



Research

Tracing environmental and livelihood dynamics in a tropical coastal lagoon through the lens of multiple adaptive cycles

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ABSTRACT. Understanding the long-term dynamics of social-ecological systems is critical to better inform sustainable management. Since Holling's adaptive cycle heuristic, published in 2001, substantial progress has been made to explore historical changes in agricultural, pastoral, and forest systems. However, the application of this heuristic in coastal fishery systems has been relatively rare. Using the Tam Giang Lagoon in Vietnam as an example of a rapidly changing environment, we explore the historical behavior of this tropical coastal social-ecological system (SES), associated livelihood pathways, and possible challenges for future livelihood adaptations through the lens of the adaptive cycle metaphor. Our analysis demonstrates that the present lagoon SES condition is the result of a series of historical events and reorganization attempts through two complete adaptive cycles. The lagoon's future vulnerability is tied to the intensification of human uses, prolonged ecological degradation, and intensifying climatic hazards. We show how the evolution of the lagoon SES resulted in divergent livelihood pathways that bring benefits to some users but also cause persistent constraints and sometimes irreversible losses to other users in shared common pool resources. A one-size-fits-all fishery management approach is therefore ill-suited for improving diverse livelihoods. We recommend that fishery policies take seriously the heterogeneity in livelihood pathways for sustainable lagoon management. We end by reflecting on the usefulness of the adaptive cycle heuristic in systematically exploring historical dynamics and identifying underlying drivers and feedbacks between the social and ecological components of complex fishery systems.

Key Words: *adaptive cycle; coastal lagoon; dynamics; livelihood pathways; social-ecological systems; Vietnam*

INTRODUCTION

Livelihoods that depend on coastal fisheries in tropical regions are threatened by a range of complex and interconnected forces, including socioeconomic, environmental, and climatic changes as well as governance and management challenges (Millennium Ecosystem Assessment 2005, Charles 2012, Cinner et al. 2012, Ding et al. 2017). Coastal communities depending on degraded coastal ecosystems will likely be most susceptible to changes in system conditions (Thomas and Twyman 2005). Recent studies confirm a range of impacts from climate change on coastal communities, including the reduction of fish stock (Allison et al. 2009, Lajus et al. 2017), the erosion of fishery activities (Dulvy and Allison 2009), and loss and damage due to extreme events (Adger 1999, Pomeroy et al. 2006). Even if the global community could limit global warming at 1.5 °C above preindustrial levels by 2050, climate-related risks to livelihoods and human well-being would persist around the globe, with numerous pressures to coastal areas (IPCC 2018). However, these impacts will be highly context-specific, depending on local socioeconomic, political, and geographic configurations. It is well established that communities with diverse livelihood systems are more resilient to external disturbances and changes compared to those that have less livelihood alternatives (Allison and Ellis 2001, Olsson et al. 2014a, b), with wealthier groups typically coping better, taking advantage of changes to thrive (Hoque et al. 2018). In other words, the same threats can cause differential impacts to individuals, groups, and communities regardless of their level of development (Tschakert et al. 2019).

Given that climate change is not the only threat, neither to livelihoods nor to natural resources, combination of climate-induced risks with nonclimatic stressors amplifies the

vulnerability of local livelihoods (Islam et al. 2014, Sumaila et al. 2011). Accordingly, rising temperature, changing rainfall patterns, increasing ocean acidification, and changes in water quality will affect the structures and ecological functioning of coastal ecosystems (IPCC 2014), and marine species' growth, distribution, recruitment, and mortality (Drinkwater et al. 2010). Eventually, these changes affect the livelihoods of resource-dependent communities (Perry et al. 2010).

In complex social-ecological systems (SESs), such as coastal fisheries, where the human system strongly interacts with natural components (Liu et al. 2007, Ostrom 2009), understanding the characteristics of the various drivers and system variables^[1] is a prerequisite not only for identifying the most urgent challenges to be addressed, but also for identifying persistent problems for long-term solutions (e.g., see Elliott et al. 2017 for an overview in marine environments). Therefore, it is helpful to distinguish fast-moving variables from slow-moving ones for prioritizing management actions and resource allocation (Crépin 2007, Walker et al. 2012, Sivapalan and Blöschl 2015). Slow-moving variables tend to act steadily over time and progress in a predictable way, resulting in long-term and large-scale impacts (Msangi and Rosegrant 2011). In contrast, fast-moving drivers are those that typically have more influence in the short term and at more local levels. The fast-moving variables are usually of primary concern to resource users (Walker et al. 2012) because they may cause sudden and obvious losses and damages to the system. However, long-term dynamics and sustainability of complex SESs are strongly coupled with slow drivers or variables (Gunderson and Holling 2002). The interactions between fast and slow variables may lead a system to a more resilient or vulnerable state (Holling 1973), or make it coevolve (Sivapalan and Blöschl

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2015). These dynamics and scale interactions challenge traditional coastal management frameworks that typically seek to identify drivers, pressures, and responses of coastal environments in a linear fashion.

Resilience thinking (Holling and Gunderson 2002) has become a crucial foundation for investigating dynamics within SESs, although often patchy and diverse forms of data make it difficult to apply system principles. SESs are highly dynamic and respond to both internally generated and external pressures (Schlüter et al. 2014). Scholarly and policy interest in SESs recognize the need to take into account the two-way feedbacks between the social and ecological domains to better inform sustainable development strategies (Cinner et al. 2009, Mace 2014). Given the complex interactions between social and ecological components, a case study approach to examine place-based realities can help inform broader conservations about how systems are functioning and build consensus about management (Schlüter et al. 2014, Herrero-Jáuregui et al. 2018).

Using the Tam Giang Lagoon in Vietnam as an example of a rapidly changing SES, our study addresses four key questions: (1) How has the lagoon SES evolved in responding to the impacts of socioeconomic, environmental, and climatic changes?; (2) How did these changes affect the nature of the social-ecological interactions through adaptive processes?; (3) How did different groups of resource users benefit or face new risks related to these social-ecological changes?; and (4) What are the likely challenges for future livelihood adaptation? To provide answers to these questions, we synthesize historical information, available current data, and empirical insights from fieldwork regarding the lagoon SES and convey these insights through the metaphor of the adaptive cycle (Holling 2001).

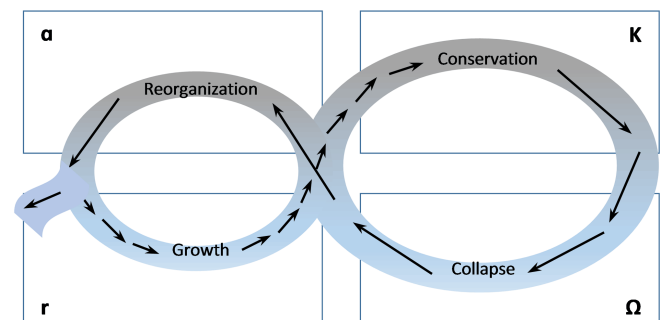
This study offers insights into SESs research, and the management of fishery systems, in two ways. First, research to date has focused almost exclusively on dynamics and characteristics of the social and ecological components of SESs (Salvia and Quaranta 2015, Aldana-Domínguez et al. 2018, Antoni et al. 2019), with limited explicit attention to differences and heterogeneities in livelihood pathways associated with SES changes. This study examines such heterogeneities within the lagoon system, demonstrating how and why groups have pursued different paths and how such an understanding can enhance the efficacy of fishery management and policy interventions. Second, our research makes visible the many nuances, interactions, and feedbacks between the social and ecological system components over > 100 years that help to fine-tune the application of the adaptive cycle heuristic in fishery-based and other common pool resources worldwide.

THE ADAPTIVE CYCLE AS A HEURISTIC FOR ANALYSIS

The concept of the adaptive cycle with its four phases (Fig. 1) was developed by Holling (1986) to explore the dynamics of complex systems under external disturbances and changes (Daedlow et al. 2011). A system moves slowly from the growth phase (r) to the conservation phase (K) in the forward loop of the cycle where the dynamics of the system are reasonably predictable (Walker et al. 2004). In the K phase, the system becomes more vulnerable, less resilient and responsive to external disturbances (Walker et al. 2004). The system can then rapidly progress to the collapse phase (Ω), and eventually to the reorganization phase (a). In contrast to

the change from r to K, the shift from Ω to a occurs in the back loop and is unpredictable (Walker et al. 2004). According to Holling's theory, an SES is generally more resilient in the growth and reorganization phases but less resilient in the conservation and collapse phases because of its reduced capacity to absorb and resist external shocks and to maintain its structures and identity (Allison and Hobbs 2004). In a dynamic SES, minor disturbances may trigger transitions between adaptive phases when they occur in the low-resilience phases. The system can return to the previous r phase to begin a new cycle, or possibly shift to different states or regimes (Vang Rasmussen and Reenberg 2012) where the system loses its original structure, functions, feedbacks, and identities (Crépin et al. 2012, Biggs et al. 2018). Regime shifts are often large, persistent, and unexpected changes in coupled SESs, inducing major impacts on ecosystem services with considerable consequences for human well-being (Scheffer et al. 2009, Rocha et al. 2015, Biggs et al. 2018, Rocha et al. 2018). From a social-ecological perspective, the use of the adaptive cycle heuristic is therefore helpful in understanding dynamics of system changes and how these changes interact with system resilience to drive an SES to a more or less vulnerable point for an imminent regime shift.

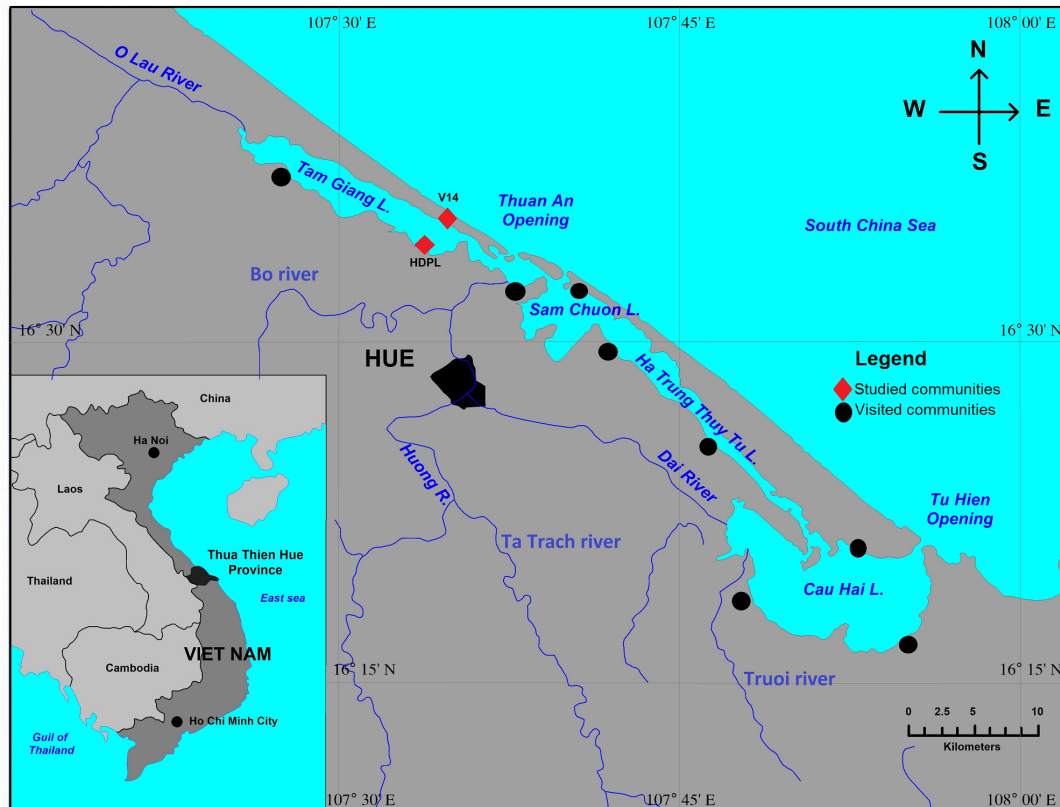
Fig. 1. The adaptive cycle showing four phases (r, K, Ω , a) of adaptation. Short arrows indicate a slowly changing situation; long arrows indicate a rapidly changing situation. Adapted from Gunderson and Holling 2002.



This heuristic of the adaptive cycle is not a predictive model, and phases do not always progress sequentially (Abel et al. 2006). A system does not necessarily pass through all four phases of each cycle and can possibly move from and between phases (Walker et al. 2004). Furthermore, the duration of each phase or cycle varies depending on the resilience of the system itself and the magnitude and interaction of external shocks and disturbances. A system could take decades to move from conservation to collapse but may only need one year to reach reorganization from collapse; alternatively, a system could remain for decades in one cycle but then rapidly transition into a new cycle in just few years (Goulden et al. 2013, Antoni et al. 2019).

Although the adaptive cycle was initially developed for ecological research applications, it has also proven useful for investigating the dynamics of SESs (Walker et al. 2004, Abel et al. 2006). The metaphor of the adaptive cycle is arguably the most holistic method and hence is widely applied in interdisciplinary research. Allison and Hobbs (2004) used this metaphor to conceptualize

Fig. 2. Map of the Tam Giang Lagoon and study sites. Adapted from Tuyen et al. 2010.



the dynamics of the Western Australian agricultural region and identify its capacity for system renewal. Their study involved not only the ecological and social but also the economic domains to investigate system behavior over 100 years. Nkhata et al. (2008), based on a literature review of the adaptive cycle metaphor, proposed a conceptual framework for analyzing changes in long-term social relationships in relation to SES management. Beier et al. (2009) applied the adaptive cycle in combination with historical narratives to trace dynamics and examine changes in forest management and land use policy in the Tongass National Forest in the U.S. Abel et al. (2006) employed resilience theory and the adaptive cycle heuristic to identify critical factors precipitating the collapse and reorganization phases of regional SESs in Australia and Zimbabwe. Although their study was unable to clearly identify the sequential passage of cycles as implied by Holling's theory, it nonetheless revealed that the resilience of the systems was controlled by slowly changing variables. Other studies have applied the adaptive cycle in quantitative ways. For instance, Daedlow et al. (2011) quantitatively distinguished phases in recreational fisheries governance in Germany. They highlighted the importance of social identity and intergroup dynamics in reorganization and adaptation processes. Vang Rasmussen and Reenberg (2012) identified changes in land use in a Sahelian agro-pastoral system and quantified specific indicators to assess overall system resilience.

Although there is ample evidence of the usefulness of the adaptive cycle heuristic, further research can sharpen our understanding

of processes of change in SESs across diverse geographical and policy contexts, and guide adaptation strategies against future pressures. We therefore argue that a case study approach applying the heuristic to scrutinize small-scale and rapidly progressing systems is indeed valuable, although assembling information on the system to explain the evolving large-scale system can be challenging (Leenhardt et al. 2015, Teuber et al. 2017). Below, we map data for a coastal fisheries-based SES in a developing Asian nation onto the adaptive cycle framework and subsequently use emerging insights to delineate future adaptation priorities.

STUDY SITE AND METHODS

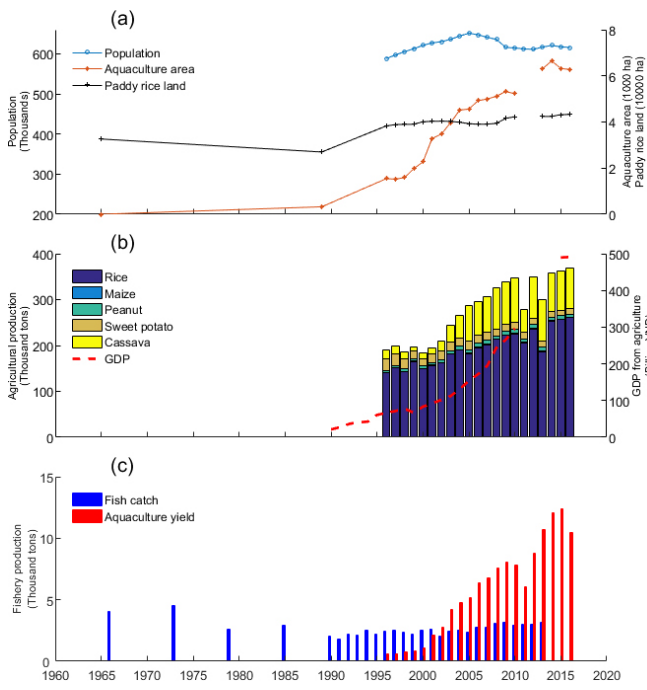
Tam Giang Coastal Lagoon

The Tam Giang Lagoon is a large, high-value, and multiuse coastal wetland area in central Vietnam with ~220 km² water surface area (Tuan et al. 2009, Tuyen et al. 2010). It is formed by three interconnected sublagoon systems, expanding 70 km in length along the coast and 2–5 km in width, across five districts in Thua Thien Hue province (Fig. 2). The lagoon is currently connected to the sea through two inlets but over time has been significantly modified by floods and typhoons, especially the flood of 1999 (Thanh 2002). The combination of the inlets' dynamics with complex tidal regimes has caused unstable ecological conditions and significantly destabilized bioresources in the lagoon (Thanh 1997). Notably, the closure of the largest inlet, Tu Hien, between 1994 and 1999, resulted in detrimental impacts on water quality, biodiversity, and brackish water aquaculture (Thanh 2002).

Being situated in the downstream floodplain area, the lagoon water environment and productivity also highly depend on inflows from rivers on the western side of the province. It is estimated that $\sim 6 \times 10^9 \text{ m}^3$ of river water and 620,070 tons of suspended sediments are annually discharged into the lagoon (Thanh 2002, Quan et al. 2016). The lagoon and its catchment are characterized by a tropical monsoon climate with high annual rainfall, average temperature and humidity (3332mm, 25.5 °C, and 87.5%, respectively; Thua Thien Hue Statistics Office 2016).

The lagoon plays an essential role in local economic development (Fig. 3) and biodiversity protection. It consists of diverse habitats including seagrass, mangrove forests, and shallow tidal and swampland ecosystems, and is home to > 1000 plant and animal species (Tuan 2012, Quan et al. 2016). Its resources support approximately half of the provincial population ($\sim 500,000$ persons) whose livelihoods rely entirely or partly on fisheries-based activities (Thua Thien Hue Statistics Office 2016). Until 2005, the lagoon was an open access area where anyone was allowed to catch fish, with no regulation or restriction regarding fishing gear. As a result, fishers employed several types of methods, including highly destructive practices, e.g., tiny mesh size nets, electric fishing gear, bottom trawling gear (IUCN 2008). Exploitative fishing practices, along with poorly defined property rights on the lagoon water area and adjacent lands resulted in unsustainable aquatic resource usage and intra- and intervillage conflicts, both of which ultimately eroded fishers' livelihoods and well-being (Huong and Berkes 2011).

Fig. 3. Changes in population and land use (a), contribution of the lagoon to the local economy (b), and fish catch and aquaculture yields (c) in the Tam Giang Lagoon.



Data collection

This study combines primary and secondary data about the lagoon SES collected during two fieldwork campaigns (October

2017–January 2018, and December 2018–February 2019). A mixed-method approach was adopted, comprising scoping visits, semistructured interviews, focus group discussions, participant observation, and participatory workshops and follow-up interviews.

Primary data

Ten scoping visits were undertaken to communities around the lagoon to identify suitable sites for data collection. Two lagoon communities were ultimately selected, namely Ha Do Phuoc Lap (HDPL) and Village 14 (V14) in Quang Dien District, Thua Thien Hue Province (Fig. 2). These two villages engage in both fishing and aquaculture but represent the lagoon's two predominant livelihood groups, inland and coastal, each with distinct social-ecological characteristics. All conversations were held in Vietnamese, with the help of a local assistant. All interviews were audio-recorded with participant consent and transcribed for basic content analysis.

Semistructured interviews were conducted with individuals in each community to elicit characteristics and changes of the local SES and establish trustworthy working relations for subsequent research activities. Taking into account the size of population in each village, 17 and 14 interviews were conducted in HDPL and V14, respectively (n = 31; Table 1). Community leaders were approached first, then additional participants through snowball sampling. The semistructured format ensured that all key questions were addressed while providing ample space for interviewees to freely express their own experience and knowledge (Ritchie and Lewis 2003). The interviews covered household livelihood activities, changes in the lagoon SES, and associated adaptive responses.

Table 1. Summary of characteristics of participants in interviews and focus group discussions (FGDs). Two lagoon communities studied: Ha Do Phuoc Lap (HDPL) and Village 14 (V14).

Participant characteristics	Interviews		FGDs		
	HDPL	V14	HDPL	V14	
Total number of participants	17	14	20	19	
Gender	Male	16	15	17	
	Female	1	1	5	2
Age	Range	34–77	33–71	34–77	28–70
	Average	51	54	52	46
Main occupation	Fishing	8	5	10	11
	Aquaculture	9	9	10	8

Two focus group discussions (FGDs) per community were organized separately for households whose dominant livelihood was either fishing or aquaculture, with 9 to 11 villagers, respectively, representing different socioeconomic and demographic backgrounds (n = 39; Table 1). This design made it possible to capture a representative cross-section of local residents and avoid bias through overly influential individuals. Each FGD consisted of two parts: first, participants constructed a timeline of social-ecological development from the 1970s onward (Brattland et al. 2019). On a large paper, they indicated key milestones of change in environmental and ecological conditions, livelihood activities, and governance structures, based on discussion and consensus. Second, mental models (Tschakert and Sagoe 2009) were used to systematically identify and deliberate key events and drivers of

change, their interactions, causes, and consequences for ecological and livelihood dynamics, and adaptive responses and future trends. In addition, several transect walks accompanied by villagers were undertaken to households, local markets, communal water areas, and aquaculture ponds to understand the lagoon environment, community-built infrastructure, and farming and other livelihood practices.

Finally, a participatory workshop was organized in Hue City in January 2019 to review and discuss preliminary results. It involved 23 participants, representing both communities, most of whom had been part of preceding research activities. Four follow-up interviews were conducted with selected workshop participants to address outstanding questions and inconsistencies.

Secondary data collection

Time series of climate and hydrology data were collected from the Vietnam Center for Hydro-Meteorological Data. Water quality data was obtained from the Department of Natural Resources and Environment, peer-reviewed publications, and project reports. Socioeconomic data such as fish catch yield, aquaculture and agriculture production, and demographic characteristics were collected from the Departments of Fishery and Statistics of Thua Thien Hue Province. These time series data were synthesized to assess long-term trends in SES conditions of the lagoon.

Adaptive cycle construction

The first author began by developing an historic timeline, depicting key events and milestones where the SES had undergone significant changes, based on the FGD results. Within each period in the time line, the main characteristics of the lagoon were identified, with particular emphasis on ecological conditions, community livelihood activities, and adaptations to disturbances and shocks. Then, insights obtained from the semistructured interviews were used to complement the time line. Contradictory information was further discussed and reconciled during the participatory workshop and follow-up interviews. In addition, time series data was plotted to illustrate the dynamics of change and system behavior in the social and ecological components of the lagoon system. Because there has not been a standard method or guideline to identify exact transition points between phases of an adaptive cycle, we followed some recent studies (e.g., Aldana-Domínguez et al. 2018, Antoni et al. 2019) and largely relied on the time line constructed with the participants to distinguish individual phases. Accordingly, phases were distinguished by decisive events and/or changes that had induced transitions in the system states and had driven the system through the adaptive cycle. Decisive events encompass catastrophic disturbances (significant floods or typhoons), new policies, institutional changes, new practices, and biophysical changes (Ostrom 2003, Fath et al. 2015, Antoni et al. 2019). Finally, we illustrated nuanced changes and key features in the socioeconomic conditions of the communities associated with each phase.

RESULTS

The adaptive cycle of the Tam Giang fishery system

Linking information obtained from the interviews and FGDs as well as secondary data with the adaptive cycle framework helped explain the lagoon SES evolution, the role of key drivers in triggering transitions, and the core features of the phases (Fig. 4).

The following provides a narrative description of relevant phases in the Tam Giang Lagoon SES.

Early growth 1 (r1): Customary fishery management (Pre-1954)
Historically, the lagoon surface constituted a communal property. The lagoon management was based on a customary approach whereby the government relied on the traditional community of fishermen (*van*) to oversee fishery activities. The lagoon resources were mainly exploited for the *van's* subsistence livelihoods and used in exchange for cereal products from nearby agricultural villages. A *van* was established by a group of ~40–70 households living on fishing boats in close proximity (Nguyen and Kim 2011, Binh 1996). Each *van* was administratively assigned to join a nearby agricultural village for demographic management and fishing fee collection. The agricultural village organized an annual auction among the *van* for the rights to exploit lagoon resources in its territory. The *van* leader collected a contribution from each of his members to pay the fishing fee. The *van* had its own regulations to support its members' lives, controlling fishing time and gear, and unsustainable fishing activities. It followed a relatively nomadic life while navigating different fishing grounds, depending on the movement of fish and weather conditions. This lifestyle helped build strong social cohesion among fishers and communities in resource usage and protection (Nguyen and Kim 2011). The *van* had its foremost power in managing the lagoon resources as emphasized by villagers with “*Phep vua thua le lang*” (The King's law comes after the village's customs).

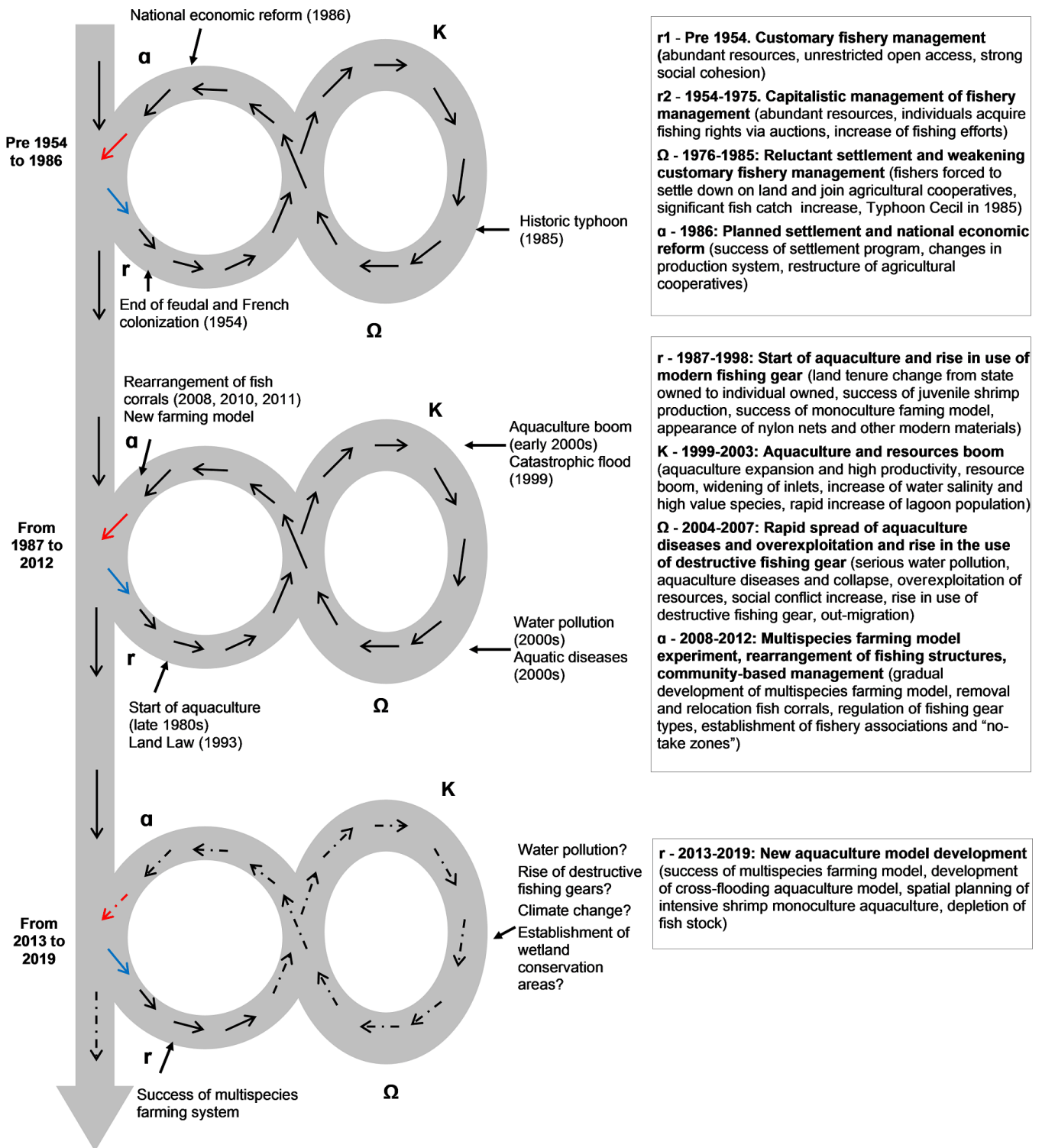
Late growth 1 (r1): Quasi-capitalistic management during the Vietnam War period (1954–1975)

The lagoon resource usage experienced its first significant and well-documented change during the Vietnam War (1954–1975) when the lagoon surface was allowed to be owned and leased out by individuals through auctions (Nguyen and Kim 2011). District governments organized annual auctions open to everyone; however, most fishers, usually *van* members, were not able to compete because of limited financial capacity while the wealthy, i.e. landlords and government officials, often won bids. Winners then leased out their usage rights to several *vans*, based on negotiations with *van* leaders. In this period, exploitation rights were therefore controlled by the auction winners, and fishers generally had to pay a much higher fishing fee relative to the past. This new management approach significantly changed the system as annual fish catch increased considerably and peaked at 4500 tons in the late 1970s (Mien 2006). Because auctions were renewed annually, the new winners then asked for higher fees from each *van*, spurring an increase of fishing effort.

Collapse 1 (Ω1): Reluctant settlement and weakening customary fishery management (1976–1985)

After the war, the country drifted toward socialism. This new political paradigm rapidly changed the economy and production structures, with several changes directly affecting the lagoon management and fishery livelihoods. Accordingly, fishers of the *van* were forced to settle in nearby agricultural villages and join agricultural cooperatives and undertake farm labor. Agricultural cooperatives were formed without sufficient considerations of customary community-based resource management practices (Ruddle 1998). Fishers were faced with the practical challenge of carrying out farm jobs, with little to no experience and knowledge

Fig. 4. Summary of the adaptive cycle showing the evolution of the Tam Giang Lagoon social-ecological system and the phase characteristics from 1950s to 2019. Blue and red arrows indicate the starting and ending points of each cycle, respectively. Continuous arrows illustrate past phases and dashed arrows imply possible future phases.



regarding crops, diseases, seasonal calendars, and harvest techniques. In addition, the mechanical structure and operation of the agricultural cooperative system limited the flexibility and creativity of fishers and farmers (Cox and Le 2014, Raymond 2008). New livelihood practices also undermined the social cohesion among former fishers and eroded their fishing expertise. Therefore, fishers gradually left agricultural lands to return to their fishing activities after a few unsatisfactory years of farm work (Nguyen and Kim 2011). During this period, the government paid little attention to lagoon resource management (Ruddle 1998), and fishers were again able to freely exploit the lagoon. Yet, the former *van* regulations on aquatic resource usage and protection were not as strictly enforced as previously. Hence, the power of customary management started to significantly erode.

At the same time, fishers adopted and expanded more effective fishing gear, e.g., fish corrals and aggregating devices, to increase catch yield. However, because the country's economy was supposedly self-sufficient (Nguyen and Kim 2011), both fishery and agricultural products had extremely limited markets and were mainly traded locally. This bottleneck favored the development of a bartering system between fishery and agricultural communities around the lagoon. Fishers, usually women, brought fish and shrimps to agricultural communities in exchange for cereal products based on reciprocal demand. The bartering in the Tam Giang Lagoon differed from bartering elsewhere (Machado 2018) in that there were neither fixed places/markets nor specific times for exchanges; instead fishers would go around the villages to find their "customers." This fish-for-rice exchange bolstered social connections between fishers and farmers, which subsequently provided a support network during ill-fated times, such as during natural hazards or failed harvests. In fact, three severe natural disasters harmed the lagoon areas, causing 1029 human deaths, 349 injuries, and hundreds of disappearances (DaCosta and Turner 2007). There is no reliable record for property loss or damage; however, according to eyewitnesses, thousands of houses and other physical structures (dykes, ponds, fish corrals, etc.) were destroyed.

Reorganization 1 (a1): Planned resettlement and national economic reform (Doi moi; 1986)

After the most detrimental of these disasters (Typhoon Cecil in 1985), the government launched a resettlement program to reduce future damages and losses. Every household was allotted an area of land of 300 m², regardless of demographic characteristics. In 1986, a massive migration of fishers and families from boats onto land began, not surprising given their typhoon experiences. This resettlement quickly helped establish new social networks between newcomers and native villagers. Although social trust took time to be formed, bonding and linking social capital soon materialized (DaCosta and Turner 2007). Fishers were successfully settled into their new villages.

Major changes affecting the lagoon SES came from the 1986 national economic reform policy. Ten years after the reunification (1975–1985), Vietnam was facing an extreme economic crisis due to low production of key sectors and a high inflation rate (700%; Mallon 1997). Therefore, at the Sixth Nation Congress of the Communist Party in 1986, the Vietnamese government introduced and approved a comprehensive economic reform, known as *Doi moi* (Innovation) to ultimately increase production,

open markets, and promote international trading. Under *Doi moi*, agricultural cooperatives were quickly reformed as the government recognized market forces in the operation of cooperatives, allowing individuals to independently operate their production activities. Because of this policy, fishers and farmers were allowed to own parts of the lagoon surface for fishing purposes. This engendered major changes in the lagoon as many fishers then had the right to build concrete structures (fish corrals) on the water (known as fixed-fishing gear). Most importantly, fishers gradually split into two distinct groups: fixed-gear fishers who owned fishing gear permanently attached to lagoon areas, and mobile-gear fishers who conducted fishing activities along the shores of the lagoon.

Growth 2 (r2): Start of aquaculture and rising use of modern fishing gear (1987–1998)

Soon after resettling, some fishers started experimenting with aquaculture, in simple ways. Juvenile shrimp, crabs, and small fish caught were stored in a net or bamboo pond in the lagoon for a few months without providing any manufactured feeds. These species consumed only natural food to grow, and therefore no investment was needed, only labor. This simple method brought high profits to fishers, and it rapidly expanded to become a popular livelihood activity. Aquaculture developed further into the 1990s when an aquaculture company succeeded with an intensive giant tiger shrimp production in one village (Thuan An). At the same time, the success of local nursery centers in producing tiger shrimp juveniles completely changed traditionally extensive aquaculture. Fishers first applied the intensive aquaculture model in unproductive agricultural land areas adjacent to the lagoon. However, aquaculture ponds quickly expanded over the lagoon banks because of high profit (Mien 2006). In the meantime, many fish corrals on the lagoon were temporarily converted to net-ponds to pursue aquaculture, which had not been done before. This expansion continued for several years until the lagoon space was densely covered by ponds, nets, and other fishery structures. This diversified approach increased aquaculture in the lagoon by 80-fold from 1990 to 1998 (from 20 ha to ~1600 ha) and up to 200-fold by 2006 (~4500 ha; Thua Thien Hue Statistics Office 2005, 2010). Large areas of the lagoon became privatized, divided between three distinct groups: mobile-gear fishers, fixed-gear fishers, and aquaculture farmers.

The national economic reform rapidly opened the door for technology transfer into Vietnam. During this period, the appearance of modern materials and fishing equipment such as nylon nets and electric gear (Boonstra and Nhung 2012, Boonstra and Hanh 2015, Hanh and Boonstra 2018) dramatically increased fish catch yield because of capture efficiency. One research participant noted that "... since nylon nets were introduced in our village, it helped save a lot of initial money and incredibly increased fish catch ..." (Community leader, HDPL, 60 years old). According to Binh (1996), this period witnessed a significant increase in fish corrals from 450 sets in 1984 to 1529 sets in 1993. The availability of modern fishing equipment also helped fishers diversify their livelihood activities by creating more types of fishing gear to catch assorted and higher value species as demanded by expanding markets. It is estimated that there were 32 types of fishing gear used in the lagoon at that time (Mien 2006) and most of these were invented or improved during the period of nylon net appearance.

Conservation 2 (K2): Aquaculture and resource boom (1999–2003)

A catastrophic flood in 1999 brought new livelihood opportunities, despite its detrimental impacts on the lagoon communities. This flood significantly widened the two existing inlets (Tu Hien and Thuan An) and opened a new one (Hoa Duan). This led to changes in the hydrological regime of the lagoon, consequently improving the water exchange between the lagoon and the sea after a long period of closure. This process increased the water salinity and increased flushing because of faster currents (Andrachuk and Armitage 2015), thereby favoring a brackish water environment. Yet, it also reduced water pollutants that had been trapped in the lagoon because of aquaculture ponds and fishing structures. As a result, fish stock and other bioresources rapidly improved (JICA 2003), especially salt-water-tolerant species that had higher market value. Following the flood, both fishers and aquaculture farmers arguably had the highest harvest of their careers, lasting for three to four years (also confirmed by Andrachuk and Armitage 2015).

Besides the advantages brought by the natural environment, socioeconomic factors also contributed to the success of local livelihoods. Increasing shrimp export demand and a series of supportive governmental policies (Nayak et al. 2016) led to a rapid expansion of aquaculture areas and a surge in the number of villagers joining aquaculture (Fig. 3a). Accordingly, large areas of fishing grounds, fish corrals, and substantial agricultural land adjacent to the lagoon were converted to aquaculture ponds shortly after these policies were issued. In our two study communities, most villagers were engaged in aquaculture during this time. The aquaculture wave peaked in the mid-2000s, when villagers not only invested their own financial capital but also took loans from local banks and other financial sources to pursue aquaculture. With growing experience, aquaculture took off at an industrial level, including some commercial companies and process factories to streamline exports. The expanding brackish water conditions in combination with higher market prices gave rise to the use of more efficient fishing gear, especially long-bottom steel frame traps, locally known as *lu* (Fig. 5). Although catch yield in this period was not as high as in the 1970s, because of stock degradation, there was nonetheless a remarkable increase over time (Fig. 3c).

Fig. 5. Most common fishing gear (*lu*) currently being used in the Tam Giang Lagoon. A newly made single *lu* (left) and fishing boats with *lu* being used by fishers (right). Source: first author.



Collapse 2 (Ω): Aquaculture diseases, overexploitation of resources, and destructive fishing gear (2004–2007)

The rapid expansion of aquaculture and insufficient management accelerated the accumulation of pollution, degradation of water quality (Fig. A1.1), and the emergence of aquatic diseases. Whitespot and yellow-head were two common diseases across the lagoon; they first occurred in some few aquaculture ponds; however, as farmers had no disease knowledge, they freely drained contaminated water into the lagoon without any treatment or warning to their neighbors. This rapidly disseminated disease vectors across the whole lagoon, transferring diseases to other aquaculture ponds, and reducing wild species in the lagoon. Because no efficient guidelines from government agencies were issued to address the crisis, farmers regrew stocks after every disease collapse. Many interviewees mentioned that they would regrow three to four times in a typical season in response to disease losses. Aquaculture farmers experienced the most difficulties, being indebted with no prospect to repay their loans. Most farmers in HDPL are still indebted today because of aquaculture development loans they received in the 2000s, and the collapse of stocks through disease has had a dramatic consequence for community livelihood activities. Many villagers had to leave their homeland in search for other work to pay back the loans. Some came back to take up aquaculture again around 2008/2009, after the collapse, and when a new farming model emerged (the multispecies polyculture farming model).

Fishing-based households faced arduous times too. Water quality became extremely degraded as a result of the high density of aquaculture ponds and fish corrals. Poorly managed fish corrals in deep lagoon water prevented water flow and exchange with the sea, leading to an accumulation of pollutants and sediments and a rise in eutrophication (Marconi et al. 2010). Reduction in water exchange also intensified aquatic disease prevalence for wild fish, and decimated fish stocks because the disease vectors were retained longer in the lagoon.

Nonetheless, the escalation in efficient yet destructive fishing gear usage was likely the principal cause of fish stock decline. Although electric gear and trawling destroyed ecological habitats, *lu* harvested all sizes of fish and other productive bottom-feeding fish species (Andrachuk and Armitage 2015) that play an important role in ecological reproduction. Since its introduction, *lu* became a widely applied tool to fish in the lagoon. As noted in our focus group discussions, “...millions of *lu* are used by almost all groups of fishers across the lagoon. Everyone uses *lu* to catch fish.” Such overfishing is reflected in statistical data from the mid-2000s to the present (Fig. 3c). In the 1970s, when fishers still used simple gear made from bamboo and wood, the annual fish catch amounted to 4500 tons (Thanh 1998) but it decreased to around 2000 to 3000 tons after the 1990s (Department of Fisheries 2014).

The expansion of aquaculture and fish corrals fueled the privatization of lagoon surface water while limiting major fishing grounds available for mobile-gear fishers. This fact amplified social conflicts between aquaculture farmers and fixed-gear fishers on the one side and mobile-gear fishers on the other, mainly over spatial usage rights of the lagoon (Andrachuk and Armitage 2015). While the government had no effective solutions against the decline of the lagoon SES, villagers tried various strategies to

survive during this difficult period. It was common for households to divide their labor force across different jobs, allowing women and young children to stay in the village and pursue extensive aquaculture and fishing for subsistence purpose while men migrated to urban areas to earn income. As a result, the population of the lagoon communities experienced a notable decline after a long progressive increase (Thua Thien Hue Statistics Office 2005, 2010).

Reorganization 2 (a2): New farming model experiments, community-based management, and rearrangement of fishing structures (2008–2012)

Aquaculture farmers were seemingly trapped because of the risk of aquatic diseases. Some pioneers travelled to adjacent provinces to learn new aquaculture models and replace their mono-species cultivation. Pilot experiments of new multispecies polyculture already occurred around 2006/2007; however, successes were not noted until 2008. In this new model, farmers cultivate different species in the same pond with consideration for ecological habitat differences and growth characteristics of each species. Generally, one pond would include three main species: fish, shrimp, and crabs. By cultivating different species rather than concentrating on shrimp (too sensitive to environmental variation and prone to diseases), farmers were able to spread the harvest season to maintain good prices for aquaculture products. Although this new model did not generate profits as high as intensive shrimp cultivation, farmers still recognized its suitability to the water conditions. Mono-species aquaculture continued to be practiced in parallel with polyculture farming, but only in specific planned areas by the local government.

Beginning in 2008, the provincial and district governments issued and implemented several fishery-related policies aimed at improving lagoon water quality and ecological recovery by removing fishing structures that prevented water exchange between the lagoon and the sea. The most effective policy concerned the removal and rearrangement of fish corrals in the entire lagoon surface between 2008 and 2011 (Thua Thien Hue Provincial People's Committee 2008, 2010a, b, 2011). Within four years, nearly 50% of the fish corrals (757 sets) occupying approximately 800 ha were completely removed from the lagoon, and the remaining ones were relocated to widen water flow and enhance aquatic habitat recovery (Table A2.1). The government provided a range of support and allowances to the affected farmers, such as up to a six-month rice allowance, financing for transferring to other jobs, and vocational training for young farmers. However, only a few farmers followed this opportunity to diversify their livelihoods to less resource-based activities such as buying a market kiosk to trade fishery products or opening a grocery shop. Other policies specifying fishing gear to be legally allowed or banned were also issued.

Despite the application of several management efforts and policies, the lagoon resources and environment experienced continued degradation because of poorly defined property rights, social conflicts over resource competition, and overfishing (also confirmed in Nguyen et al. 2018 and Huong and Berkes 2011). Recognizing the problems in the lagoon, the local government finally changed the fishery management system, encouraging community participation. In 2009, the first Fishery Association (FA) was established in the lagoon's south, which was a milestone

for the development of a comanagement system. Each FA was assigned to manage its fishing territory and activities and to mediate conflict among members, striving for sustainability of the lagoon ecosystem and community livelihoods. By the end of 2016, 47 FAs were established, with rights allocated to use and manage > 85% of the lagoon's surface (~16,000 ha; Department of Fisheries 2016). Although FAs have not yet reached their full potential, they have improved responsive awareness among fishers and farmers in protecting the lagoon environment and have opened a channel through which to convey community concerns to the government.

In addition, the government established no-take habitat protection zones to facilitate the lagoon's ecological recovery. In each zone, different hard structures were put in place, e.g., concrete pipes or tree bundles, to promote aquatic resources reproduction. Annually or seasonally, the Department of Agriculture and Rural Development will release juveniles to these zones to increase the lagoon's fish stock. A total of 23 such zones covering 615 ha were established between 2009 and 2016 (Department of Fisheries 2016).

Early growth 3 (r3): Success of new farming systems: multispecies polyculture and cross-flooding aquaculture (2013–2019)

Currently, the lagoon SES is dominated by multispecies farming systems and the lingering use of *lu*. After several years of experimentation, the multispecies polyculture farming model is now well stabilized and highly successful. Almost all interviewed aquaculture farmers have changed their farming system from monoculture to polyculture and this innovative farming model has helped reduce pollutants in ponds because benthic (bottom-dwelling) species can recycle the food left by surface (pelagic) species. The risk of aquatic diseases is now much lower than during times of intensive shrimp cultivation.

Facing decreasing water salinity, some aquaculture farmers are now developing an even more advanced farming model called "cross-flooding aquaculture." This approach is also based on polyculture principles but it is more economic and environmentally adaptive. It helps fish continue to grow during the rainy season when the lagoon water salinity and temperature would otherwise be too low, by drilling onsite wells to extract saline water from the underground aquifers to the ponds. Participants in V14 strongly agreed that this model had boosted their livelihoods and well-being. Income from recent aquaculture helps them to pay back old loans and rebuild their houses. Given the model's economic value, the commune government is planning to convert 4.3 ha of unproductive agricultural land to aquaculture (Quang Cong Communal People's Committee 2018). However, it is cautiously noted that cross-flooding aquaculture is not suitable in all areas of the lagoon, especially the western side that borders with inland areas, because of low salinity of the aquifer.

Having learned the painful lessons of aquatic diseases associated with intensive shrimp monoculture, the local government is now paying more attention to spatial planning and management. The provincial government issued a comprehensive guideline for intensive shrimp cultivation to be applied to the entire lagoon and adjacent areas (Thua Thien Hue Provincial People's Committee 2014). It requires any individual practicing intensive monoculture to meet several standards, ranging from the selection of juveniles

to waste water treatment. Despite recent government efforts and the successful multispecies farming system, the majority of lagoon villagers expressed a pessimistic view regarding the lagoon's sustainability.

Heterogeneity in livelihood pathways

The adaptive cycle provides an in-depth understanding of the evolution of the Tam Giang SES. The observed changes were far from uniform, resulting in different outcomes to lagoon communities. Here, we incorporate information from the detailed description of the adaptive cycle of the Tam Giang fishery system coupled with insights from the interviews to, first, illuminate livelihood pathways of local communities and, second, assess the role of key drivers and system variables in shaping these pathways.

Figure 6 illustrates the divergence of livelihood pathways into first two and then three distinct trajectories that emerged as a result of the social-ecological dynamics in the lagoon for > 100 years. Livelihood conditions of fishing-based communities went through an upward trend until the emergence of aquaculture as a new livelihood activity. Despite some significant challenges and failures, aquaculture farmers became the wealthier group, largely because of owning important physical capital, i.e., aquaculture ponds. In contrast, fishing households experienced a slow but continuous degradation of living conditions and household well-being driven by significant declines of fish stock and lagoon resources and shrinking access to fishing grounds. Understanding this heterogeneity in livelihood pathways as shaped by historical changes in the SES is a vital precondition for designing future fishery management plans that incorporate dynamic and differentially vulnerable livelihood groups, with their distinct needs and aspirations.

Cross-scale processes and the role of system variables

The Tam Giang lagoon system has undergone a wide range of social and ecological changes in which transitions between phases of the adaptive cycles were triggered by both cross-scale processes and cross-domain interactions, as reflected in the nested adaptive cycles in Figure 4 and further details in Figure 7. Top-down processes (represented on the vertical axis in Figure 7) such as the national economic reform, the national policy on coastal aquaculture development, and credit programs catalyzed rapid expansion of aquaculture ponds and fish corrals, leading to cascading changes at the lagoon scale. The latter includes habitat alteration, amplified water pollution, the spread of aquatic diseases, and fish stock decline. These processes gradually eroded the customary fishing system. Bottom-up processes including inadequate aquatic disease management, overharvesting, and the use of destructive fishing gear scaled up to prompt changes in fishery governance system at the provincial level.

Moreover, the lagoon dynamics are shaped by numerous cross-domain interactions between the social and ecological components rather than by single variables (represented on the horizontal axis in Fig. 7). For example, the catastrophic typhoon in 1985 widened the lagoon inlets and increased salinity levels, which initially created favorable conditions for aquaculture development and fishing activities but subsequently accelerated the ecological degradation of the SES and overexploitation.

Equally important for future management actions is a solid understanding of the role of variables that influence an SES

trajectory. In the SESs, variables can be described as “fast” or “slow” (meant as relative terms) to characterize their role in system changes and their pace of impacts. Fast variables are those triggering change over the short term, e.g., pest species emergence, crop production, or aquatic diseases, compared to variables that change more slowly, so-called slow variables, e.g., water pollution accumulation. Dynamics of fast variables are strongly influenced by slow system variables; for example, aquatic diseases are usually caused by prolonged water pollution accumulation. The identification and interpretation of the slow and fast variables are based on our best judgment informed by first-hand knowledge of the lagoon, qualitative data obtained from the interviews and FGDs, and some relevant literature (e.g., Huber-Sannwald et al. 2012, Walker et al. 2012). We nonetheless acknowledge the possibility of alternative explanations with different sets of fast and slow variables.

Considering the proposition by Gunderson and Holling (2002), Kinzig et al. (2006), and Walker et al. (2006) that critical changes in and sustainability of most SESs are determined by a small set of three to five key slow variables at any one scale, we confirm this “rule of hand” with our results revealing the prevalence of slow variables in driving long-term dynamics and behaviors in the lagoon (Fig. 7). These slow variables encompass national (economic) policies, international markets, fishing technology development, property and land use rights, and climate-induced changes at larger scales, as well as water salinity, water pollution, fish stock and diversity, lack of livelihood alternatives, and (new) aquaculture models at the local SES scale. Changes in these slow variables accelerate fast variables, e.g., aquaculture expansion, aquatic disease outbreaks, overfishing, and increase of destructive fishing gear, and the response to environmental and other shocks, resulting in the transitions between phases in the adaptive cycle.

Challenges for future livelihood adaptation

Coastal environments are rapidly changing (Elliott et al. 2019). Because social and ecological resilience is directly coupled and coevolves, a future SES collapse can be assumed when society fails to anticipate or grasp key problems of a system (Diamond 2005). Based on insights from the literature, field observations, and interviews, we elucidate four factors that will likely challenge lagoon communities to adapt their livelihoods to possible conditions in the near future.

Climate change

Historical hydro-climatological changes (Fig. A1.2) and projected climate changes are well documented at both national and local scale (Vietnam Institute of Meteorology, Hydrology and Climate Change 2008, 2015). Future increased rainfall amount and variability will likely affect coastal water quality, increasing dissolved nutrient concentration and loads coming from the rivers (Hesse et al. 2015), toxic bacterial blooms (de Souza et al. 2018), and salinity reductions (Anthony et al. 2009, Christia et al. 2018). Associated consequences could spread aquatic disease and pollution risks and delay the seasonal aquaculture calendar and fish growth.

Changes in temperature patterns with a warmer summer predicted in the lagoon can amplify heat shock and disease stress for aquaculture species (Marcos-López et al. 2010). Hotter conditions will require farmers to equip high-tech machines, e.g., oxygen/air supply systems, to maintain optimal pond conditions for aquaculture species. Hotter summers will also cause more

Fig. 6. Illustrative representation of dynamics of climatic, environmental, and socioeconomic and governance factors (a), leading to differential livelihood pathways (b) over time in the Tam Giang social-ecological system (Data from the detailed description of the adaptive cycle of the Tam Giang fishery system, interviews, and focus group discussions). A catastrophic typhoon (1) caused extreme losses and damages to lagoon communities. Consequently, a resettlement program together with the national economic reform (*Doi moi*) and the availability of modern fishing materials, i.e., nylon nets, (2) changed the household lifestyle from nomadic fishing to fixed fishing and improved livelihood conditions (3). A series of supportive policies (land law, decision of the Prime Minister, and credit program), success of shrimp juveniles, and increase of shrimp export market (4) combined with an increase in the saline water environment due to the impact of a historical flood (5) led to a rapid expansion of aquaculture and fish corrals. Consequently, distinct livelihood trajectories emerged. Aquaculture-based households quickly became a better-off group (6) while fishing-based households started experiencing a downward trend (7) due to the reduction of fishing grounds and overcrowding. Rapid and uncontrolled expansion of aquaculture and fish corrals and inadequate management caused substantial water pollution and disease blooms throughout the lagoon (8). Aquaculture-based households lost revenues rapidly (10); fishing-based families experienced slight declines (11) compensating with more destructive fishing gear leading to a further decrease of fish stock (9). Remarkable governmental efforts to improve ecological conditions led to the removal of 50% of fish corrals and rearrangements of the remaining ones to increase water flow and exchange between the lagoon and the sea, even though the ecological system was not sufficiently improved. The convergence of the establishment of no-take zones (12), decrease of water salinity due to high variability and increased rainfall (13), and progressive increase in pollution (14) forced households to change livelihood strategies. Some aquaculture-based households recovered because of the success of the new farming model “cross flooding aquaculture” (15) while most others managed to slightly improve their livelihood conditions with multispecies aquaculture farming (16). The livelihoods of fishing-based households eroded further (17). Climatic and environmental trajectories move closer to the catastrophic end of the spectrum while socioeconomic policies and interventions remain unknowns regarding social-ecological system resilience (18). Policy responses to improve ecological habitats and water quality and to adapt to climate change will be the key elements to enhance the livelihood conditions of resource users (19).

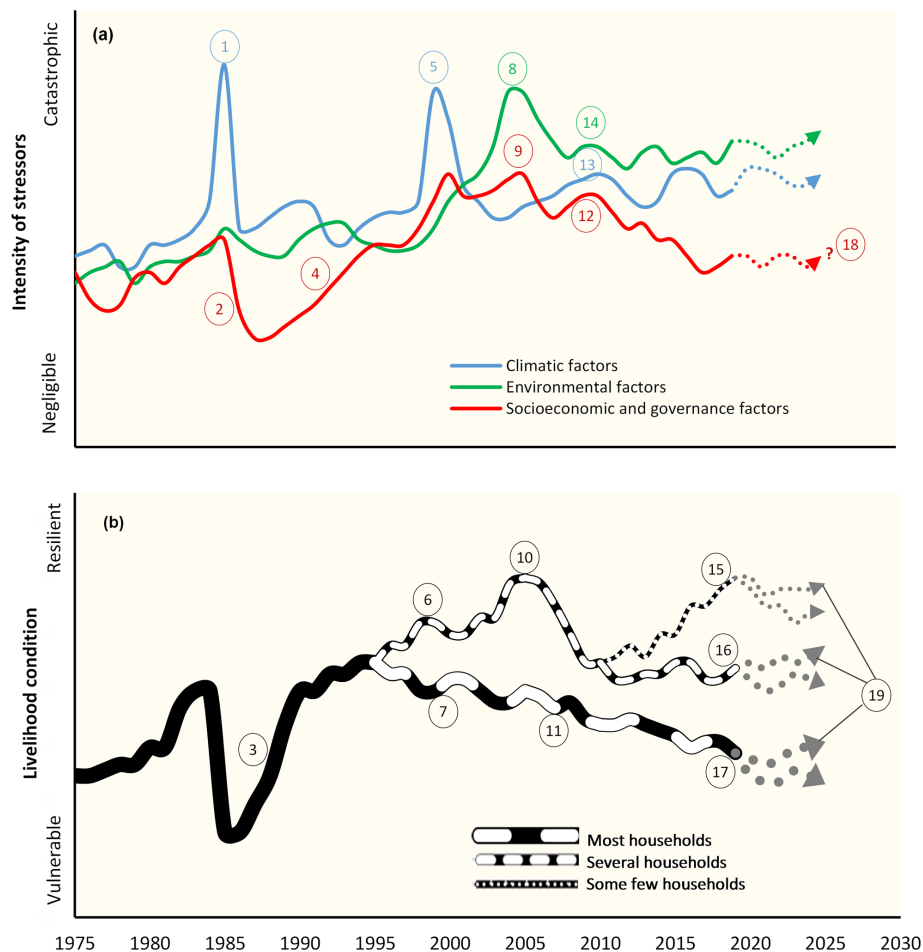
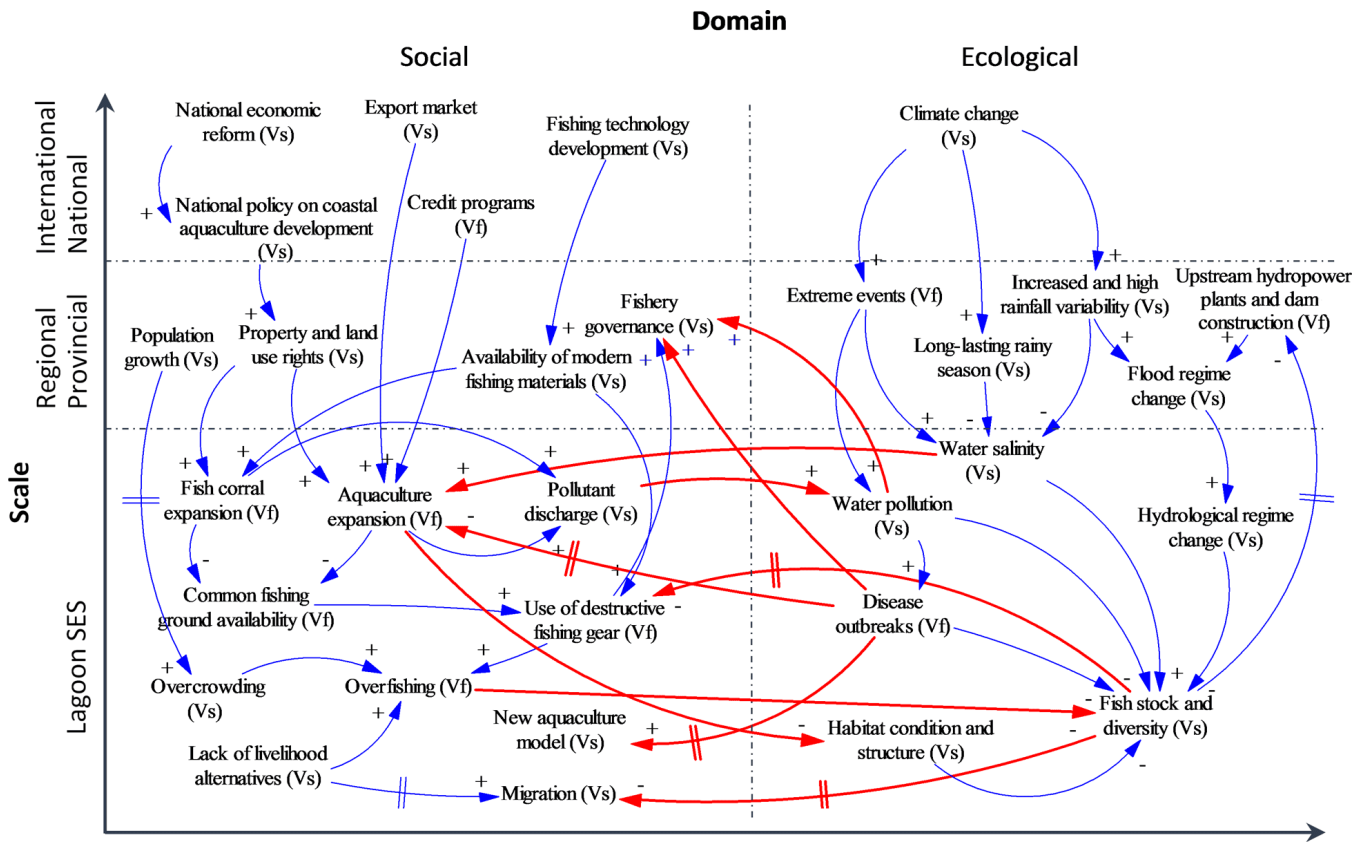


Fig. 7. Causal loop diagrams representing cross-scale processes (vertical) and cross-domain interactions (horizontal) driving social-ecological dynamics in the Tam Giang Lagoon. Blue arrows indicate multiscale relationships between system variables. Red arrows represent critical interactions between the social and ecological parts of the lagoon social-ecological system. The cross sign on red arrows signifies a time-delay process. Vf and Vs denote fast and slow variables, respectively.



adverse consequences for both existing multispecies and planned intensive monoculture farming because of high stock density. It is also possible that convergence of rising sea levels (Fig. A1.3) and water storage in upstream hydropower plants and reservoirs will result in increased salinity, exceeding optimal levels in the summer. These processes may coincide and lead to harvest losses in both aquaculture and fishing. Increasing intensity and frequency of extreme events along Vietnam’s coast (Ministry of Natural Resources and Environment 2016) may well pose additional threats to the lagoon communities and infrastructure associated with their production systems.

Changes in lagoon spatial planning and use

In an attempt to recover the lagoon ecosystem, the local government has established several ecological habitat protection zones (no-take zones) since 2009. Now, the central government, with financial support from the UNDP, is planning to convert parts of the lagoon to protected wetland conservation areas. Although villagers in our study foresee positive impacts of no-take zones on ecosystem recovery, they emphasize that these zones cannot compensate for the decline caused by destructive fishing gear and other unsustainable practices. Although the fixed fishing structures and aquaculture areas remain unchanged, or even increase in some parts of the lagoon, many mobile-gear fishers

complained that more no-take zones would constrain their livelihoods as these areas would diminish communal fishing grounds. Unless the government properly manages destructive fishing gear and provides livelihood alternatives, no-take zones appear to bring benefits only to a small number of people while constraining the majority of lagoon-dependent residents. Although long-term contributions of no-take zones to the ecological system and fish stock recovery are expected, the impacts of these zones on livelihoods of mobile-gear fishers, the poorest group, are likely to be negative.

Uncertain sustainability of new farming models

The long-term sustainability of the new farming models remains unproven, despite their economic profits, because aquaculture diseases continue to occur in different places all year round. More polyculture farming, especially cross-flooding aquaculture, requires more fresh feeds (small fish caught from the lagoon) and it accelerates fishing efforts, leading to a further decline of the lagoon fish stock that has already been degraded for a long time. Aquaculture farmers raised concerns about the expansion of the new monoculture farming model as they see substantial negative impacts to the lagoon water environment and ecosystem. Given that the lagoon communities experienced a collapse of monoculture farming in the 2000s, their concerns regarding the

future of new mono-species farming are justified, irrespective of the government issuing regulations and guidelines.

Path dependency

In response to the social-ecological changes, fishery households have skillfully evolved their livelihood adaptations. Although some adaptations were successful for coping, others have caused long-term degradation of ecosystem capacity. Notably, continuous application of more manufactured feeds to maintain aquaculture production, and cultivation of non-native species, i.e., white leg shrimps (*Litopenaeus vannamei*), in unplanned areas discharge more pollutants and potential disease vectors to the communal lagoon areas. A majority of fishers using more effective gear, especially *lu*, and investing in fishing to offset the low catch is responsible for much of the recent depletion of fish stock. These past and current maladaptive strategies have favored obtaining short-term benefits at the expense of long-term system sustainability. With limited capacity to adopt more innovative adaptation measures, lagoon-dependent communities will likely continue their past and current development paths. Such path dependency is often resistant to necessary changes to adapt to future climate change (Barnett et al. 2015). It also signals a mismatch between villagers' behavior and the social-ecological system conditions, ultimately locking them into a social-ecological trap (Boonstra and Hanh 2015).

DISCUSSION

Given the need for systematic investigations of the dynamics of coupled SESs (Leenhardt et al. 2015, Herrero-Jáuregui et al. 2018), this study uses the adaptive cycle heuristic to trace the changes and identify critical drivers responsible for the transitions between cyclic phases in the Tam Giang Lagoon in Vietnam, a typical dynamic SES. Our findings suggest that adaptive-cycle dynamics of this SES were driven by a series of historical events and two-way interactions between the social and ecological system components. Historical changes in the lagoon SES have given rise to divergent livelihood pathways. Looking toward the future, local communities are likely to face increasing challenges induced by the intensification of human uses, prolonged ecological degradation, and climate change. Here, we reflect on insights from applying the heuristic of the adaptive cycle, the role of slow and fast variables for SES sustainability, system feedbacks, livelihood pathways, and potentially looming collapses.

We substantiate that the adaptive cycle heuristic provides a systematic framework to understand holistic dynamics of coupled SESs, including human activities and natural disturbances. In our case, we traced these dynamics based on empirical evidence from and triangulation between quantitative and qualitative data to distinguish periods of growth, conservation, collapse, and reorganization. Expanding on existing literature reviews on the usefulness of the adaptive cycle in explaining the dynamics of changes in SESs (Goulden et al. 2013, Salvia and Quaranta 2015), we highlight three aspects from our case study that we consider useful for future management actions.

First, although intrinsic cyclicity is a key concept of Holling and Gunderson's (2002) adaptive cycle, the phases may not necessarily progress in a sequential manner because a sufficiently large external disturbance can disturb the cyclicity (Abel et al. 2006). Our results empirically reflect this conclusion as the Tam Giang SES moved

from late growth to a collapse without going through the conservation phase, as a result of inadequate policies followed by a catastrophic typhoon. Knowing that the absence or presence of phases can be strongly influenced by policy interventions, we recommend that policy makers carefully examine critical thresholds (also called tipping points) in order to comprehend immediate needs for action and longer term management options to nudge the system toward a more desirable state. As stated by Walker and Meyers (2004), Scheffer et al. (2009), and (Crépin et al. 2012), critical thresholds are fundamental for regime shifts but also hard to identify. Hence, monitoring potential indicators of imminent transitions when a threshold is approaching, as recommended by Scheffer et al. (2009), is more desirable. For example, the extinction or dramatic decline of native fish or the emergence of invasive species in a fishery system are early warning signals, indicating the system is approaching a threshold. Given the early warning signals of possible shifts, resource managers are well served to move the system away from the threshold to avoid shifts or, alternatively, should prepare to adapt when shifts are unavoidable (Crépin et al. 2012). In the case of the Tam Giang SES, careful monitoring to reduce overexploitation and improve water and ecological conditions can potentially help to increase the system's distance to a looming regime shift.

Second, identifying exact transition points between adaptive phases remains an analytical challenge. This could be due to insufficient quantitative indicators to distinguish phases (Angeler et al. 2015), or divergence in interpretation of qualitative data (Daedlow et al. 2011). Although quantitative approaches are often constrained by a lack of historic data and the difficulty in selecting appropriate indicators (Vang Rasmussen and Reenberg 2012), qualitative analyses require a triangulation of various sources of data, as shown in this case study, and could potentially lead to biased descriptions. To avoid such bias, especially in systems with limited historic data, future studies are well served by combining both approaches.

Third, applying the adaptive cycle provides a holistic picture of changes. Such a picture, we find, is powerful in raising community awareness of environmental and ecological degradation and facilitating social learning processes. This finding mirrors the suggestions by Folke et al. (2010) and Olsson et al. (2006) that SES transformations should consider crises as "windows of opportunity" to gather knowledge and experience to navigate the system to a desired regime. The majority of our interviewees showed a remarkable understanding of cause-effect relationships between resource exploitation, lagoon sustainability, and livelihood conditions. Despite their insights, many continued unsustainable practices, irrespective of the lagoon's degradation. Why is that? We suspect that, for most households, exploiting the lagoon resources is the only way to sustain their livelihoods, because of low educational levels and limited livelihood alternatives. Moreover, the enforcement of governmental management rules is still far from targets. Numerous fishers explained that illegal fishing with destructive gear was omnipresent in the lagoon, providing little incentive to comply with the rules. Hence, the problem is not user ignorance but inadequate governmental spending on controlling destructive gear. We recommend more resources to encourage fishers to comply with fisheries rules and foster opportunities for economic diversification at the local level to reduce pressures on the lagoon.

Well-targeted policy responses are also needed regarding the various roles fast and slow variables play in determining the SES dynamics. In a tropical fishery system such as the Tam Giang Lagoon, the slow variables, e.g., water salinity, water pollution, fish stock abundance, and livelihood alternatives, drive fast variables, e.g., aquaculture expansion and aquatic diseases, and hence play a critical role in long-term system sustainability. Fast variables tend to act in the short term, thus are less useful in characterizing the long-term state of the system (Adger et al. 2005). However, based on empirical results of the Tam Giang Lagoon, we recommend adequate consideration of fast variables in short-term management plans to support the sustainability of the system. The reason for this is that fast variables may cause persistent problems for the system, aquatic diseases eroding the stability of aquaculture tied to inefficient management. Following Fischer et al. (2015), we encourage deliberate efforts to address the interplay between slow and fast variables as key to achieving fishery management targets.

Equally vital is a better understanding of two-way interactions and feedbacks in driving the resilience of coupled SESs (Cinner and David 2011, Schlüter et al. 2012). Such interactions are evident in the Tam Giang Lagoon system. For example, high-profit aquaculture expansion polluted the lagoon water environment, leading to degraded fish stock and more aquatic diseases and social conflicts, which in turn precipitated the collapse of the aquaculture system and erosion of livelihood systems. Our interviewees reiterated that the environmental feedbacks from the social to ecological system elements were rather straightforward, e.g., aquaculture expansion polluting water, or overfishing decreasing fish stock and diversity, while the institutional (government) feedbacks from ecological degradation to required policy actions occurred slowly and were more difficult to track, e.g., reduced fish stock and diversity because of the control of destructive gear. Tardy government responses indicate a lack of resources and technical capacity in the governance system (Varjopuro et al. 2014). Yet, any delay in governmental response to severe problems increases the risk of the system approaching imminent collapse. Findings from this study underscore the need to speed up governmental responses to more effectively address persistent management issues such as water pollution, aquatic diseases, and fish stock decline, in order to safeguard the lagoon SES sustainability. This, we recommend, should entail capacity building for government officials responsible for the lagoon and fisheries management, including using the heuristic of the adaptive cycle as both a descriptive and anticipatory tool.

Adaptation to changes in governance systems and ecological conditions can allow some households to experience an upward livelihood trajectory. However, a more nuanced assessment shows that pathways change over time, depending on interactions between socioeconomic, climatic, and environmental factors, and only certain households reap the benefits. In a rapidly changing environment like a coastal lagoon, the possession of productive property (aquaculture ponds) plays a fundamental role in household adaptation. Aquaculture households use their pond as a valuable deposit to take a loan and invest in aquaculture during boom years or off-farm activities in bust years. Owning aquaculture ponds also guarantees an opportunity to immediately take advantage of innovative aquaculture models. This, in turn, widens the livelihood adaptation space and increases

the resilience of aquaculture households. In contrast, fishing households were not able to recover after the aquaculture expansion. Their livelihood trajectory declined, with adaptation efforts persistently constrained because of fishing ground reduction, water pollution, disease outbreaks, and fish stock declines. Interviewed fishers lamented the fact that diversifying fishing gear was the only way to survive, acutely aware of the associated fish stock depletion.

Our results illustrate heterogeneous trajectories across groups of households, explaining critical thresholds that lead to inequitable benefits and erosion of social cohesion. This mirrors findings by Hoque et al. (2018) who show that the adaptive success of one group reduces the adaptive capacity of another group in fisheries-based common pool resource management. Such insight requires adjustments in management policies. We recommend that policy makers take into account socioeconomic diversity and the needs of different resource users in designing plans and processes. Moreover, because social cohesion is a core attribute of the success of comanagement in small-scale fisheries, policies should attempt to reduce inequitable benefits while fostering social cohesion and trust to encourage active fisher participation in lagoon comanagement. Finally, any policy and management plan, e.g., establishment of wetland conservation areas, that further constrains the livelihoods of marginalized groups should be designed with extreme caution, especially when livelihood alternatives are limited. Acknowledging the complexity and power dynamics in policy-making processes, we underscore the need for rigorous analyses of differential livelihood trajectories, uneven adaptive capacities, and the multilayered factors that shape the vulnerability and resilience of various user groups in order to design inclusive and sustainable management policies.

Although our primary research objective was not to specifically examine regime shifts, insights from narratives of the fishery SES evolution embedded in the adaptive cycles provide signs of regime shifts in the Tam Giang lagoon. At least two regime shifts, as characterized in Biggs et al. (2018) and Rocha et al. (2015), were evident, namely the collapse of fisheries and common pool resource decline. Accordingly, the system transitioned from customary fishery management with abundant resources, open access, and strong social cohesion to a highly regulated system with dwindling resources, restricted access, and social conflict over resource competition. In addition, rapid construction of aquaculture ponds has changed the lagoon's original diverse habitats, leading to abrupt and persistent modifications in the lagoon structure and functions. These transitions, however, did not occur in isolation but were linked to each other, causing cascading effects. In other words, the occurrence of a regime shift accelerates subsequent shifts, as explained by Rocha et al. (2018). In the Tam Giang lagoon SES, the transition from open fishing areas to aquaculture-dominant systems resulted in several subsequent effects, including water pollution, aquatic diseases, resource decline, and governance changes. Negative consequences of these shifts for both social and ecological subsystems are now well recognized. The local government instigated several management efforts to address these undesirable consequences; however, the system has not sufficiently recovered.

Because SESs are constantly changing and coadapting (Folke 2006, Brattland et al. 2019), the risk of a regime shift is often difficult to recognize (Rocha et al. 2014). Such a shift is typically

costly and difficult to reverse, in some cases even irreversible (Rocha et al. 2014, Biggs et al. 2018). Given the range of factors influencing the likely regime shifts in the Tam Giang SES, resource managers and policy makers struggle to pinpoint suitable strategies, resources, and capacities. As Crépin et al. (2012) argued, addressing global factors, e.g., climate change and global warming, is difficult for local managers. We therefore suggest pressing management efforts should concentrate on resolving local factors, e.g., water pollution, overharvesting, and social conflicts, which may reduce the likelihood of a next regime shift in the Tam Giang.

Finally, with respect to the cyclical behavior of the Tam Giang Lagoon system, a new collapse seems predictable because of human use intensification coupled with risks from a changing climate. Livelihood-based fishing activities are likely to continue to degrade key resources, despite regulatory efforts. Most research participants expressed a rather pessimistic outlook for the future. Although novel aquaculture farming models provide hope, they also undermine the ecological resilience of the whole lagoon SES. Thus, avoiding a new collapse and steering the system toward sustainability ought to be the foremost priority of management policies. This requires governance systems to design and implement frameworks for long-term monitoring of system dynamics and shifting risks, in parallel with explicit attention to deep leverage points that potentially result in transformational systemic change (Abson et al. 2017). Effective enforcement of existing fisheries management policies regarding mesh size and the banning of destructive gear and regulations on water treatment and aquatic diseases are most imperative to improve ecological resilience and safeguard rural livelihoods. Diversifying local livelihood options, as also requested by most villagers, will lessen dependence on the lagoon, create needed space for adapting to future socioeconomic and climatic challenges, and foster sustainable development among the lagoon communities.

CONCLUSION

In this study we have shown that the adaptive cycle heuristic is indeed a helpful tool to appreciate long-term dynamics and identify major periods in the evolution of coupled SESs that lead a system to its present conditions. As in other tropical regions, small-scale fishery livelihoods in low-lying coastal areas in Vietnam are susceptible to multiple socioeconomic, environmental, and climatic shocks and disturbances. Changes in the SES may bring benefits to some but also cause persistent constraints or sometimes irreversible losses for others in shared common pool resources. This study provides a unique illustration of livelihoods of lagoon-dependent communities being shaped by SES changes, not in homogenous ways but distinctly differentiated by resource user groups. This nontrivial nuance is of practical importance for policy makers to ensure that differential needs and aspirations of resource users are reflected in supportive fishery policies. Such targeted treatment fulfills one critical recommendation regarding transformation of SESs as proposed by Andrachuk and Armitage (2015): “we need to examine the ways that governance initiatives will be beneficial for some people and detrimental for others, and we need to be fully aware of locally contested interests and acknowledge competing priorities for fisheries management and human well-being.” Actively working with such stakeholder differences reduces the risk of social conflicts and resource

competition that often arise in common pool resource management.

We end by endorsing the adaptive cycle heuristic for examining the detailed dynamics of coupled complex systems and identifying key drivers and feedbacks between their social and ecological components within and beyond fishery systems. At the same time, we recognize the limitations of the adaptive cycle as an anticipatory tool and recommend complementing the heuristic with participatory scenario building to envision and design equitable and resilient management initiatives.

^[1] In this study, we use the terms “drivers” and “system variables” interchangeably. Because dynamics of coupled social-ecological systems are multiscale dependent, and an SES rarely operates at one single scale, drivers can be viewed as parts of the system under consideration.

Responses to this article can be read online at:

<http://www.ecologyandsociety.org/issues/responses.php/11489>

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Data Availability Statement:

The data/code that support the findings of this study are available on request from the corresponding author, [H. T. T]

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Appendix 1. Background information about the environmental and ecological changes in the Tam Giang Lagoon

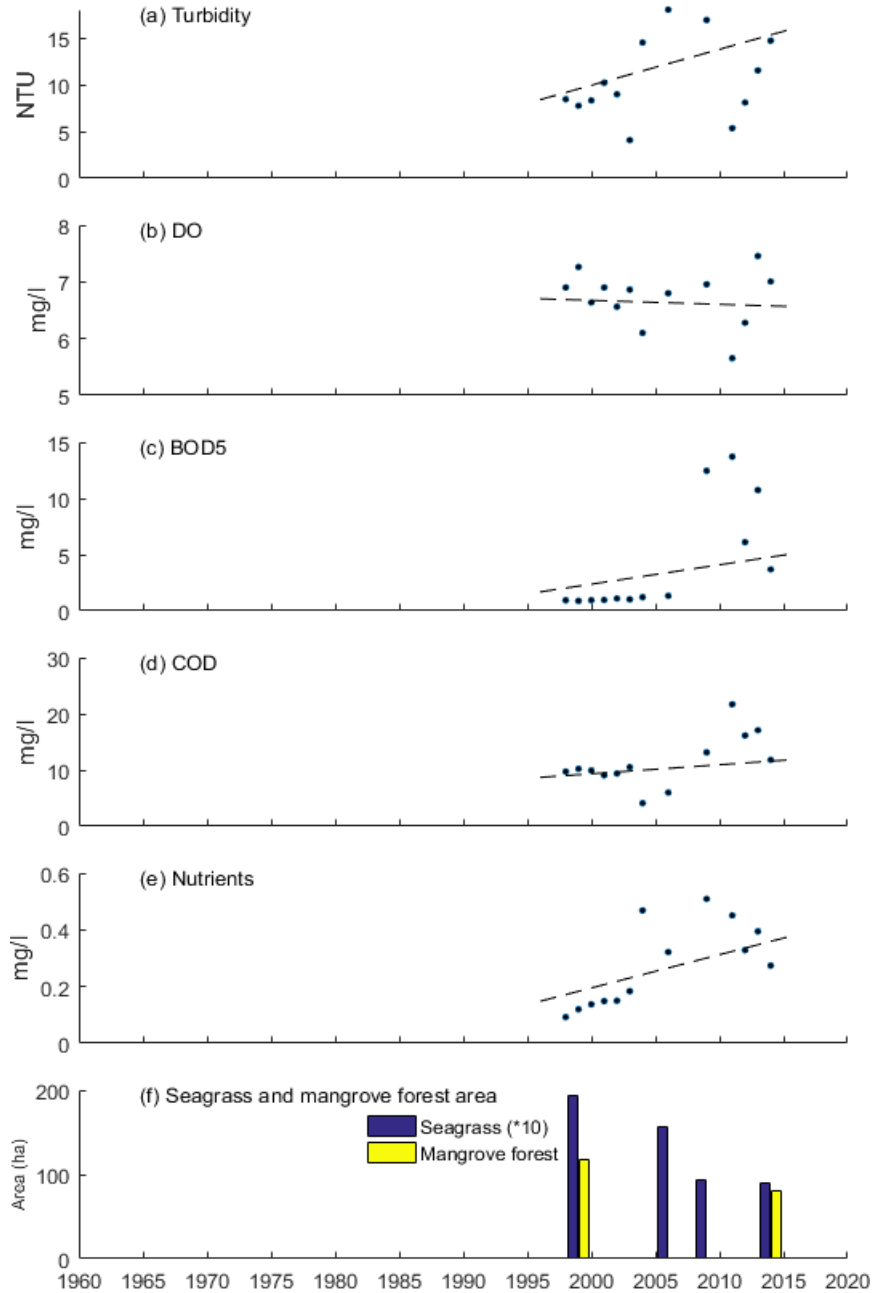


Figure A1.1. Changes in the lagoon's natural conditions (DO, BOD5 and COD stand for the dissolved oxygen, biological oxygen demands, and chemical oxygen demand, respectively. Nutrients include NO_3^- and PO_4^{3-}). Data collected from multiple sources.

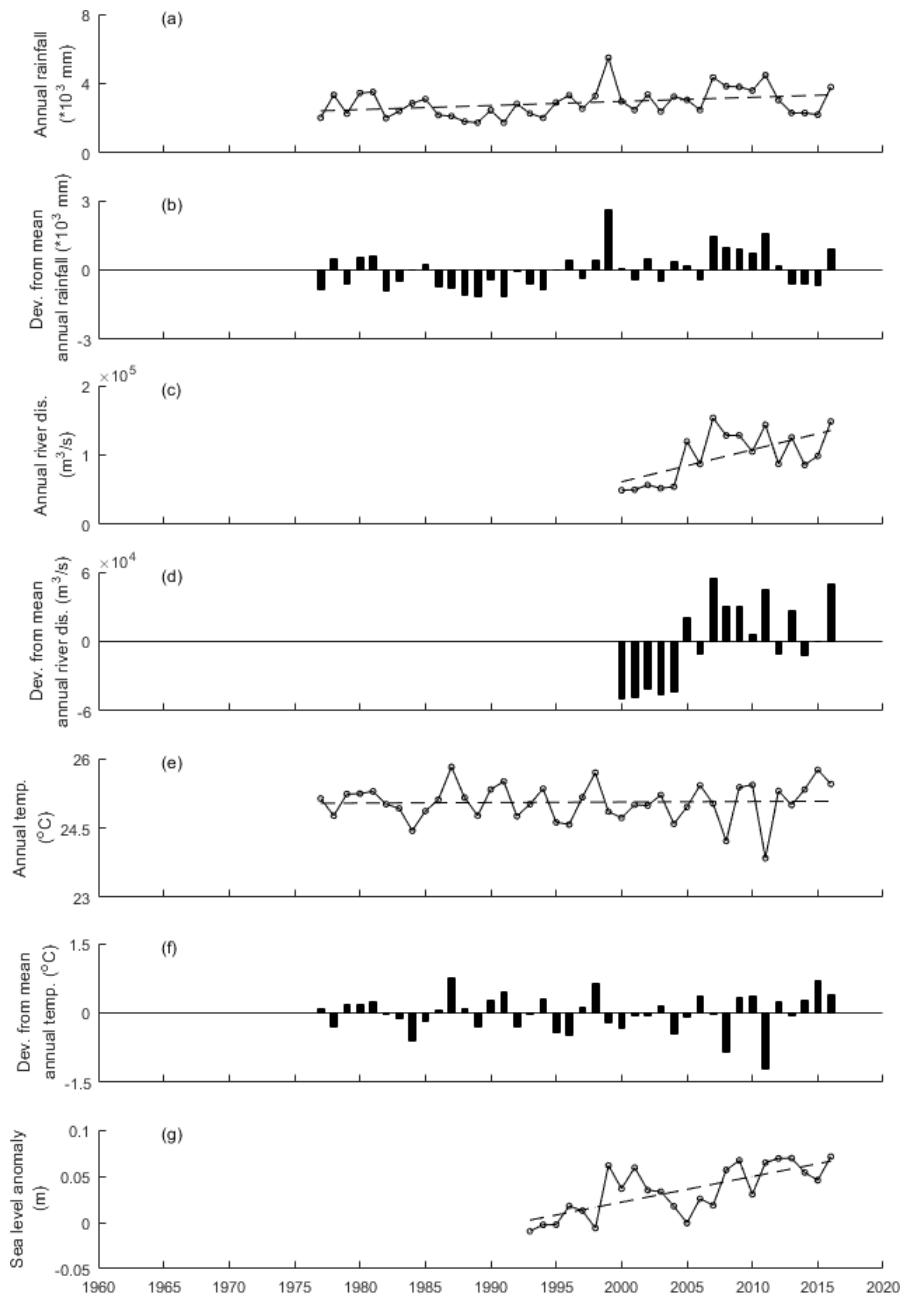


Figure A1.2. Time series of annual trends in hydro-climatological factors in the Tam Giang Lagoon (Meteorological data were derived from the Hue meteorological station and hydrological data from the Kim Long hydrological station).

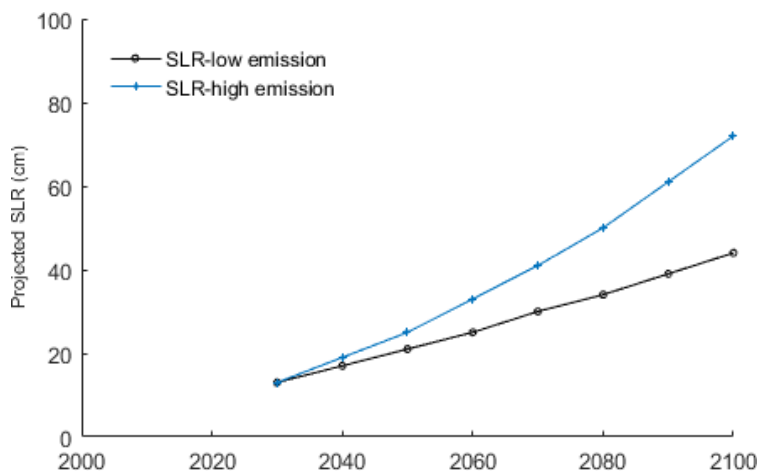


Figure A1.3. Future projected sea level rise (SLR) along the coast of Thua Thien Hue Province (Ministry of Natural Resources and Environment 2016)

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Appendix 2. A government policy effort to improve the lagoon ecological condition

District	Status of fish corrals		Fish corral removal required		Fish corral left for production		Change (%)
	Number of household engaged	Number of fish corrals	Number of Household engaged	Number of fish corrals	Number of Household engaged	Number of fish corrals	
Phong Dien (2008)	116	113	n.a	65	n.a	48	-57.5
Quang Dien (2010)	370	441	172	243	198	198	-55.1
Phu Vang (2011)	361	351	158	158	203	193	-45.0
Phu Loc	665	665	n.a	291	n.a	374	-43.8
Total	1512	1570	n.a	757	n.a	813	-48.2

(Note: “n.a” meant data was not available)

Table A2.1. Fish corrals re-arrangement in the Tam Giang Lagoon (Thua Thien Hue Provincial People's Committee 2008, 2010a, 2010b, 2011)

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