

# Evolutionary social and biogeophysical changes in the Amazon, Ganges–Brahmaputra–Meghna and Mekong deltas

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**Abstract** Policy-making in social-ecological systems increasingly looks to iterative, evolutionary approaches that can address the inherent complexity of interactions between human wellbeing, provision of goods, and the maintenance of ecosystem services. Here, we show how the analysis of available time-series in tropical delta regions over past decades can provide important insight into the social-ecological system dynamics in deltaic regions. The paper provides an exploratory analysis of the recent changes that have occurred in the major elements of three tropical deltaic social-ecological systems, such as demography, economy, health, climate, food, and water. Time-series data from official statistics, monitoring programmes, and Earth observation data are analysed to explore possible trends, slow and fast variables, and observed drivers of change in the Amazon, Ganges–Brahmaputra–Meghna and Mekong deltas. In the Ganges–Brahmaputra–Meghna delta zone, increasing gross domestic product and per capita income levels since the 1980s mirror rising levels of food

and inland fish production. In contrast, non-food ecosystem services, such as water availability, water quality, and land stability appear to be deteriorating. In the Amazon delta, natural and anthropogenic perturbations are continuously degrading key ecosystem services, such as carbon storage in biomass and soils, the regulation of water balance, and the modulation of regional climate patterns. In the Mekong delta, rapid economic development, changing land-use practices, and salinity intrusion are progressively putting more pressure on the delivery of important provisioning services, such as rice and inland aquaculture production, which are key sources of staple food, farm incomes, and export revenue. Observed changes in many key indicators of ecosystem services point to a changing dynamic state and increased probability of systemic threshold transformations in the near future.

**Keywords** Socio-ecological systems · Deltas · Amazon · Ganges–Brahmaputra–Meghna · Mekong · Dynamic principal component analysis

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## Introduction

Deltas are economic and environmental hot spots, home to a significant proportion (>500 million) of the world population (Ericson et al. 2006) and sheltering rich and bio-diverse ecosystems (Bianchi and Allison 2009). The rivers that flow through the deltas are an important source of fresh water and nutrients, and create the ideal environmental conditions for food production (e.g., agriculture, fish farming, and aquaculture production) and the support of biodiversity (Syvitski 2008; Seck et al. 2012; Kuenzer and Knauer 2013; Wong et al. 2014). The increasing pace of human development in coastal deltas over the past five

decades has strained environmental resources and produced extensive economic and socio-cultural changes in deltas (Duval-Diop and Grimes 2005; Kuenzer and Renaud 2012; Ernoul and Wardell-Johnson 2013). Deltaic regions all over the world are changing rapidly due to human actions (e.g., pollution of water and sediment flow reduction/increase), climatic variability (e.g., droughts and sea-level rise), and resource exploitation (e.g., mining, groundwater exploration and hydrocarbon extraction) (Kuenzer and Renaud 2012; Holgate et al. 2013; Restrepo 2013; Ibanez et al. 2014; de Araujo Barbosa et al. 2016).

Changes in average weather conditions in deltaic regions strongly influence important physical and chemical properties within the ecosystems (Tsai et al. 2005; Morrison et al. 2006; Larsen et al. 2011). Extreme drought and rainfall peaks affect sediment shedding from the hinterland, water salinity, abundance of photosynthetic organisms, turbidity load, flood level, nutrient recycling, and biological productivity, with strong potential effects on supporting, provisioning, cultural, and regulatory ecosystem services (Dearing and Jones 2003; Naidoo et al. 2008; Maya et al. 2011; Hinderer 2012; de Araujo Barbosa et al. 2015). Thus, deterioration of deltas will cause reduction of important ecosystem services and increase the susceptibility of these areas to extreme climatic events (Nijssen et al. 2001; Aerts et al. 2006; Frappart et al. 2006; McMullen et al. 2009; van Slobbe et al. 2013; Szabo et al. 2015b).

The majority of tropical deltas in developing economies may be defined as complex, coupled social-ecological systems, supporting high population densities with particular vulnerabilities to sea-level change and upstream river management (Stanley and Hait 2000; Llovel et al. 2010; Walsh et al. 2014). Evaluating the specific nature of current vulnerabilities and how these may change in the near future requires consideration of the recent social-ecological dynamics (Duval-Diop and Grimes 2005; Dearing et al. 2012; Kuenzer and Renaud 2012). Here, we examine how social and ecological elements may have interacted over time to give rise to the complex dynamics that characterise the modern social-ecological systems present in the Amazon, Ganges–Brahmaputra–Meghna (GBM) and Mekong deltas (Fig. 1).

## Research objectives

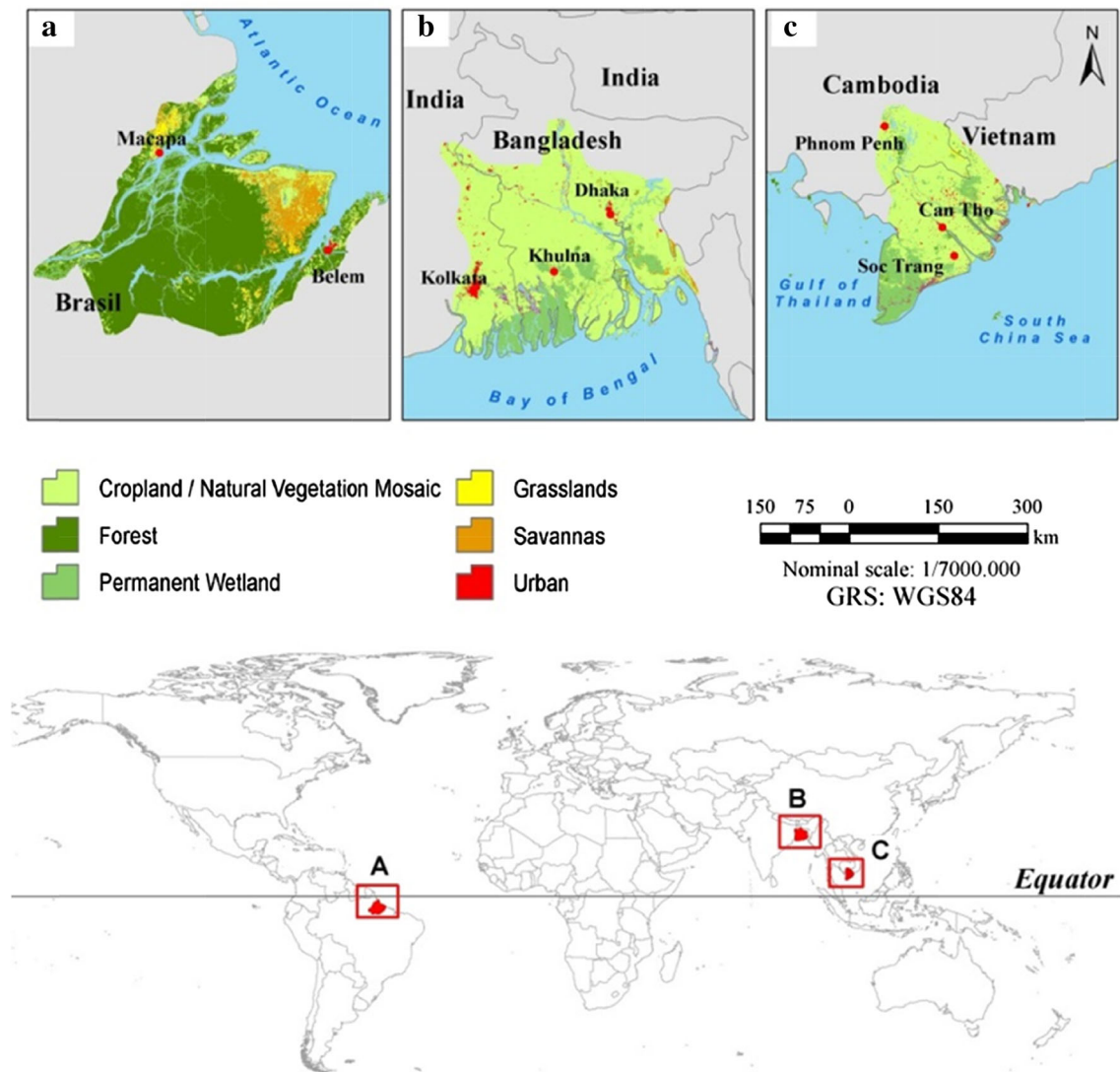
Multi-decadal trends for social, economic, ecological conditions and external drivers provide an evolutionary perspective that enable us to explore the recent changes in social-ecological dynamics, trade-offs, driver-responses, multivariate dynamics, and regime shifts (Hossain et al. 2015a, b; Zhang et al. 2015), also giving insight into what

might constitute the conditions for safe and just operating spaces (Dearing et al. 2014). Ideally, an evolutionary perspective considers a large set of highly interconnected variables, with high spatial and temporal resolution, that allows a detailed analysis of relationships over an extended multi-decadal period (Costanza et al. 2012; Dearing et al. 2014; Dippner and Kroncke 2015). Unfortunately, many regions of the world, including tropical deltas, are deficient in key records for major social and ecological variables. Therefore, here, we adopt an initial analysis of limited data to compare and contrast general properties of three major world deltas. We address the following general questions: (1) What are the observable dynamics, including key drivers and feedback loops, that are steering the system toward its current equilibrium or disequilibrium state? (2) How are these dynamics affected by human intervention and ongoing environmental change? (3) Are there any common human development trajectories, including population change, ecological deterioration, rates of poverty, and indicators of human wellbeing?

## Study sites

### Amazon

The Amazon delta (Fig. 1a) is one of the last frontiers for the land development and agricultural production in Brazil (UNEP 2004; Viers et al. 2005; Lorena and Lambin 2009; Garrett et al. 2013). The human populations living in the Amazon delta are highly dependent on the local extraction of natural resources (Ludewigs et al. 2009; Guedes et al. 2012), and the densely inhabited areas now show declines in the abundance of fish and game, water quality, and in the quality of soils for smallholding agricultural production (Almeida et al. 2003; Brabo et al. 2003). Natural and anthropogenic perturbations in the Amazon delta region are reported to be degrading its capacity to maintain carbon storage in biomass and soils, rainfall regimes, river flow, nutrient cycling, and the modulation of regional climate patterns (Boerner et al. 2007; Foley et al. 2007; Klemick 2011; de Araujo Barbosa and Atkinson 2013). The delta is also predicted under climate change scenarios to experience a decrease in rainfall, and it is unclear how this will impact social and ecological systems developing in the delta (Nepstad et al. 2011; Vergara and Scholz 2011; Tao et al. 2013). In the Amazon River basin as a whole, the major mechanisms of economic development have modified the landscape continuously, starting in the 1950s, and leading to what we now see as widespread environmental degradation. Recent studies argue that deforestation in Amazonia decreased by 77 % since 2004 and stabilized after 2009, as a consequence of forest policy interventions,



**Fig. 1** a–c Spatial extent of the three deltas, namely the Amazon, GBM, and Mekong, defined as described in “[Conceptual framework](#).” This figure contextualises the three deltas, geographic

locations across the globe, and main land cover classes as observed from the Moderate Resolution Imaging Spectroradiometer (MODIS) in 2013, at 1-km spatial resolution

private sector initiative, and market conditions (Godar et al. 2014). Therefore, the long lasting deforestation in the region may have passed a threshold and is now moving toward recovery, which may be an indicative of forest transition. However, this might not be the case in the Amazon estuary, as some of the main factors influencing deforestation; there are still challenging Brazil’s efforts in preserving its tropical forests (Godar et al. 2012; de Araujo Barbosa et al. 2014a, 2016).

### Ganges–Brahmaputra–Meghna

The GBM delta (Fig. 1b) is notable for an extremely high population density, natural mangrove forest ecosystems (the Sundarbans), and a vast complex of intertidal and

estuarine areas that provide nursery grounds for many species of fish and invertebrates across multiple political boundaries (Babel and Wahid 2011; Hossain et al. 2012, 2013; Siddique-E-Akbor et al. 2014). This delta has been experiencing a rapid urban growth, which has resulted in widespread social and economic inequality across different spatial scales (Brichieri-Colombi 2004; Sharma et al. 2010; Babel and Wahid 2011; Webster and Jian 2011). The recurrence of flood events in the region has long been viewed as a necessary trade-off against the relative beneficial conditions available for agriculture and food production (Asada and Matsumoto 2009; Islam et al. 2010a; Sharma et al. 2010; Ruane et al. 2013). Nonetheless, during the dry season, the GBM delta experiences the tidal water movement of more than 100-km inland, and a relative sea-

level rise exceeding the global average that reflects the impact of land subsidence, all of which contributes to an increasing salinity problem (Hanebuth et al. 2013; Pethick and Orford 2013; Rogers et al. 2013; Shearman et al. 2013; Gupta et al. 2014; Higgins et al. 2014). Furthermore, infrastructure developments, such as the Farakka barrage on the main Ganges channel, have been influencing the regime of water flow in the region, with negative effects on water availability (Hossain et al. 2015a). In the long run, climate threats are likely to include changing distribution of river floods, warming temperatures, and changes in rainfall regime, which in turn will maximize current vulnerability to climate extremes, posing substantial challenges to sustainability in a region undergoing intense social changes (Chakraborty 2004; Markandya and Murty 2004; Asada and Matsumoto 2009; Cook and Lane 2010; Islam et al. 2010b; Khan 2012; Varis et al. 2012; Gain and Giupponi 2014).

## Mekong

The Mekong river delta (Fig. 1c) is the world's third largest delta, and it is formed by a large trans-boundary river system travelling through China, Myanmar, Lao People's Democratic Republic (Laos) Kingdom of Thailand, Cambodia, and Vietnam (Tin et al. 2001; Kotera et al. 2008; Armitage et al. 2015; Givental and Meredith 2016). It is a territory where regional meteorological and hydrological regimes support diverse social and economic activities, as well as a diverse and productive natural environment. The delta provides 50 % of Vietnam's rice production and 80 % of the aquaculture production (Nguyen 2011; Gummert 2013). Rice-cropping systems in the Mekong delta have shown signs of stress in response to an increasing number of severe floods, droughts, storms, and tropical cyclones, followed by growing population demand for food production (Lusterio 2009; Nguyen 2011; Berg and Tam 2012; Huysveld et al. 2013; Son et al. 2013; Ahmed et al. 2014). Food production systems are rapidly expanding into the flood and salinity-intrusion areas (Tuong et al. 2003; Kotera et al. 2014), as a result of engineering works aimed at protecting populations and infrastructure from storms, rice-cropping systems, and shrimp farms from saltwater intrusion (Berg et al. 2012; Nguyen et al. 2014). The construction of several large-scale dams, and major channel-bed mining activities (Piman et al. 2013), has now been reported as the cause of an imbalance between flow and sediment entrainment conditions (Xue et al. 2011), affecting human livelihoods and the ecological equilibrium in the delta. Predictions of exposure to the effects of climate change for the Mekong delta include a rising sea level, rising temperatures, increased variability in rainfall regime, and higher frequency of extreme events (Kotera et al. 2008;

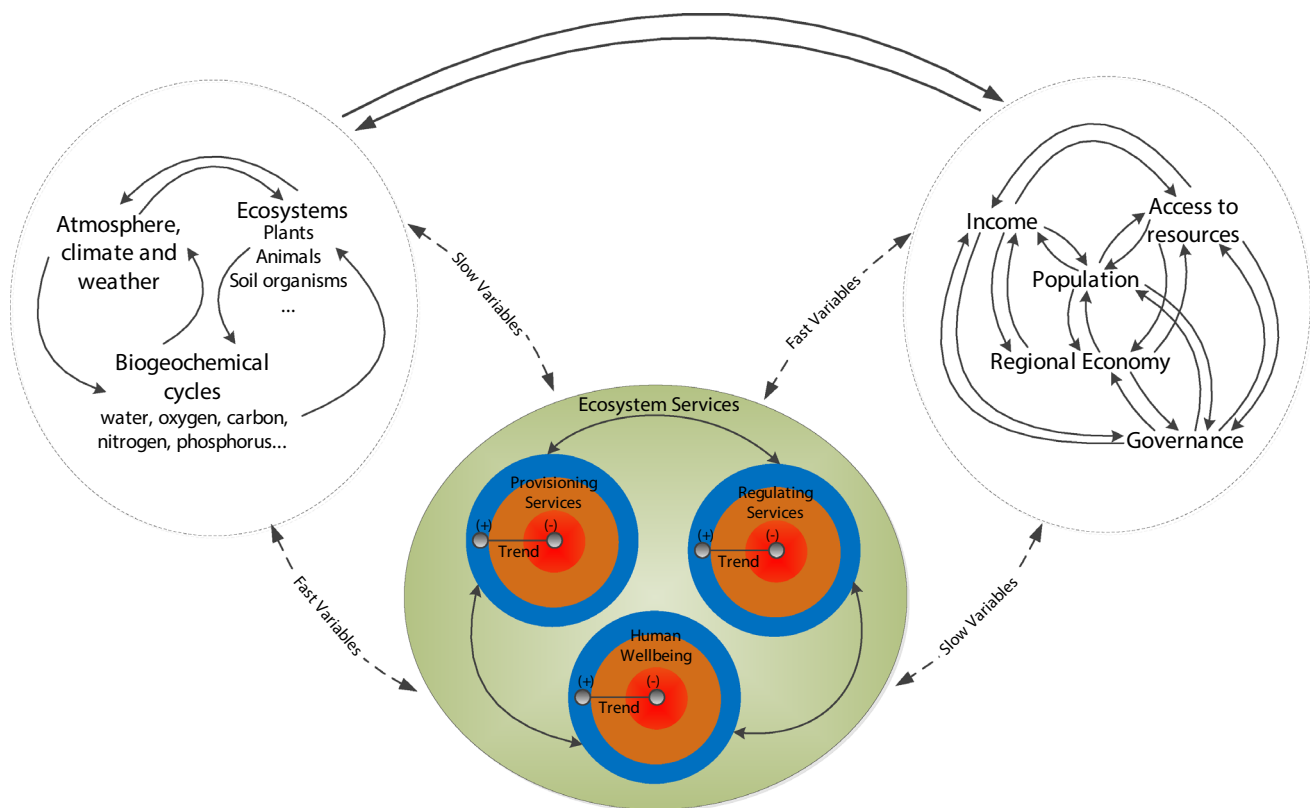
Haruyama and Ito 2009; Nguyen et al. 2014). These changes are likely to have strong negative impacts on the production of food and human wellbeing (Nguyen 2011; Berg et al. 2012; Berg and Tam 2012; Kotera et al. 2014). The combined effect of economic development, agricultural production practices, and change in consumption patterns is likely to increase the relative vulnerability of this delta to social and ecological changes (Few and Pham 2010; Coclanis and Stewart 2011; Dun 2011; Kuenzer and Renaud 2012; Quyet et al. 2012; Piman et al. 2013; Smith et al. 2013; Dang et al. 2014; Vu et al. 2014).

## Methods and techniques

### Conceptual framework

The framework used in this study (Fig. 2) serves to provide a rationale for the dynamic and integrated approach used in this work to investigate social and biogeophysical changes occurring in the three tropical deltas. This framework is based on a set of indicators, reflecting the current and past state of provisioning and regulating ecosystem services. These two ecosystem service categories are considered to be of key importance, having major direct and indirect impacts on human wellbeing. For example, deforestation can affect people's livelihoods by eliminating access to provisioning services and leading to changes of landscape, which can in turn increase the risk of natural hazards (Alcamo et al. 2003). Indirect effects can operate through a number of biophysical, socio-economic, and political processes. More specifically, soil salinity can negatively affect food security and health outcomes by impacting water quality (Alcamo et al. 2003; Szabo et al. 2015a). Lack of safe drinking water may lead to communal tensions and violence (Meier et al. 2007; Fjelde and von Uexkull 2012), though the impact of increasing/decreasing ecosystem services on human wellbeing indicators seems to have produced conflicting findings over the decades (Millennium Ecosystem Assessment 2005).

Provisioning services encompass crops, livestock, freshwater, fisheries, and aquaculture (Carpenter et al. 2009), and are thus critical to reducing the risk of food insecurity and enhancing broader wellbeing. Regulating services, which in this study, mainly involve regulation of water, and air quality can affect human wellbeing in a number of ways. For example, failure to prevent air pollution can lead to ill health, which is increasingly a challenge in the context of rapid urban growth in many delta regions. Other examples include development of adequate infrastructure, such as buffering zones along the coasts through the plantations of mangroves and beach forests (Butler and Oluoch-Kosura 2006). Regulating services are



**Fig. 2** Systemic dynamic relationships between environmental and human dimensions affecting the changes on ecosystem services and human wellbeing through time

intrinsically linked to provisioning ecosystem services through a two-way relationship. For example, deteriorating quality of water and food may trigger new environmental policies with new regulations that constrain land-use practices. Finally, external drivers, include, on the one hand, human drivers, (e.g., national governance and international trade) and, on the other hand, environmental factors (e.g., rising temperatures and sea levels). All these factors affect boundary conditions and the internal dynamics of ecosystem services and wellbeing interactions. Ultimately, all these dynamics have an impact on the wider socio-economic development of the delta regions and beyond. The variables chosen for our analysis were selected to provide clear insights into the hypothesised relationships and complex dynamics of society and nature under an ecosystem services framework (Costanza et al. 2012; Dearing et al. 2014).

### Delta definitions

For the purposes of data collection, we have defined the spatial extent of each delta primarily by the area downstream of the first distributary, as mapped by the Shuttle Radar Topography Mission (SRTM). For the GBM, the altitude of the first distributary (the Hoogli river) at the

Farraka Barrage is about 18–20 m asl. Using an SRTM contour map, the 18–20-m asl contour includes the main areas of frequent flooding along the Brahmaputra river and in the Sylhet basin. This definition is represented by over 45 districts in whole division areas of Khulna, Barisal, Dhaka, and Sylhet, but also a large part of Chittagong division in Bangladesh, and the districts of Nadia, South 24-Parganas, and North 24-Parganas in India. For the Mekong, the first distributary point at Phnom Penh lies at about 7–9 m asl. The Mekong SRTM contour map shows that this would delineate a delta mainly in Vietnam with a small part in Cambodia, and excludes Ho Chi Min City (Vietnam) and the Phnom Penh Municipality (Cambodia). The Amazon is less a delta and more an estuary. Therefore, we follow Ericson et al. (2006) use of a 5-km buffer from coastline that intersects roughly with the first distributary. This definition maps well to the distribution of municipal districts.

### Data collection and analysis

Data availability for deltas is a challenging issue, because official statistics tend to map onto national or regional administrative areas rather than physiographically-defined areas. Here, we have compiled data from official regional

**Table 1** Data collected for the three deltas grouped by data category (physical drivers, provisioning services, and human wellbeing), data temporal coverage for the Amazon (AM), Ganges–Brahmaputra–Meghna (GBM), and Mekong (MK), with respective data sources and geographical locations, where the data were collected

Category	Data	Temporal coverage			Source	Geographical location		
		AM	GBM	MK		AM	GBM	MK
Physical drivers	Temperature	1960–2013	1961–2013	1984–2013	Brazilian Meteorological Service (INMET 2013); Bangladesh Meteorological Department (BMD 2014); Vietnam Hydro-Meteorological Service (NHMS 2014); Mekong River Commission (MRC 2014)	Belem, Macapa, Altamira, Soure, Cameta and Breves municipalities	Khulna, Barisal and Patukhali districts	Soc Trang, Can Tho, An Giang and Vinh Long provinces
	Rainfall	1960–2013	1950–2013	1984–2013				
	Relative air humidity	1960–2013	–	1984–2013				
	Water level	1968–2013	1979–2013	1988–2013				
Regulating services	Water level (–desirable/+undesirable)	1964–2012	–	1988–2012	Brazilian National Water Agency (ANA 2014); Brazil's National Institute For Space Research (INPE 2014); de Araujo Barbosa et al. (2016); Bangladesh Water Development Board; Bangladesh meteorological department; Islam et al. (2011); Vietnamese Hydro-Meteorological Service (NHMS 2014); Mekong River Commission (MRC 2014)	Amazon River (Macapa and Almeirim) Amazon estuary	Khulna, Barisal and Patukhali districts	Can Tho, An Giang and Vinh Long provinces
	Water discharge (–desirable/+undesirable)	1898–2013	1978–2008	–				
	Water quality (salinity) (high salinity undesirable)	–	1964–2008	1984–2013				
	Water quality (water pH) (low pH undesirable)	1952–2013	–	–				
Provisioning services	Forest cover (high forest cover desirable)	1982–2013	1985–2014	–				
	Sediment concentration (–desirable/+undesirable)	–	–	1986–2010				
	Shrimp production	–	1991–2007	–	Brazilian Institute of Geography and Statistics; Brazilian Institute for Applied Economic Research; Bangladesh Bureau of Statistics; General Statistics Office of Vietnam	Amapa and Para states	Khulna, Barisal and Patukhali districts	Long An, Tien Giang, Ben Tre, Tra Vinh, Vinh Long, Dong Thap, An Giang, Kien Giang, Can Tho, Hau Giang, Soc Trang, Bac Lieu, and Ca Mau provinces
	Fish production	–	1950–2010	1989–2013				
Human Wellbeing	Aquaculture production	–	–	1989–2013				
	Rice production	1944–2013	1961–2013	1989–2013				
	Cassava production	1944–2013	–	–				
	Animal production	1990–2013	–	1989–2013				
Human Wellbeing	Agricultural production	1944–2013	–	–				
	Total population	1960–2013	1950–2014	1989–2013	Brazilian Institute of Geography and Statistics (IBGE 2014); Bangladesh Bureau of Statistics (BBS 2013); General Statistics Office of Vietnam (GSO 2014); Food and Agriculture Organization of the United Nations (2014)	Amapa and Para states, Brazil	Khulna, Barisal and Patukhali districts, Bangladesh	Can Tho, An Giang and Vinh Long provinces, Vietnam
	Real inflation-adjusted GDP	1960–2013	1960–2014	1989–2013				
	Employment	1990–2013	1990–2014	1989–2013				
Human Wellbeing	Food security	1990–2013	1990–2013	1990–2013				

sources (with two variables at the country level feeding into food and nutrition) to create realistic regional time-series of major physical drivers, regulating and provisioning ecosystem services, and human wellbeing over multiple decades (Table 1). We use  $z$  scores to standardize our variables, allowing us to position variables, relative to other variables, and therefore establish relevant comparisons between observed social and ecological states and transitions along the time-series. For a total set of variable observations, dimensionless  $z$  scores are obtained by subtracting the variable mean from an individual raw score, and dividing by the standard deviation (Eq. 1).

$$z = \frac{(x - \mu)}{\sigma} \quad (1)$$

In Eq. 1,  $z$  refers to  $z$  score,  $x$  is the value of a given variable,  $\mu$  is the mean of the total set of observations for a given variable, and  $\sigma$  is the standard deviation. Data for provisioning services and drivers are plotted with  $y$  axes, showing positive  $z$  scores for high levels of each variable (e.g., high grain yields). Data for regulating services are plotted on reversed  $y$  axes, showing positive  $z$  scores for desirable ecological quantities and negative  $z$  scores for undesirable (e.g., low salinity), as determined locally (Table 1).

### Dynamic principal component analysis

Connectivity is increasingly viewed as an important property of complex systems, especially with regard to the higher levels of connectivity and homogenisation observed in unstable systems (Scheffer et al. 2012). Here, we use dynamic or sequential principal component analysis (PCA) to provide a crude measure of the multi-decadal changes in connectivity (Billio et al. 2010; Zheng et al. 2012; Zhang et al. 2015) between provisioning and regulating ecosystem services in the three deltas. We applied this approach to ecosystem service time-series indices since the 1960–1970s (1990s in the case of the Mekong delta), calculating covariance using a 10 years moving window. PCA axis 1 (the first eigenvalue) captures  $\geq 50$  % of the variation for the combined data sets in all three deltas.

### Key system variables

#### *Physical drivers*

In each delta, the selected variables define the observed changes affecting the physical environment that will, in turn, feedback into key ecosystem services (Nelson et al. 2006; Carpenter et al. 2011; Potschin and Haines-Young 2011). For example, increasing variability in average values of temperature, rainfall and relative air humidity

directly affect ecosystem conditions and services, and are key variables in sustaining people's livelihoods across all levels of society (O'reilly et al. 2003; Walker et al. 2008; Sullivan and Huntingford 2009; Harborne 2013; Sara et al. 2014). In deltas and estuaries, water level plays an important role in preserving biodiversity, enabling agriculture, climate buffering, and flood control. In addition, the effective monitoring of water levels through time provides important insights into current and past management (e.g., prioritization of hydropower over other ecosystem services) (Day et al. 2008; Omer 2009; Taguchi and Nakata 2009; Notter et al. 2012). Nevertheless, the situation observed in these deltas over the decades is only partially driven by physical drivers, and human activities are of critical importance. Therefore, an integrated approach to the problem of environmental change, its short and long-term effects on ecosystem services, is a key to achieving environmental sustainability in deltaic regions (Dearing et al. 2014; Darby et al. 2015; Mononen et al. 2016).

#### *Regulating services*

The variables chosen here represent the multiple regulating ecosystem services found in deltaic regions (Withers and Jarvie 2008; Barbier et al. 2011; de Araujo Barbosa et al. 2014b; Iacob et al. 2014; Yoo et al. 2014; Gonzalez-Esquivel et al. 2015). These variables provide the valuable information about the major trends in important regulating services (e.g., climate regulation, water regulation, nutrient cycling, erosion control, flood control, and others) (Feld et al. 2009; King and Brown 2010; Ma and Swinton 2011; Nedkov and Burkhard 2012; O'Leary and Wantzen 2012) and provide the basis for exploring interactions with drivers and social conditions. Over time, the interactions between salinity (water quality), water pH (water quality), sediment concentration (erosion control, water quality), and forest cover (climate regulation, erosion control) define the evolution of many common biophysical effects in the three deltas (de Araújo Barbosa et al. 2010; Sabater and Tockner 2010; Basher 2013; Clarkson et al. 2013; Turner et al. 2013; Grimaldi et al. 2014; Sturck et al. 2014; Ter-rado et al. 2014; Beier et al. 2015; Fezzi et al. 2015; Harmackova and Vackar 2015). These effects influence ecosystem regulating services, with potential repercussions not only at the local, but also at the regional and global scales (Rodriguez et al. 2006; Teferi et al. 2010; Lateral et al. 2012; Bagley et al. 2014; Downing et al. 2014; Hicks et al. 2015; Trumbore et al. 2015; Westphal et al. 2015).

#### *Provisioning services*

To represent the trajectories of provisioning services in the three deltas over time, we use a set of key variables able to

give important information about the major components of ecosystem services availability and flow at the delta scale (Gonzalez-Esquivel et al. 2015; Ramirez-Gomez et al. 2015; Mononen et al. 2016). The variables in Table 1 serve as indicators not only of how much food has been produced in these deltas, but also the current level of natural resource exploitation and the intensification of various production systems in place (Gonzalez-Esquivel et al. 2015; Ramirez-Gomez et al. 2015; Suich et al. 2015). When linked to wellbeing indicators (Table 1), these variables give valuable information on how the trajectories in food production translate into the actual availability of food to the populations living in the delta. Furthermore, we can hypothesise how increases or decreases in production feedback into important regulating services and human wellbeing indicators (Essington and Munch 2015; Macadam and Stockan 2015; Albert et al. 2016; Wood et al. 2016).

#### *Human wellbeing*

We selected variables that would provide conceptual and methodological confidence for plotting long-term trajectories of human wellbeing (Bieling et al. 2014; Vidal-Abarca et al. 2014; Escobedo et al. 2015). Previous measures of socio-economic impacts of globalisation and large-scale development interventions have largely been restricted to indicators focused only on income, which do not necessarily reflect social needs and priorities (Deutsch et al. 2003; Malovics et al. 2009; Dasgupta 2010; Jordan et al. 2010; Pretty 2013; Reyers et al. 2013; King et al. 2014). A set of indicators providing data on more explicit social facets, such as freedom and choice, human health, and social relations, would be of great value, but such data, even when available, does not provide a sufficient temporal resolution to connect with the main objectives of this study. Therefore, we represent human wellbeing using simple and representative metrics, with time-series of population growth, employment, gross domestic product (GDP), and food security providing the means to understand the multifaceted impacts of biophysical change, globalisation, and economic development on people's lives, as the system co-evolves through time (Chiesura and de Groot 2003; de Freitas et al. 2007; Farley 2010; Bieling et al. 2014; Howe et al. 2014). GDP has widely been perceived as a measure of output rather than wellbeing, but in cross-country data, GDP per capita is positively correlated with life expectancy and negatively correlated with infant mortality, material living standards, health, education and political voice: all factors that are important for defining human wellbeing (Cohen et al. 2014; de Oliveira and Quintana-Domeque 2014; Hou et al. 2015; Ngoo et al. 2015; Schmelzer 2015; Schoenaker et al. 2015; Vecernik and Mysikova 2015).

## Results

### Amazon

#### *Physical drivers*

The data for rainfall, temperature, and relative air humidity were collected from six meteorological stations in the estuary and averaged to give insight into the climatologic variability operating at the delta scale (Fig. 3c). We can see that there is a strong increasing trend in the mean temperatures starting in the early 1990s. Mean temperatures in the delta have significantly increased during the period 2000–2013 (from  $\sim 31$  °C during the 1960s to  $\sim 32$  °C). Annual mean rainfall values in the Amazon delta show a drying trend in the period 1960–2000 (from  $\sim 2800$  to  $\sim 2200$  mm since 2000). Average values corresponding to relative air humidity have responded promptly to changes in temperature and rainfall. The decadal relative air humidity has decreased from an average of  $\sim 85$ – $83$  %.

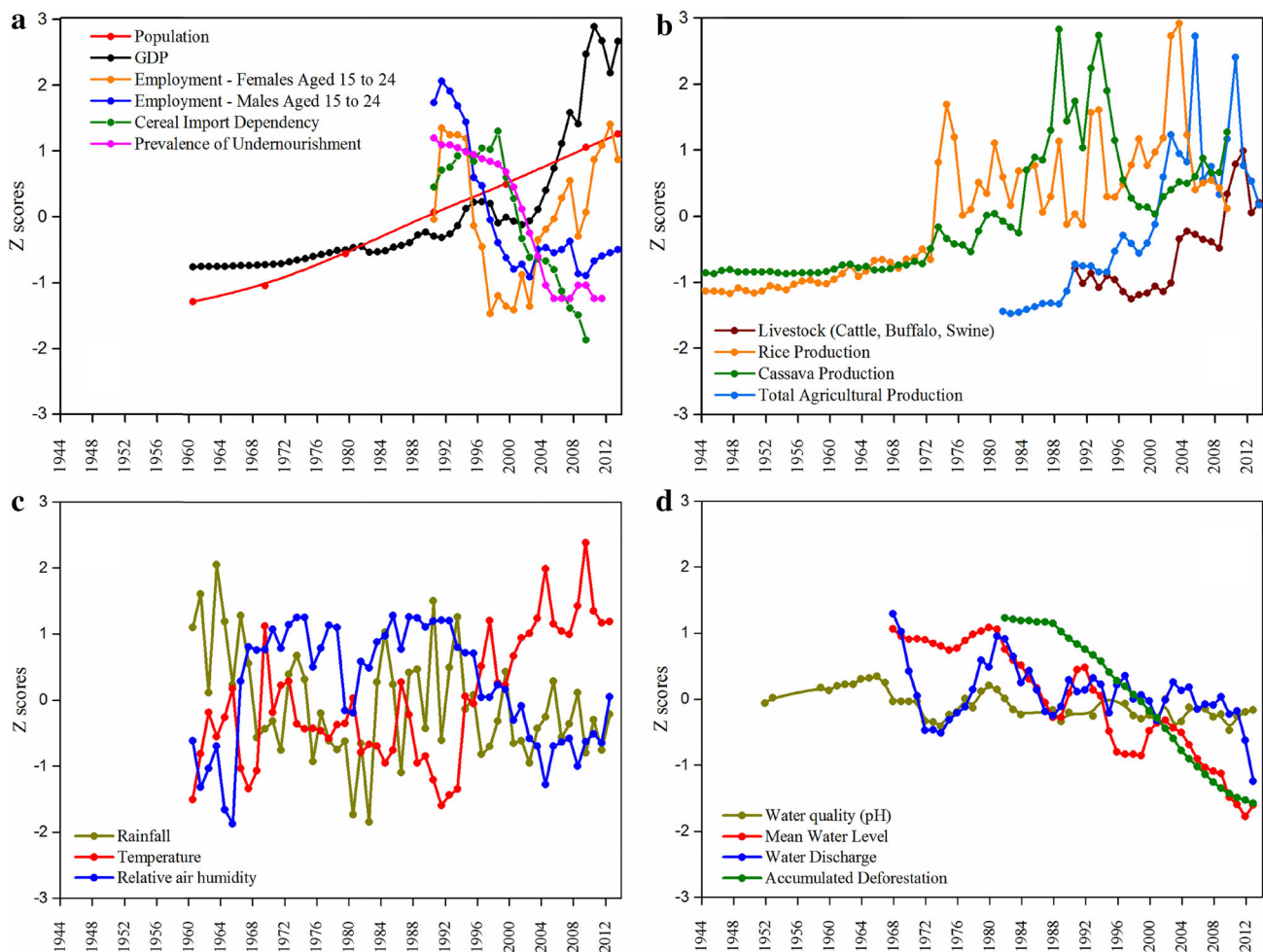
#### *Regulating services*

Figure 3d shows trends in water pH, water discharge, and water level in the delta. Water acidity in the Amazon delta shows a relatively stable trend over the period, with mean pH values observed in the main river channel declining during 1960–1975, showing smallest variations after that (starting in 1984). The line data trajectory shows a rising trend on mean water discharge values, starting to pick up constant pace after 2005. The average water discharge in the Amazon delta shows an intermittent pattern, with major changes starting to take place after 1968. The mean water levels in the Amazon delta are increasing rapidly (starting in 2000), with negative impacts on related regulation services. The annual deforestation values here represent annual figures only for the Amazon delta region, comprising the federative states of Amapa and Para (de Araujo Barbosa et al. 2016). The rise in mean water levels is associated with the increasing number of flooding events taking place in the delta (Bradshaw et al. 2007; Espinoza et al. 2012; Pinho et al. 2015). The peak in deforestation occurs during the late 1990s and persists during the early 2000s till 2005. There is a decreasing trajectory in the annual values of deforestation in the Amazon delta starting during 2006.

#### *Provisioning services*

For most of the period 1944–2013, the production of cassava and rice remained high in the region, with fluctuations in accordance with government subsidies, and in response





**Fig. 3** Amazon delta 1944–2014: annual data for **a** human wellbeing, **b** provisioning services, **c** physical drivers, and **d** regulating services. The *plotted lines* represent desirable (ascending progression) and undesirable (descending progression) *z* score values for regulating

to markets. In Fig. 3b, we see a sharp decrease in the production of cassava (starting during mid 1990s) and rice (starting in the early 2000s). These changes in agricultural production in the region are followed closely by significant increases in livestock production. More recently, production of other commodities, such as corn, sugarcane, and soybean, has influenced the sharp rise in overall total agricultural production.

#### Human wellbeing

Human wellbeing indicators, such as GDP, collected at local level show a general increase over the period (Fig. 3a). Nevertheless, GDP in the Amazon delta has decreased during the early 1990s and early 2000s, returning to an upward trend after 2005, with occasional changes throughout the entire period (from 1960 to 2013). The total population of Para and Amapa (the two

services (mean water level along the main river channel; river water discharge; water quality along the main river channel; accumulated deforestation in the delta)

federative states in the Amazon delta) show a significant rise starting in 1960 (increasing from 1.2 million to nearly 9 million inhabitants), an increase of 660 % over the last 50 years. This has been followed by an equally rapid increase in the percentage of population living in urban areas, a general trend observed in most of the developing and developed world. The positive trend in GDP is reflected in the general improvement of other social indicators, such as school attainment and child mortality rate. However, the apparent improvement in human wellbeing indicators does not have the same positive impacts on the proportion of population employed. It is clear (Fig. 3) that employment is still a major issue, especially for young male individuals. During this time, food security indicators have improved, although with slight changes in the early 2000s (for cereal import dependency ratio) and later on after 2008 (for the prevalence of undernourished children).

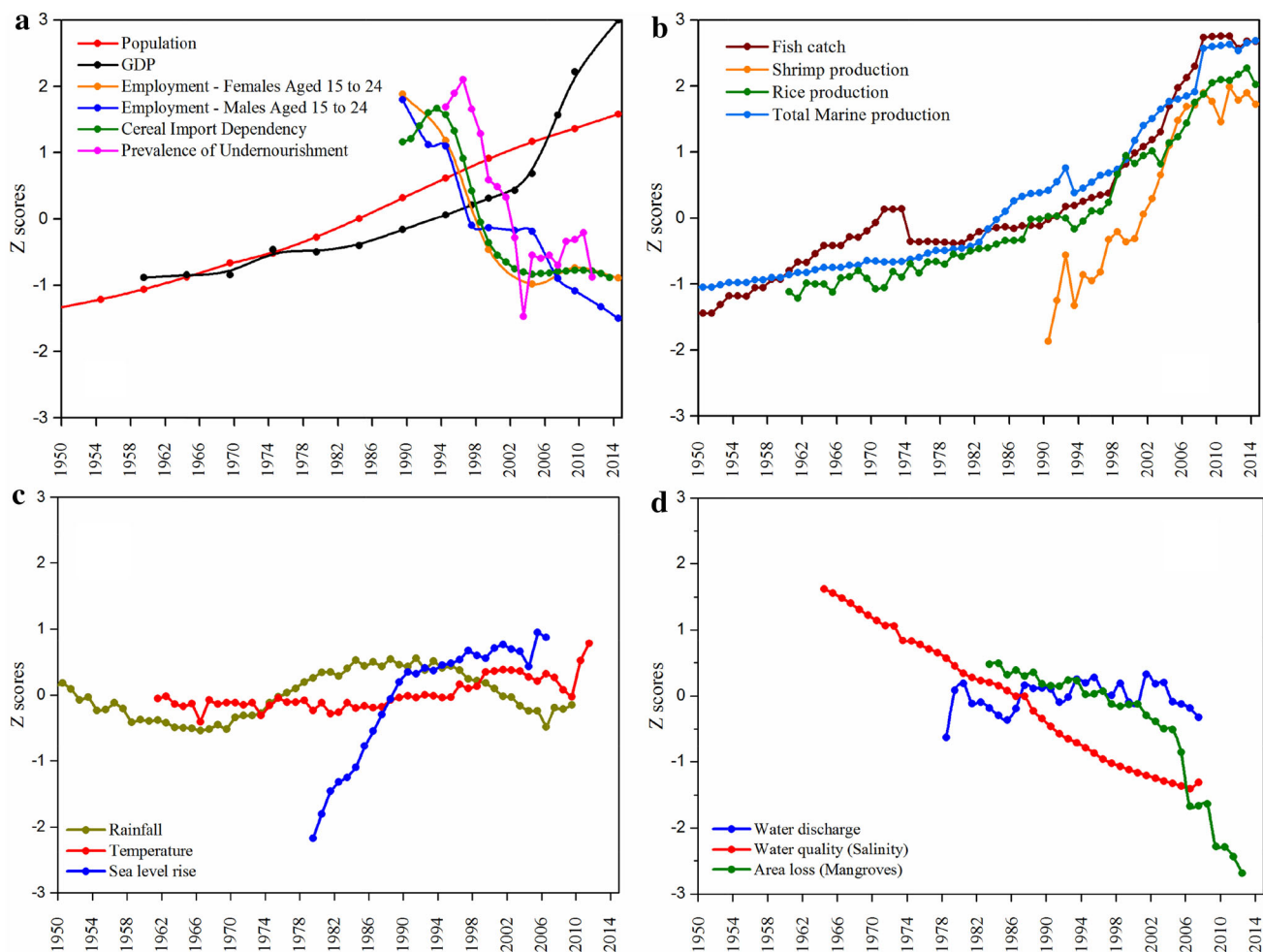
## Ganges–Brahmaputra–Meghna

### Physical drivers

Temperature figures show a step change at  $\sim 1990$  (when the mean temperature rose  $>26^\circ\text{C}$ , whereas mean temperature was  $<26^\circ\text{C}$  before 1990s) (Fig. 4c) (Hossain et al. 2015a). Mean annual rainfall increased from  $\sim 2500$  mm before 1970 to 3000 mm after 1970. However, mean annual rainfall has decreased from  $\sim 3000$  to  $\sim 2000$  mm after 2007. From 1978 onward, sea level shows a rapid upward trend [confirming what has been pointed previously by Auerbach et al. (2015), Brown and Nicholls (2015) and Kay et al. (2015)]; this trend shows signs of slow down after 1990.

### Regulating services

Salinity concentrations in the south-west coastal area of GBM have increased from 5000 Siemens (S) in 1970 to 50,000 S in 2005, suggesting that water quality in the region has degraded  $\sim 10$ -fold within a 30 years period (Fig. 4d). Although the mean (smoothed) annual water discharge shows a relatively stable trend, the original data show fluctuation over the time period from 1977 to 2007. The mangrove forests in the region are undergoing accelerated deforestation, impacting the ability to provide important ecosystem services (e.g., erosion control); this has been developing much before 1982, with this trajectory becoming even more evident after 2004. Some of the peaks in the water discharge curve are linked to major flood



**Fig. 4** Ganges–Brahmaputra–Meghna delta 1950–2015: annual data for **a** human wellbeing, **b** provisioning services, **c** physical drivers, and **d** regulating services. Sea-level rise refers to changes in mean sea level computed at tide stations. The *plotted lines* represent desirable

(ascending progression) and undesirable (descending progression) z score values for regulating services (river water discharge; water quality at the coastal zone)

events, especially 1988, 1995, 1998, and 2002 (Younus 2014; Khan et al. 2015).

#### *Provisioning services*

Total rice production across the GBM delta rose four-fold in the period 1961–2013 (Fig. 4b). Although, the rice production has been rising steadily since 1961, with a rising trend that starts in 1995. Similarly, total inland fish catches, marine fish catches, and shrimp production have increased between 1950 and 2010. Total fish catches increased between 1950 and 1970 (from 200,000 to 600,000 t), whereas fish catches remained at a stable level between 1970 and 1990, before increasing sharply after the 1990s. A similar sharp rising trend is observed for shrimp production with ~3-fold rise between 1991 and 2008. Although the marine fish catch shows a steadily increasing trend since 1950; in 1974, it has significantly dropped, going through a period of recovery (1982–1997), followed by a sharp rising trajectory starting in 1998 (Hossain et al. 2015b).

#### *Human wellbeing*

Total population in the GBM has been constantly increasing since 1950 (Fig. 4a). Human wellbeing indicators, such as GDP increased 35-fold (from ~4200 to ~150,000 million USD in the period 1960–2012) with a rate of 1053-million USD year<sup>-1</sup> between 1960 and 1999 increasing sharply to 8300-million USD year<sup>-1</sup> since 2000. Consequently, the food security indicators show constant signs of improvement (with decreasing trend in cereal import dependency), although we can still observe deviations from the major trend in reducing the prevalence of undernourished children, which starts after 2005. While GDP and population in the region have been growing steadily since the early 1950s, the situation seems very different when it comes to employment rates for both young men and women in the GBM delta, as it has been dropping constantly, with a significant increase from 1998 to 2005.

### **Mekong**

#### *Physical drivers*

Mean temperature has tended to increase, while relative air humidity and rainfall have been decreasing since 1990s (Fig. 5c). Extremely hot years occurred in 1998, 2010, 2012, and 2013. As mean temperature increased, air relative humidity tended to decrease in the period 2000–2013. It is likely that saturation pressure of water vapour increased, while vapour pressure has remained the same, causing the relative humidity to drop. Consequently, decreasing air humidity and rainfall can have negative

impacts on crop production through the higher crop irrigation requirement.

#### *Regulating services*

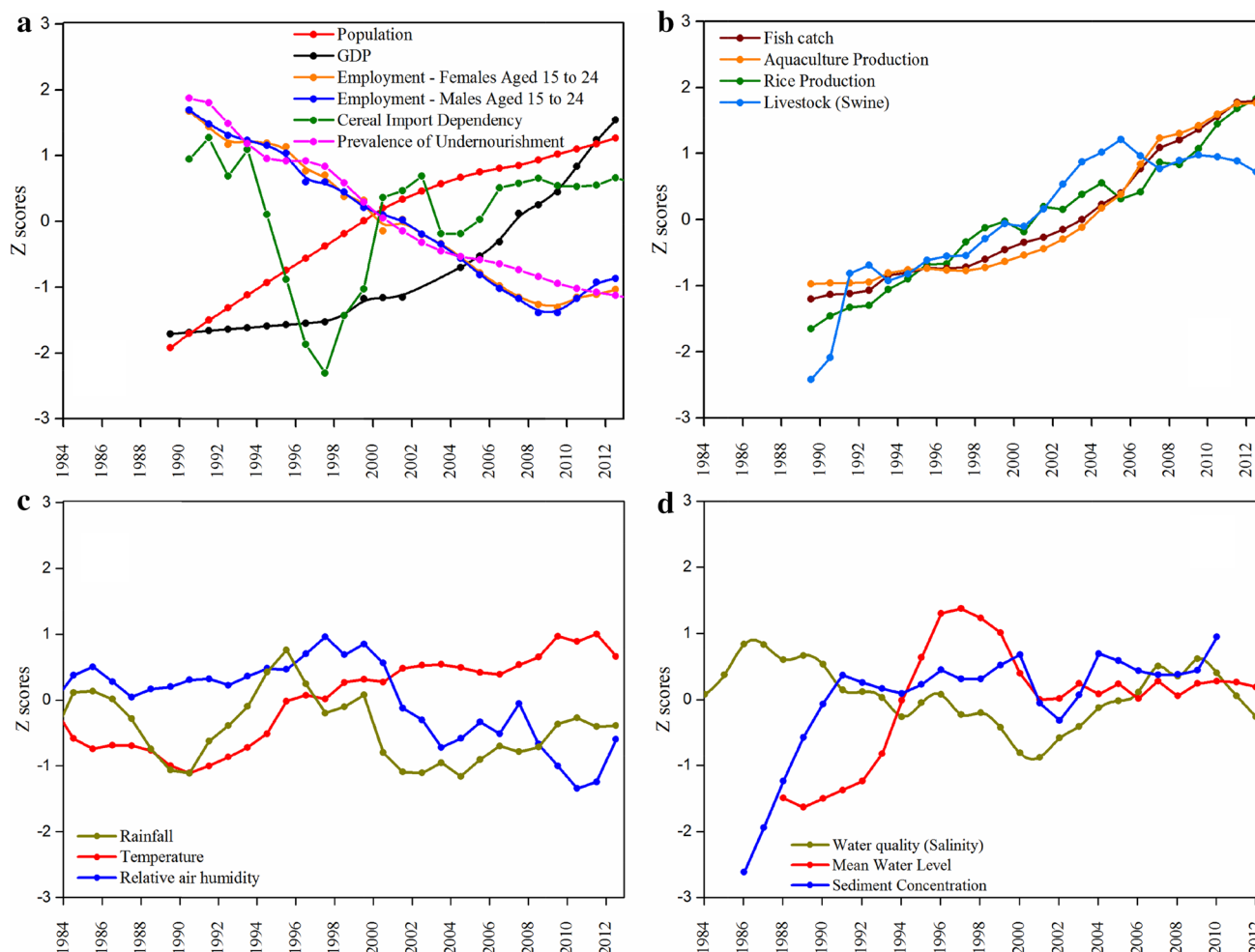
Levels of salinity, the concentration of suspended sediments, and average water levels have been changing considerably over the last few decades (Fig. 5d). After 1989, water levels initiated a rising trajectory until 1996, when it is followed by a decreasing trend until 2001, where it seems to be following a more “stable” trajectory. This has been accompanied by a rising trend sediment concentration between 1986 and 1991, ending latter to give way to a more stable trajectory. The Mekong delta shows a decreasing trend in salinity levels, between 1984 and 1986, when it starts a sharp decreasing trajectory until 2002, soon after changing its trajectory toward higher salinity values. Salinity intrusion in the Mekong is under constant change, continuing to cause negative impacts, as seen recently with 2016, being one of the worst years on record.

#### *Provisioning services*

Positive trends can be observed in for production of all main crops and livestock (Fig. 5b). Between 1990 and 2013, annual production of rice has generally increased, with only a few declines observed during the 2000s. The trajectory for total fish catch shows a similar positive trend, closely followed by aquaculture production, with a few years, where fish catch is positioned just below the aquaculture production. Nhan et al. (2007) highlight that in the early 1990s less than 5 % of the area suitable for aquaculture was used for that activity, but this proportion increased to 22 % by 2004 (Fig. 5b). Livestock production rose significantly, with starting point during the 1990s, with its trajectory moving upward during the period 1993–2006, and more recently (2008), it shows a descending trajectory.

#### *Human wellbeing*

The region experienced increasing pressure from rising population numbers (Fig. 5a). Population numbers in the Mekong delta have increased sharply with a change of 36 % in the period 1990–2013. It has been followed (although not running as rapidly) by GDP, which has been following a major upward trend since 1990, a tendency that starts becoming more consistent during the early 2000s. During the same period, the employment ratio among the young population has been decreasing constantly, with a recent, although still modest, improvement starting in 2010. The food security indicators in the Mekong delta show signs of constant improvement in the form of a steadily decreasing trajectory in the prevalence of undernourished children. Deviations from this trend occur



**Fig. 5** Mekong delta 1984–2013: annual data for **a** human wellbeing, **b** provisioning services, **c** physical drivers, and **d** regulating services. The plotted lines represent desirable (ascending progression) and

undesirable (descending progression)  $z$  score values for regulating services (mean water level along the main river channel; water quality along the main river channel; sediment concentration)

during the period between 2009, but, nevertheless, the situation seems very different from dependency on cereal imports. The sharp decrease during the early 1990s is replaced by a sharp rising trajectory after 1997.

### Connectivity between provisioning and regulating services

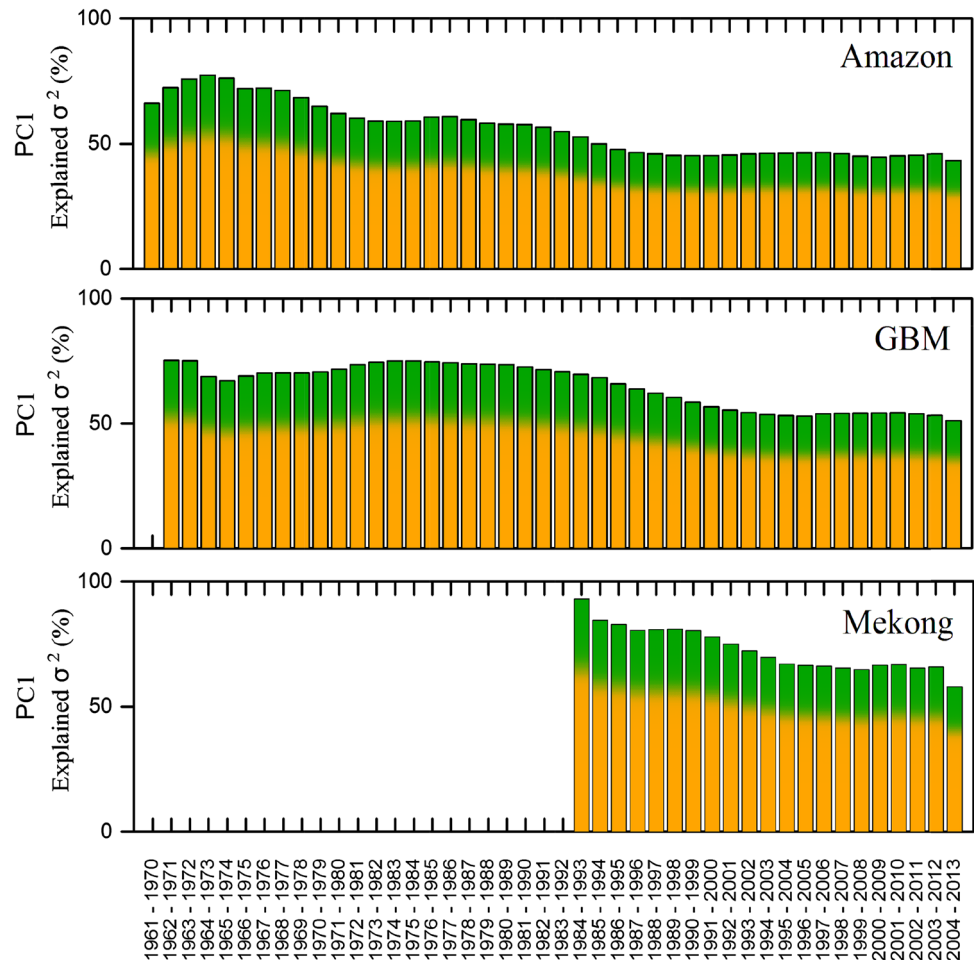
The connectivity analyses (Fig. 6) show remarkably similar results with the PCA 1 curves showing relatively high values before the 1990s with declining trends to the present day. The decline in PCA 1 values appears to start earliest (the early 1990s) in the Amazon, later (late 1990s) in the GBM, and latest (the early 2000s) in the Mekong. This common pattern may reflect the general effect of market economies and globalisation since the 1990s. We tentatively interpret the higher values before 1990 in terms of tightly coupled provisioning and regulating services at the regional scale, promoted by nationalisation and subsidies. For example, deteriorating

water quality may have been more directly linked to standardized land-use and agricultural practices that were often centrally controlled. The later effects of globalisation appear to have reduced the strength of this coupling, a finding that may be interpreted in alternative ways. The growth of provisioning services may have risen without producing proportional negative environmental impacts (e.g., Mekong: Fig. 5), perhaps, as the result of farming diversification and technological advances. However, equally, the findings could be interpreted as an acceleration of environmental deterioration occurring despite a slowing down of agricultural production (e.g., Amazon, GBM: Figs. 3, 4).

### Discussion

The general pattern of long-term trends from at least 1990 across the three deltas describes rising population and GDP, rising or fluctuating provisioning services,

**Fig. 6** Dynamic principal component analysis using a 10 years moving window applied to time-series indices for provisioning and regulating ecosystem services in each delta. The bars represent the proportion of variance ( $\sigma^2$ ) explained by the first principal component during the moving time window



fluctuating climate drivers, and declining or fluctuating regulating services. In addition, employment levels of young people have declined markedly. Major regional exceptions are found in the Amazon, where there has been a rise in temperatures since the mid-late 1990s and continued growth in livestock production in the Amazon since the mid-2000s at the expense of rice and cassava production. Over a multi-decadal timescale, none of the deltas currently show any variable running on with a quasi-stationary pattern. In system terms, all the deltas are in non-stationary or transient states with a little evidence for stability or equilibrium.

The most rapid trends in each delta (relative to all others) are for GDP growth which has risen  $\sim 3$  st dev. units since 2002 (Amazon), 1994 (GBM), and 1999 (Mekong). These levels of growth illustrate the successful economic development of the three regions associated with national schemes for poverty alleviation and the large-scale effects of globalisation since the 1990s. Certainly, the rising trend of GDP in GBM has resulted in an improvement of other indicators, such as school attainment and child mortality rate (Dalal and Goulias 2010; Chowdhury et al. 2013). A

major part of the economic growth has been based on the intensification of agriculture and aquaculture, as shown by the rapid trends in provisioning services reflecting the use of hybrid grains, fertilizers, pesticides, and technological advances, such as irrigation techniques. The most rapid trends for these are livestock production since 2000 (Amazon), shrimp cultivation (GBM), and aquaculture production (Mekong).

When the data exist, the evidence suggests that the rise in provisioning services has adversely affected the regulating services. In the Amazon delta, the rising trend for deforestation ( $\sim 3$  standard deviation units between 2002 and 2010) seems to be a direct consequence of the expanding livestock grazing (de Araujo Barbosa et al. 2016), and contrasts with claims that deforestation rates across the whole Amazon basin are stabilizing (Godar et al. 2014). In the GBM and Mekong, the declining water quality ( $\sim 2$  standard deviation units 1982–2008 and 1986–2000, respectively) is the result of higher salinity levels caused by shrimp ponds, inefficient irrigation, lower river discharges, and marine intrusions (Haider and Hosain 2013; Abedin et al. 2014; Pokrant 2014; Kay et al.

2015). Local studies in the GBM coastal zone show that conversion of rice fields to shrimp farms is almost certainly a factor in increasing soil and surface water salinity (Hossain et al. 2015a).

Across the three deltas, the chains of causation that link governance and policy to farm decisions, through to production levels, and environmental degradation are varied and complex. For example, deforestation in the Amazon represents a local and direct human activity, driven by a diverse set of demands generated across the globe, dependent upon complex interactions between domestic and trans-boundary drivers. Over time, transitions in global and regional temperatures and salinity values are driven by various distal (upstream), environmental, direct and indirect human actions that make them more or less uncontrollable within the deltaic system (Ferguson et al. 2013; Folke et al. 2004; Janssen et al. 2004; Ullah et al. 2015). In the Mekong delta, the adverse effects arising from climate change, altered natural flow patterns in water and in sediments (as a consequence of hydropower development), have already created trans-boundary environmental tensions and reduced the capacity of people to maintain their livelihoods (Lu and Siew 2006; Li and He 2008; Xue et al. 2011; Manh et al. 2015).

In system terms, we can argue that for all three deltas, the inherent dynamics of function, resilience, connectivity, and feedback have significantly changed. The boundary conditions (e.g., climate, regional economies) that constrain the system functioning have significantly changed over the studied time periods. System resilience as defined by the condition of ‘slow’ variables (e.g., forest cover, water quality) shows long-term decline. National policies and globalisation have affected the coupling of ecosystem services. In addition, in each delta, there are examples of rapidly rising or declining trends that may be viewed as the result of strengthening positive feedback mechanisms that link land-use decisions to farm incomes and profit generation that, in turn, link to environmental degradation, often in the absence of robust environmental regulations. We may surmise that, in system terms, all three social-ecological systems may have moved outside safe operating spaces into unsustainable configurations.

Therefore, the overall changes in these deltaic social-ecological systems may be described in general terms as unsustainable trade-offs between rising food production and a deteriorating natural environment, though, perhaps, only to a limited extent in the Mekong. The leading question is what the long-term consequences might be. Lower rates of deterioration in recent years in the GBM and recent fluctuations of water quality in the Mekong suggest that the long-term environmental decline may be stabilizing (Li and He 2008; Tho et al. 2012; Renaud et al. 2015). However, the most recent provisioning data indicate

slowing or stabilizing trends for rice and livestock production (Amazon), rice production (GBM), and livestock production (Mekong). We may therefore ask whether these are the result of negative feedback loops driven by deteriorating regulating services, that are now constraining food production, or whether market conditions have changed, or more sustainable methods have been introduced?

Unfortunately, this is difficult to answer. The connectivity analyses underline the possible negative and positive effects of globalisation on the relationship between provisioning and regulating services, but do not provide evidence for causation. Regulating services may have declined generally, but the evidence for negatively impacting agricultural production levels is equivocal, because the effects of ecological degradation, environmental regulation, and land-use selection on provisioning services are conflated. In our exploratory analysis, we are constrained by the availability of data and a simple trend analysis of standardized data that cannot compare trends in terms of absolute effects without calibration. For example, one  $z$  score unit of change in temperature may be more harmful to crop production than the same relative change in salinity. However, the general decline in regulating services has to be viewed as an unsustainable loss of natural capital with the possibility, as argued elsewhere (Raudsepp-Hearne et al. 2010), for time-lagged declines in crop and fish production as positive feedback mechanisms strengthen (Hossain et al. 2015a). The possibility that rapidly declining regulating services in the Amazon and GBM are now increasingly decoupled from agricultural production levels (though not the agricultural practices themselves) is consistent with a heightened risk for rapid social-ecological change as unsustainable system dynamics play out through tipping points and regime shifts. It may be uncertain whether these mechanisms are happening already, but they will certainly be accentuated by the observed rises in temperature which may be expected to adversely affect pollination, crop yields, and surface water quality. From a systems perspective of sustainability, the current deltaic systems lie outside safe and just operating spaces in potentially dangerous zones (Dearing et al. 2014). Current work is aimed at developing simulation models that can both capture the complex dynamics revealed here and anticipate the effects of alternative governance measures on future social-ecological states.

## Conclusions

This paper shows that the biophysical and socio-economic changes in the three deltas have similar origins. Several well-established mechanisms exist to explain the overall

variation that we observe in the three deltas. These mechanisms are created and maintained by feedbacks originated from the interaction between society and the environment. Current and past observed condition were shown here using a series of records, denoting changing patterns of rainfall, temperatures, sea-level rise, water levels and discharge, sediment flow, and forest cover, in the context of intensive social changes. The complex myriad of interactions currently in place in these deltaic systems will increasingly be affected by changes in the average weather conditions, management practices, and the fast pace of resource exploitation. The power of international and institutional arguments that emphasize the necessity for sustainable economic development, and adaptation to changes in climate, has yet to translate into effective safeguards for the sustainable use of natural resources in these deltas and the livelihoods and wellbeing that depend upon them. This finding suggests that the sustainability of tropical deltas urgently requires the decoupling of local economic growth from local resource use before irreversible ecological shifts develop.

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