe do mato* during *lançantes*. Within the floodplains, there are patches of land of higher elevation that do not flood called *Aikas*. Today, *Aikas* largely contain patches of forest, fallow or upland *açai* stands. *Aikas* have become to play the role of safety net, particularly for the production of annual crops during the years of extreme high tidal floods.

Local ecological knowledge for managing structure and composition of trees species at individual holdings to adapt to changing flood patterns

Expert *Caboclo* floodplain farmers manage different types of tree species at specific locations across individual holdings to help maintain the production of both subsistence and commercial floodplain forest and river resources under a range of flood levels, current strength and salinity or sediment contents that are highly variable and unpredictable (Fig. 5). Much of the selected trees provide key functions in reducing current, erosion, water retention and other ecological services and goods (Table 2). The selected species help farmers to mitigate the damage on the environment produced by *lançantes*. In addition, the selected forest species help to reduce the loss of agroforestry, forest

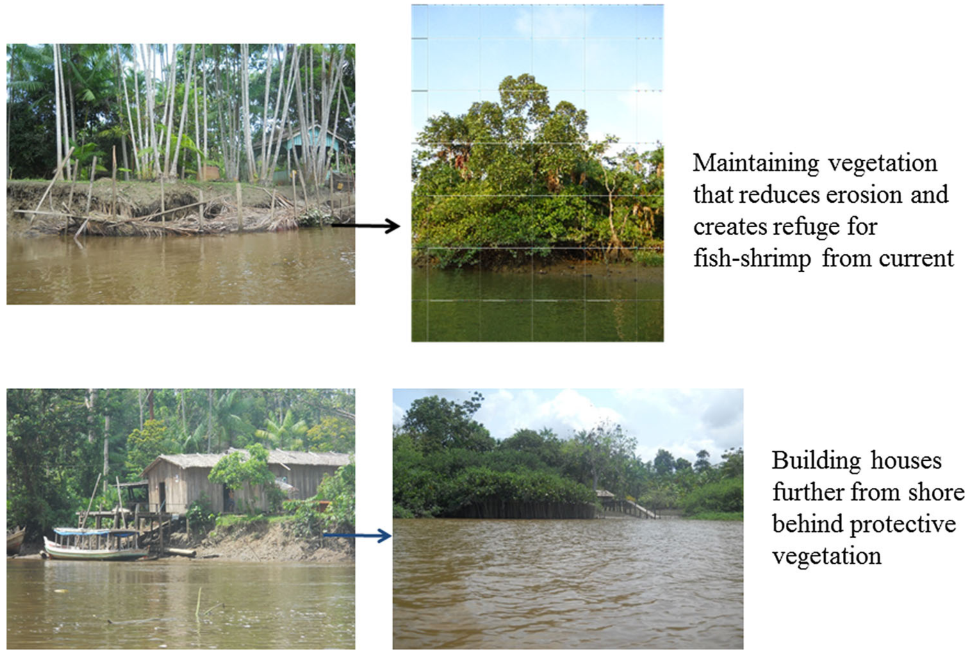

Fig. 5 Community-level responses

and agricultural products during extreme tidal flood events. Expert farmer-fishers have also mentioned that the selected trees, palms and shrubs are especially good for containing the intrusion of saltwater into streams and other small water bodies that they maintain in their landholdings.

Local ecological knowledge in managing micro-topography to adapt to changing flood patterns

Many informants reported to maintain stocks of *peixe do mato* (forest fish) in their landholdings by enriching their forests and fallows with fish attractor tree and shrub species. *Caboclo* maintain knowledge of types of trees, shrubs and palms whose roots maintain *poços* (wells) at different locations along *igarapés* to allow fishing and shrimping at either extremely low river levels (wells do not dry and trap fish and shrimp during low tides) or high river levels and when having wind and waves in secondary and main channels (by maintaining pool with calm waters and low current) (Fig. 6). Table 2 contains tree species that are often maintained along *igarapés* and the edges of *poços* to secure a *matapi* (traditional shrimp trap) for shrimping in the *poço* during extreme events or to secure a *jupati* ou *taboa* (traditional fish traps) used to trap *peixe do mato* in the *poço* during *lançantes*. A *taboa* is an old and less productive stem of the *açai* palm that is hollow and enough space for a fish to enter but not turn to leave from the same direction as entered. These stems are cut from multistem *açai* palm clumps to maintain young and more productive stems in the stand. The old stems can be placed in the *igarapé* and *peixe do mato*, and in particularly extreme events, fish of secondary channels enter the forest and seek refuge from current in them. At tides subside, the openings of these hollow stems are closed with hands removed from *igarapés*, trapping the fish within them. In the floodplain forest floor, there are often undulations and expert farmer-fishers call the highest point *torrão* and lowest point *curvão* with areas of only less than 10 m^2. In addition to *poços* in *igarapés*, matapis can also be placed in the low-level *curvão* in the floodplain forest floor to catch shrimp during *lançantes*. These undulations can be created naturally as sediments build around bases of tree stems or palms, or they can be managed by cutting herbaceous vegetation in dry season, particularly *Tiririca* (*Cyperus rotundus*), *Aninga* and *Açacurana* (*Zanthoxylum* sp.), and clumping in piles in *várzea baixa* which will then accumulate sediment in following high-water-level season and create a *torrão–curvão* undulation. Placing clumps of cut vegetation in the floodplain forest floor can create a *torrão* (small hill or rise) by trapping sediments high enough where farmer-fishers can plant less flood-tolerant crops in dry season. Again, the elevation variation in the floodplain is subtle (Fig. 2), but knowledge of how to use, manage and produce across them between seasons, lunar phases and extreme events is maintained by expert farmer-fishers.

Local ecological knowledge in adapting to changes in the timing, intensity and duration of saltwater intrusion into the delta

Some secondary channels are experiencing increased frequency of saltwater intrusion. Expert farmer-fishers cite the

Table 2 The most common tree, palms and shrub species that are managed by expert farmer-fishers for the production of fish and game species

Forest species	Forest fish	River fish	Animals
Andorinha	Traira, Jeju		
Tapereba			Guariba, Macacu de Cheiro
Buriti	Traira, Jeju	Sardinha, Pacu, Tambaqui, Camarão, Matupiri	Kutia
Seringueira	Aracu	Sardinha, Pacu, Tambaqui, Pirapatinga	
Açacu			Kutia, Veado, Anta
Virola	Aracu, Jandia, Anujá	Sardinha, Pacu, Tambaqui, Pirapatinga, Matupiri	Coati
Ingá-Cipó			Macacu Prego, Guariba, Quandu, Kutia, Mucura, Paca, Macacu de Cheiro, Anta, Coati
Andiroba	Aracu	Sardinha, Pacu, Camarão	Macacu Prego, Macacu de Cheiro
Macucu	Aracu, Traira	Tambaqui, Matupiri	Macacu Prego, Kutia, Paca, Veado, Macacu de Cheiro
Açai	Aracu, Jandia, Anujá, Puraquê	Camarão, Pirapatinga	Macacu Prego, Guariba, Quandu, Soiá, Macacu de Cheiro
Tento			Soiá, Paca, Veado
Murumuru	Aracu	Sardinha, Pacu	Kutia, Mucura, Macacu de Cheiro
Pracuuba		Camarão	
Jatauba	Aracu	Sardinha, Pacu, Tambaqui, Pirapatinga	
Cupuaçurana			Macacu Prego, Macacu de Cheiro
Pacapeá			Veado
Quaxinguba	Aracu	Sardinha, Tambaqui, Pirapatinga	Macacu Prego, Kutia, Paca, Veado, Macacu de Cheiro
Genipapo	Aracu	Sardinha, Tambaqui	Macacu Prego, Guariba, Kutia, Veado, Macacu de Cheiro
Urucuri			Macacu Prego, Macacu de Cheiro
Ingá-Cururu			Macacu Prego, Guariba, Quandu, Kutia, Mucura, Paca, Macacu de Cheiro, Anta, Coati

presence of saltwater species and increased abundance of other species tolerant to both fresh- and low saltwater conditions. Often these species have higher commercial value, presenting an income opportunity from sea-level rise or drought in upstream meso-river basins to estuarine farmer-fishers. A crab species locally known as *Siri* (*Callinectes bocourti*) is one saltwater species that arrived in several communities with an extreme saltwater intrusion event that occurred in the delta in October 2012, after more than a decade of absence. Similarly, an increase in the catch of three highly valuable fish species (*tainha*, *sarda* and *mapara*[1]) was reported during October 2012. Expert farmer-fishers took children and other young relatives to beach to show how to capture, transferring knowledge of how to benefit from this rare extreme event. *Açai* is produced in areas of the AD that experience a pulse of saltwater twice daily with high tides. It is produced nearer headwaters of secondary streams that contain primarily freshwater. The salinity threshold for açai production is still unknown.

Discussion and conclusion

Research on ILK and its function in mitigation and adaptation to changing flood patterns in deltas is very limited and fragmented. Our study makes an important contribution in bringing the perspective of seeing ILK as the practices and strategies of vulnerable populations, such as the farmer-fishers, to deal with the constraints and opportunities brought by sea-level rise and market booms, for example. It is undeniable that ILK is a critical resource for farmer-fishers to build resilience, to reduce vulnerability and to adapt social–ecological systems to sustainably manage natural resources, conserve or intensify production in the face of increasing in frequency and intensity of extreme tidal floods and other shocks produced by changes in flooding patterns caused by

[1] Noted to be adapted to both high and low saltwater conditions, they are present and at greater abundance in estuarine fishing in years with lower river discharge linked to lower rainfall somewhere upstream or locally in delta, that is, also when the influence of seawater is greater in delta.

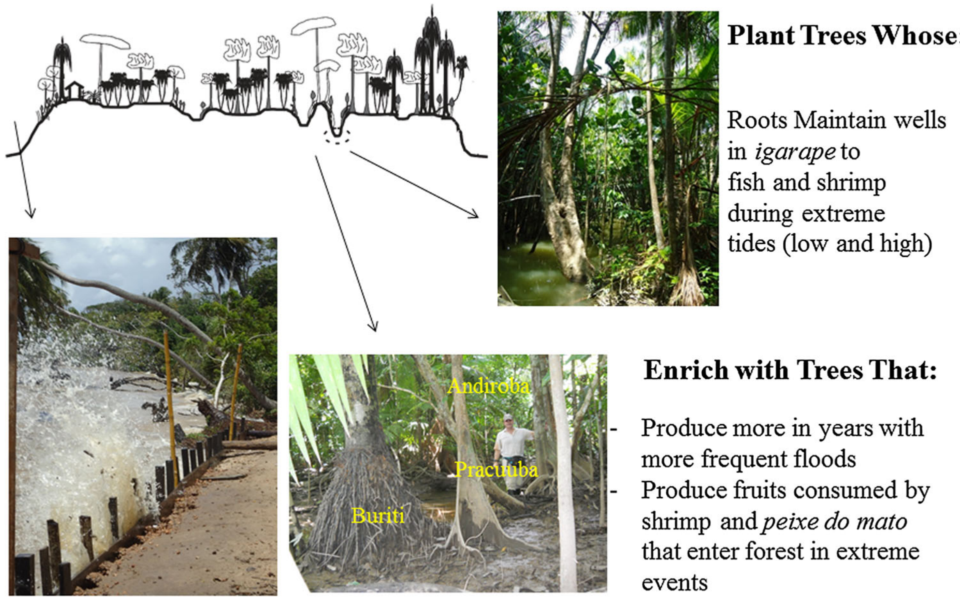

Fig. 6 Species-level adaptation

sea-level rise and other climatic and non-climatic factors. Farmer-fishers' "tradition of change" (Pinedo-Vasquez et al. 2002) greatly facilitates the generation, innovation and assimilation of ILK to engage in a process of incremental adaptation to these shocks (Pinedo-Vasquez et al. 2002).

In this paper, we documented and analyzed a case that illustrates the multiple functions and roles of ILK in helping local populations to adapt and mitigate to the current socioenvironmental changes and challenges. The case study shows how ILK is helping floodplain farmer-fishers in the Amazon delta to adapt their livelihood to both market opportunities and challenges from extreme flood events (*lançantes*), driven by a combination of sea-level rise and changing patterns of upstream river discharge.

At the landscape level, expert farmer-fishers are using ILK of impacts of *lançantes* to adapt types of land uses to maintain, develop or expand in the landscape mosaic and their location across micro-topographies. At the community level, expert farmer-fishers are applying ILK to reduce shoreline erosion and maintain place for so-called fish of the forest and shrimp to rest during *lançantes*. At the household level, they are managing the spatial configuration of flood-tolerant crop and tree species to continue production of subsistence or commercial products under a range of extreme flood level, current and saline conditions. Expert farmer-fishers use ILK to manage agrobiodiversity along a dynamic agriculture, forest and fishing continuum. We found that systems for resource production along this dynamic continuum lead to the establishment of mosaic and patchy production landscapes that also provide ecosystems services and goods at the terrestrial/aquatic interface (e.g., maintaining tree species along streams that maintain habitat for fish to survive extreme drought events, secure stream banks during extreme flood events and produce fruits on which fish and shrimp feed). They maintain a combination of intensive crop and diverse options to support subsistence and commercial activities.

The vast knowledge of expert farmer-fishers of the functioning of Amazon delta landscapes as well as ecosystems and their emphasis on managing mosaic production landscapes—the interactions between the aquatic, floodplain and upland ecosystems that compose those landscapes—helps to maintain multiple land-/resource-use options and income sources to adapt to market and environmental shocks (Pinedo-Vasquez et al. 2002; Vogt et al. 2015). They have knowledge of how to manipulate communities of indigenous and exotic species in different compositions within a land-use type (Brondízio 2008; Pinedo-Vasquez and Sears 2011). They also have knowledge of how to employ and manage a diversity of land-use types in different configurations.

These results suggest that expert farmer-fishers maintain knowledge of how to reintroduce and reconfigure individual products, communities of products and land-use types across the ecologies contained in estuarine landscapes. They maintain knowledge of types of tree species and location to manage them across the landscape to maintain fruit–fish food chain interactions functioning under a broad range of flood and environmental conditions. They also maintain knowledge of managing physical structure of *igarapés* as well as vegetation structure and composition along secondary rivers to ensure a place to fish floodplain forest species and shrimp under a broad range of hydro-ecological conditions.

ILK shaping the process of incremental adaptation (PIA) to increasing external shocks, from both climate and market fluctuations, should be considered during the design of mitigation or adaptation interventions for enhancing the sustainability of the Amazon delta. Farmer-fishers in the Amazon delta did not adapt to the perceived increase in *lançantes* by simply replacing less flood-tolerant crops with ones with greater flood tolerance, nor did they simply replace a less valuable crop with *açai* palms that is currently of high value; rather, they developed and tested management patterns and calendars for a diversity of products incrementally in more or less conscious ways.

Climate change projections and impact on coastal and lowland flooding patterns presented in the recent IPCC AR5 report (2014) are often for next 50–100 years, or across 2–4 generations. Preferences on food consumption, livelihood portfolio and amount of that portfolio dedicated to farming and fishing will change, and with it, the landscape use, management and agrobiodiversity will change. That is, adaptation of agrodiversity and agrobiodiversity in response to market signals and cultural changes across generations occurs at a higher rate than adaptation to changing flood patterns from climate changes. ILK is valuable in helping locals evaluate how to more sustainably manage a landscape for a new "miracle cash crop," often promoted in regional development agendas, by considering the gradual shifts in flood patterns observed. Drawing on ILK, they pursue new market opportunities in the context of climate changes incrementally, developing systems of production (e.g., multifunctional landscapes), rather than rapid shifts between monocrop plantations, to maintain flexibility and options to future shocks. National planners engaged in developing policies to increase sectoral resource production in the Amazon delta (crops, timber and fish) could reduce incentives to denude landscapes to plantations or aquaculture ponds as is underway elsewhere in it Freitas et al. (2015). Rather, they could create incentives for intensification and simultaneously the conservation of forest and river resources through attention to diversity of land use, its spatial pattern and particular functional composition, drawing on ILK of expert farmer-fishers presented here. This would help reduce vulnerability and build resilience of SESs, at multiple scales (Brondízio et al. 2009; Mace et al. 2012), to shifts in hydro-climate and market pressures.

Disturbances to SESs in the Amazon delta, from a changing climate as sea-level rise and changes in the rainfall patterns of the Amazon basin, will only increase in the future but with a growing contribution from non-climatic factors as the several dams under construction and land-use changes. Disturbances to SESs from globalizing markets will also increase with the installation of more efficient communications, more efficient transportation for people and goods, and more stable and widely available electricity over the last decade. The ILK accumulated by local farmer-fishers over generations to long-term exposure to these challenges and opportunities in the Amazon delta is valuable for both designing and implementing mitigation and adaptation programs aimed at enhancing sustainability of deltas to secure income, food and land of local populations into the future.

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