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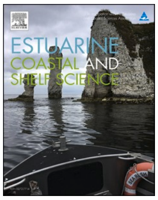

Reconciling nature, people and policy in the mangrove social-ecological system through the adaptive cycle heuristic

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ABSTRACT

While mangroves are increasingly described as social-ecological systems (SESs), performing SES research is so much more than merely documenting local resource utilisation patterns in case studies. The aim of this paper is to review and show how ecological, human and institutional resilience could be understood and fostered in an era of uncertainty, through the adaptive cycle (AC) heuristic. Uncertainties come in many forms and shapes: climate change, social and economic dynamics, natural disasters, political and institutional disruption and ever-increasing public demands for participation. Social-ecological studies form windows of experimentation that can provide insights beyond their case-specific context. In order to synthesise and structure the cumulative knowledge base arising from existing and future studies, the need for a suitable overarching framework arose. Here, the AC heuristic represents the connectedness between variables of the mangrove SES *versus* the mangrove's

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Abbreviations: AC, adaptive cycle; MMFR, Matang Mangrove Forest Reserve; NTFP, non-timber forest product; SES, social-ecological system; SES-ECO, Related ecosystems; SES-I, Interaction; SES-GS, Sensu ostrom-Governance system; SES-O, Sensu Ostrom-Outcome; SES-RS, Resource system; SES-RU, Sensu ostrom-Resource unit; SES-S, Social, economic and political setting; SES-U, Sensu ostrom-User; VJR, Virgin Jungle Reserve.

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transformability
vulnerability

accumulated capital (natural, built, human and social). We posit that the AC heuristic can be used to interpret spatial and temporal changes (ecological, social, economic, political) in mangrove SESs and we exemplify it by using the 2004 Indian Ocean tsunami as well as a century-long silviculture case. The AC, combined with the SES scheme, allows integration of the spato-temporal dynamics and the multi-dimensional character of mangrove SESs. We also reviewed the ecosystem functions, services and disservices of mangrove SESs, linking each of them to SES capital and variable (fast or slow) attributes, which in turn are closely linked to the different axes and phases of the AC. We call upon mangrove scientists from the natural, applied, social and human sciences to join forces in fitting diversified empirical data from multiple case studies around the world to the AC heuristic. The aim is to reflect on and understand such complex dynamic systems with stakeholders having various (mutual) relationships at risk of breaking down, and to prepare for interactive adaptive planning for mangrove forests.

1. Introduction and review of concepts linking the mangrove social-ecological system to the adaptive cycle heuristic

The modern world is characterised by rapid changes in ecological, economic, social and political features, which result in the need to build resilience for an uncertain future in a wide variety of terrestrial and marine social-ecological systems. A social-ecological system (hereafter referred to as 'SES' or 'SESs' for plural), also known as a coupled human–environment system, is a system of interacting and interdependent physical, biological and social components, emphasizing the 'humans-in-nature' perspective (Chapin III et al., 2009). Reconciling nature, people and policy in complex SESs requires forecasting or hindcasting their dynamics necessitating frameworks and heuristics such as the SES framework (Ostrom et al., 2009) and the adaptive cycle heuristic (see Glossary for this and other definitions), which will be introduced in-depth in Sections 1.1 and 1.3. In this paper we focus on mangrove forests as a complex system (Section 1.2).

Cormier-Salem (1999) was one of the first scientists to highlight that the mangrove forest was also "*an area to be cleared … for social scientists*", rather than being 'cleared' for land reclamation or silviculture for example (Goessens et al., 2014; Richards and Friess, 2016). She called upon cross-disciplinary approaches to develop conceptual and methodological frameworks, explicitly and jointly between natural and social scientists, rather than natural scientists only calling upon social scientists in the middle of a crisis to resolve conflictual situations or to provide solutions to stop over-harvesting (Cormier-Salem, 1999). Today, mangrove SESs are considered complex adaptive systems where actors with different values and interests interact with their natural environment (Hoque et al., 2018). Unfortunately, since Cormier-Salem (1999) no major attempts have been made to develop a transdisciplinary conceptual framework linking mangrove SESs to spatio-temporal changes.

The Adaptive Cycle (hereafter referred to as 'AC' or 'ACs' for plural) is a heuristic that serves to explore the resilience of complex systems. The SES framework enables scientists and stakeholders to understand and structure a SES so as to provide a semi-standardized framework for systemic (mangrove) studies (Hugé et al., 2016; Martinez-Espinosa et al., 2020). We believe that the AC is a good model to represent social-ecological changes in mangroves for several reasons:

- First, the management of mangrove SESs requires a clear understanding of both ecological and social interactions. As intertidal systems, mangroves are subject to the dynamics of coastal erosion and accretion, occasional storm surges, and the shifting boundaries of land and water. They are intrinsically dynamic environments – their very location and their blurred and dynamic system boundaries makes them even more dynamic than many other ecosystems – therefore offering a range of specific management challenges (Rog and Cook, 2017). Hence, the AC provides a well-suited heuristic to frame the dynamics of both the ecological and the social components of mangrove dynamics.
- Second, a range of ecological and social system components can be 'plugged in' to the AC heuristic to translate the stages of the adaptivle cycle (see Section 1.3) into measurable and comparable variables based on the social-ecological variables *sensu* Ostrom (2009) and Vogt et al. (2015).
- Third, the AC heuristic enables us to easily conceptualise, identify and address mismatches between stages in a change process, and the model enhances the early detection of system failure (*cf.* Dahdouh-Guebas et al., 2005a; Koedam and Dahdouh-Guebas, 2008; Lewis III et al., 2016). For example, the mangrove ecosystem can be near to collapse (*e.g.* 'cryptic ecological degradation' *sensu* Dahdouh-Guebas et al., 2005a), while the social (human) components of the system are still in a functional conservation stage. For instance, existing institutions and regulations may still be in place but are ineffective in dealing with the changing ecological conditions because of ineffective collective-choice rules or inadequate monitoring and sanctioning processes.
- Fourth, just using the SES model is not enough to integrate the temporal dynamics which characterize real-life systems. The SES scheme on its own is useful, but merely provides a static snapshot, in which some properties can be altered by spatial and temporal changes. The AC, combined with the SES scheme, allows integration of the spatial-temporal dynamics and the multi-dimensional character of mangrove systems.

The overall aim of this paper is to exemplify how the mangrove ecosystem is a model social-ecological system, and how ecological, social and institutional resilience can be better understood through the adaptive cycle heuristic. We do this by deliberately integrating ecological and social properties and demonstrating how these interact through time and space. The specific objectives of the paper are (i) to review the essential properties and concepts of SESs (Section 1.1), mangrove ecosystems (Section 1.2) and ACs (Section 1.3) for use by mangrove researches, stakeholders and managers, (ii) to link the mangrove social-ecological system to the adaptive cycle heuristic (Sections 2, 3 and 4) and to apply the AC to two well-known and studied mangrove-related cases (the 2004 Indian Ocean tsunami in Section 4.1 and the century-long silviculture in Malaysia Section 4.2), in order to (iii) show the potential of such an approach to sustainably manage and preserve mangrove SESs (Sections 4 and 5).

1.1. The social-ecological system

To link physical, biological and social components, Chapin III et al. (2009) visualised a comprehensive generic SES framework linking ecological and social system properties to exogenous controls and to spatio-temporal impacts (Fig. 1).

Exogenous controls, such as climate or the global economy, persist well over space and time and are hardly affected by system dynamics operating at small scales and short terms (*e.g.* canopy gaps in a forest or a single currency that devalues). However, at the regional scale, exogenous controls respond to global trends and influence slow variables at the scale of management (Fig. 1). These slow variables take a long time to establish, remain relatively constant over long time periods, yet strongly influence SESs. Examples of slow variables are soil resources, inundation regimes or faunal migration patterns on the ecological side; and wealth, trust, culture and spirituality on the social side. The weakness of (critical) slow variables is that they can quickly erode, literally (*e.g.* soil resources) and figuratively (*e.g.* trust in local economy, policy or management). Slow variables in turn govern fast variables, such as soil nutrient concentrations, daily tidal inundation, and faunal population densities on the ecological side; and income, daily access to resources, and human population densities on the social side (Fig. 1). All of these variables respond sensitively to daily, seasonal, and interannual variation in exogenous or endogenous conditions. (Chapin III et al., 2009). When changes in fast variables persist over long time periods and large areas, these effects cumulatively propagate upward to affect slow variables, regional controls, and eventually the entire globe. Changes in both slow and fast variables influence environmental impacts, ecosystem goods and services, and social impacts, which together are the factors that directly affect the well-being of human actors (Fig. 1).

The components of a SES are largely governed by different types of amplifying and stabilising feedback mechanisms. For instance, the predator-prey relationship is a typical example of a stabilising feedback, whereas the relationship between overharvesting of natural resources on the one hand and armed conflict on the other is a typical amplifying feedback (Dudley et al., 2002). The development of system structure resulting from stabilising feedbacks among system components is known as self-organisation (Chapin III et al., 2009), and is supported by numerous examples in biology (Camazine et al., 2018).

The whole productive base of a SES including, natural, built, human and social capital is called the inclusive wealth, which needs to be maintained or increased over time in order for a SES to be sustainable (Arrow et al., 2004; Chapin III et al., 2009). Some of these capitals may be replaced by others of a different category (Chapin III et al., 2009). For instance mangrove forests (natural capital) can offer wave attenuation functions that might otherwise require the construction of breakwater infrastructure (built capital), in the absence of which the shore may remain exposed and more vulnerable. Despite such replacement potential, in low-income countries the loss of natural capital has a disproportionate direct impact on sustainability, compared to a generally more manageable, indirect impact in high-income countries (MEA, 2005).

The sustainability of a SES further depends on reduced vulnerability, enhanced adaptive capacity, enhanced transformability, and increased resilience of a system (see Glossary). The first three properties can be exemplified by, respectively, the reduction of the exposure of fire-sensitive plants to wildfires (Beckage and Ellingwood, 2008), the increase in the natural capital of a mangrove forest to maintain the coastal protection function and ecosystem goods and services (Dahdouh-Guebas et al., 2005b), and the wildfire-driven transformation of woodlands into

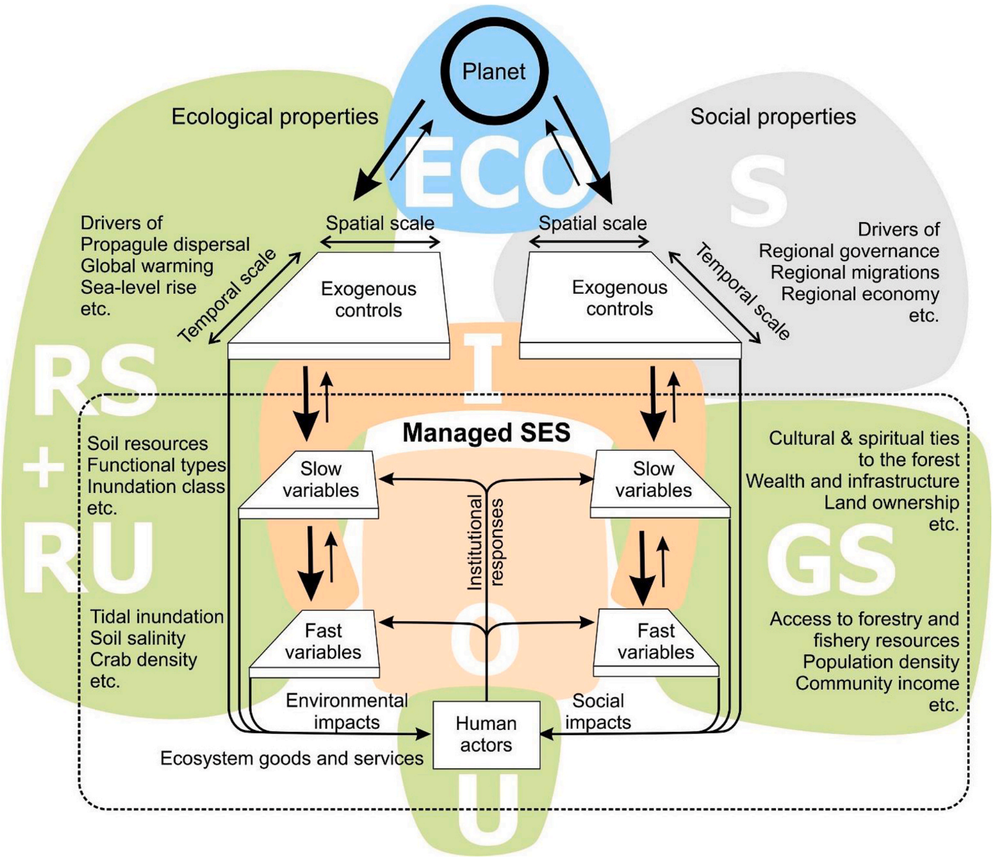


Fig. 1. Integration of social-ecological system frameworks with black text adapted from Chapin III (2009) and colour panes with abbreviations adapted from Ostrom (2009). Diagram of a mangrove SES (dashed rectangle) that is affected by ecological (left-hand side) and social properties (right-hand side). In both subsystems there is a spectrum of controls that operate across a range of spatio-temporal scales, with respective examples (see text in Section 1.1 for details). Colour panes and abbreviations (in line with Ostrom, 2009) are for SES variables (for the sake of clarity the 'SES' was dropped from the following abbreviations list): S = Social, economic and political settings; RS = Resource Systems; RU = Resource Units; GS = Governance Systems; U = Users; I = Interactions; O = Outcomes; ECO = Related Ecosystems. The green colours indicate that these components are mutually interacting; the black text is adapted from Chapin III et al. (2009).

herbaceous vegetation (Scheffer et al., 2001). Resilience, the fourth property, will be elaborated in more detail because of its core role in the present paper's theoretical framework.

The resilience of a SES is its capacity to absorb disturbance and reorganise while undergoing change but retaining its essential core function, structure, identity, and feedbacks (Walker et al., 2004). Olsson et al. (2015) thoroughly reviewed the history and multiple definitions of resilience. While the definition by Walker et al. (2004) represents but one of four different typologies of resilience definitions in ecology and social-ecological systems thinking (Olsson et al., 2015), we follow Walker's definition which elaborates on the four aspects of resilience: latitude, resistance, precariousness and panarchy. In literature on alternative stable states, the first three have often been illustrated by a two-dimensional (stability) landscape with two basins of attraction, in which a marble can freely roll (Scheffer et al., 2001). In such a stability landscape, latitude can be represented as the width of the basin of attraction, resistance as the depth (and slope) of the basin of attraction, and precariousness as the proximity to the limit (threshold) that would cause it to roll into the second basin of attraction (Walker et al., 2004). Finally, panarchy, refers to cross-scale interactions. For instance, local surprises and regime shifts at a focal scale can be triggered by external oppressive politics, invasions, market shifts, local sea-level rise or global climate change (Walker et al., 2004; Cavanaugh et al., 2019). This requires a clear definition of the scale and spatial limits of a SES.

Ostrom (2009) proposed a simple, adaptable conceptualization of a SES (Fig. 1) with an ecological core, consisting of Resource Systems (SES-RSs) and Resource Units (SES-RUs), while the social core is divided into Users (SES-Us) and Governance Systems (SES-GSs). Both ecological and social cores are framed within a Social, economic, and political setting (SES-S). In the ecological core, the SES-RSs refer to examples such as a particular protected area, a forest, a lake; whereas the SES-RUs refer to units such as trees, animals, amounts and flows of water that together make up the SES-RS. In the social core, Users (SES-Us) are the individuals who use the forest, the protected area or the lake, whereas the Governance System (SES-GS) refers to the rules regulating the use of resources, the government and other organisations that together shape the management of an area.

Interactions (SES-Is) between these subsystems then produce Outcomes (SES-Os) that describe the dynamics of the SES as a whole. These SES-Is and their SES-Os can be assessed, for example, regarding their sustainability (*cf.* Folke et al., 2016). The analytical power of Ostrom's scheme also lies in the range of second-level variables that embody the different subsystems. For example, SES-RSs are described by their productivity, their predictability *etc.*, and SES-RUs can be described by their growth rates and mobility. SES-GSs can be described by their network structure, collective choice rules and so forth, and SES-Us by their socio-economic attributes and their social capital.

By going beyond integrating ecological and social components of (mangrove) systems – by the development of measurable variables – this scheme allows SES analysis to function and affect (mangrove) science across the world. For example, stakeholders may have divergent views about how to use and manage (mangrove) systems, which (mangrove) functions should be maximised, and who should make decisions regarding their management (Mukherjee et al., 2014; van Oudenhoven et al., 2015; Hugé et al., 2016; Vande Velde et al., 2019). At the same time, (mangrove) systems in different regions may show different levels of productivity, ecological connectivity, species interactions *etc.*

1.2. *Mangroves as a model social-ecological system*

Being present on all continents with (sub)tropical and warm temperate climates and contributing to the lives and livelihoods of millions of people, mangrove SESs provide an excellent backdrop to explore the nuances of the SES concept.

Mangroves can be found in >120 countries and territories (Spalding et al., 2010). Modified from Mukherjee et al. (2014) 'mangroves' are plants that grow in tropical, subtropical and warm temperate latitudes along the intertidal land–sea interface, in bays, estuaries, lagoons and backwaters. Most of them are woody trees and shrubs, but some are non-woody (*e.g. Nypa* palm) or are herbaceous (*e.g. Acrostichum* and *Acanthus*). These plants and their associated organisms constitute the 'mangrove forest community' or 'mangal'. The mangal and its associated abiotic factors constitute the 'mangrove ecosystem'. Like many ecosystem definitions, this one originated from a natural science point of view, centred on the ecological components of such a system, and did not include its human components.

In distinguishing between the ecological and the human components of mangroves, ecosystem processes and functions and ecosystem services may be defined according to Costanza et al. (2017) as: "*Ecosystem processes and functions contribute to ecosystem services, but they are not synonymous. Ecosystem processes and functions describe biophysical relationships that exist regardless of whether or not humans benefit. By contrast, ecosystem services* – in the present paper referred to as 'ecosystem goods and services' – *are those processes and functions that benefit people, consciously or un-consciously, directly or indirectly*". We deliberately maintain the difference between 'goods' and 'services' as we suggest that this defines the difference between what is tangible and what is not. Hence, wood and fish would be goods whereas coastal protection and scenic beauty would be services, for instance.

Given its unique diversity and complexity, there has been a range of studies investigating the mangrove ecosystem's processes and functions (Lee et al., 2014; Friess et al., 2016; Friess et al., 2020). We propose a subdivision of ecosystem processes and functions into (i) trophic processes and functions, (ii) processes and functions regarding non-trophic nutritional resources, (iii) functions regarding other resources, and (iv) non-resource functions, most of which would be categorised as SES-RSs or SES-RUs (Appendix A. A1). Some key functions include the high carbon storage in mangrove trees and soils (Donato et al., 2011; Rovai et al., 2018), the attenuation of tidal and surge waves (Dahdouh-Guebas et al., 2005b), and the creation of spatial niche dimensions for terrestrial and marine flora and fauna (Cannicci et al., 2008; Nagelkerken et al., 2008; Hayasaka et al., 2012; Yates et al., 2014). In particular, the characteristic extensive above-ground root system provides shelter for a variety of fish, shellfish and invertebrates (Barbier et al., 2008; Nagelkerken et al., 2008). Any two linked ecosystem processes and functions may involve stabilising or amplifying feedback mechanisms. An example of a stabilising feedback is given by mangrove trees and crabs, whereby shading trees offer protection to crabs that are at risk of dehydration and predation by birds (Vannini et al., 1997), and crabs help to oxygenate the hypoxic or anoxic sediment by air circulating within their burrows at low tide (Koch and Nordhaus, 2010). An example of an amplifying feedback mechanism would be the outbreak of a mangrove pest such as a woodborer species (Jenoh et al., 2019), whereby the pest infects susceptible trees, which allows the pest to multiply, which in turn infects more trees.

The wide range of ecosystem processes and functions in a mangrove produce a considerable array of ecosystem goods and services (Mukherjee et al., 2014), which we categorised as wood products, non-timber forest products (hereafter referred to as 'NTFPs'), abiotic raw materials, and other goods and services (Appendix A. A2). These goods and services (SES-RS) vary depending on location and population characteristics (existing species diversity and local norms). A key service is the protection of shoreline, lives and properties (Lee et al., 2014; Feagin et al., 2010; Hochard et al., 2019). In the aftermath of several storms affecting SE Asia in the recent past (Amphan, Aila, *etc.*), the importance of mangroves has been increasingly recognised. Ecotourism in mangroves relies on the aesthetic services they provided (Avau et al., 2011; Spalding and Parrett, 2019). The most widespread goods that come from a mangrove are the timber and NTFPs, particularly for house construction and traditional lifestyle practices (Walters et al., 2008).

Since the paper by Dunn (2010) on "*the unspoken reality that nature sometimes kills us*", research attention has been given to ecosystem disservices, here defined as the *ecosystem generated functions, processes and attributes that result in perceived or actual negative impacts on human wellbeing* (Shackleton et al., 2016). The mangrove environment can be perceived to be harsh due to health risks, safety and security concerns, leisure and recreation-related dangers, and material and perceived mangrove disservices (Vaz et al., 2017; Friess et al., 2020), the latter of which we believe to be inaccurate, ambiguous or in essence harmless to humans (Appendix A. A3). Examples include disservices resulting from high salinity, anoxic conditions, high temperatures, tidal inundation, pests, foul smells, *etc.* (Friess, 2016; Friess et al., 2020), disease vectors such as mosquitoes (Friess, 2016; Ali et al., 2019), risk of injury from sharp organisms and objects (Friess et al., 2020), human-wildlife conflicts (Badola et al., 2012) among others. Along with mangrove goods and services, mangrove disservices would be strongly influenced by the SES-S and subject to path dependence.

1.3. *The adaptive cycle: a conceptual approach to manage social ecological systems*

The long-term stability of systems depends on changes that occur during critical phases of cycles (*cf.* Berkes et al., 2003; Chapin III et al., 2009). In our era governed by different types of change and uncertainty, aspects related to a system's temporal properties and cyclicity are important to elucidate, such as:

- what is meant by 'short-term' and 'long-term'?
- what is the origin of a change?
- who are the actors who have the power to change the system at different points in time and space (SES-GS)?
- whether or not trajectories of change are unidirectional and, if not, what are the possible scenarios?
- changing social-economic dynamics, public awareness, regulation and social acceptance of local practices, laws, *etc.*

The AC is a heuristic model proposed by Gunderson and Holling (2002), and applied to various cases by Gunderson & Pritchard Jr. (2002), Holling and Gunderson (2002), Gunderson et al. (2009) among others, in which complex systems, *i.e.* self-organising systems, can be seen as following a cycle generally of four phases: exploitation (r), conservation (K), release (Ω), and reorganisation (α), organised into two loops.

Each loop of the AC comprises two phases. The first loop (or front loop), formed by phases r and K, is predictable and long in duration. Phase r (exploitation) represents a period of rapid exploitation and extraction of resources from a system's assets. This means that the elements of a given system find, in this stage, the opportunity to establish through the usage of available resources. In this phase the AC is prone to be caught in the 'poverty trap', a situation in which a system cannot access enough activation energy to reach a state where positive feedbacks drive internal growth (Fath et al., 2015). After initial establishment, the system enters phase K (conservation), usually the longest phase, in which there is resource accumulation in increasingly interconnected and strongly regulated ways. Excessively tight connections eventually make a system more rigid, and therefore less resilient and prone to collapse (Allen et al., 2001; Allison and Hobbs, 2004). This is also referred to as the 'rigidity trap' (Carpenter and Brock, 2008).

The second loop (or back loop) of the AC is shorter in duration and highly unpredictable. It represents a critical moment in which the system may or may not change to another state or even another system (Walker et al., 2004). Phase Ω (release or collapse) occurs when a certain level of disturbance surpasses the threshold of stability and the system collapses. Many elements of the system are set free and bonds between them are lost. Resources that were previously accumulated within the elements of the system, as well as their interactions, are then released. Failing to survive the Ω stage results in a complete break of the system cycle, termed the 'dissolution trap' (Fath et al., 2015). If the system persists, the following phase α (reorganisation) provides great potential, as all the system's available elements are not yet coupled or bonded (Allen et al., 2014). However, inability to reorient the components of the system or to reconnect its nodes is the main trap in this phase, also known as the 'vagabond trap' (Fath et al., 2015).

Fath et al. (2015) exemplified what are the key features for success in each AC phase: in the r phase the capacity to grow needs activation energy; in the K phase the capacity to develop requires self-organisation to store information and capital; in the Ω phase the capacity to survive involves improvisation to maintain vital functions; and in the α phase the capacity to renew requires learning to reorient. In fact, the solutions to the traps of poverty, rigidity, dissolution and vagabond are embedded in all the other phases. Escaping the rigidity trap, for instance, requires growth-regulating stabilising feedbacks (typical of r phase), maintenance of diversity (typical of K phase) and of small-scale disturbances (typical of Ω phase), and buffer capacity within the system (typical of α phase), including stored capital and redundancy (Fath et al., 2015).

The AC is usually shown in two dimensions with potential and connectedness as axes (Appendix B. Fig. B1A), but a third resilience axis can also be drawn (Appendix B. Fig. B1B). The three axes can be presented all at once in a 3D cube (Appendix B. Fig. B1B,C) or two by two (Appendix B. Fig. B1A), revealing that one sequential run through the AC causes capacity of the system to oscillate twice between low and high values (Appendix B. Fig. B1D), while both resilience and connectedness build up only once from Ω to K (Appendix B Fig. B1E,F). The heuristic of the AC is based on observed system changes and does not imply fixed, regular, sequential cycling in a particular phase sequence. Systems can move back from K toward r, or from r directly into Ω, or back from α to Ω (Walker et al., 2004). We would like to elaborate the AC heuristic by saying that the (blue) ribbons representing the AC (Appendix B. Figs. B1 and B2) should also be considered as floating in the winds of change in the 3D cube. Similar to understanding a SES, interpreting the AC is dependent on the scale and spatial limits of the system, and on the social, economic, and political settings (SES-Ss). This is even more important when discussing panarchy in an AC context (Appendix B. Fig. B2). The cross-scale interactions occur between nested subsystems that are at different stages of their adaptive cycles (Chapin III et al., 2009). The entire system can thus be seen as being composed of different ACs stacked behind one another. This can cause a critical change in one adaptive cycle to escalate (Revolt) to a stage in a larger and slower one (Berkes et al., 2003). Alternatively, the cross-scale interaction may facilitate the α and/or r phase by drawing on the memory (Remember) that has been accumulated and stored in a larger, slower cycle (Berkes et al., 2003) (Appendix B. Fig. B2).

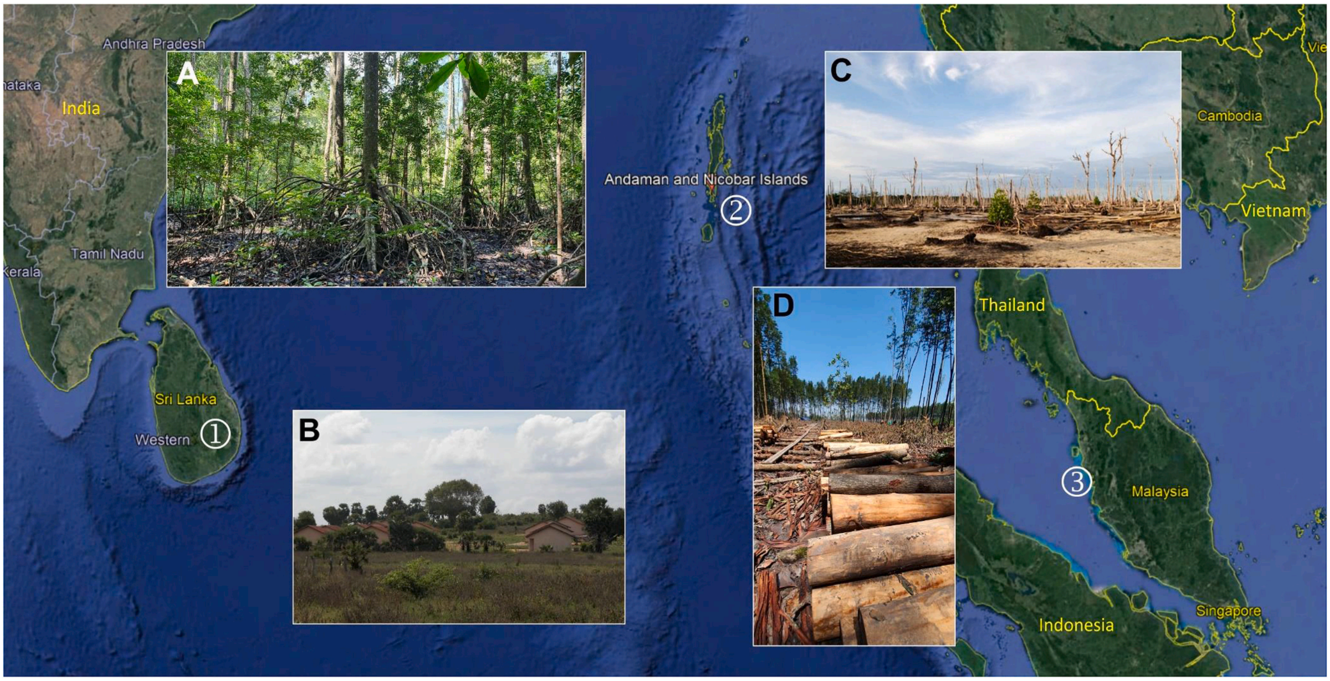
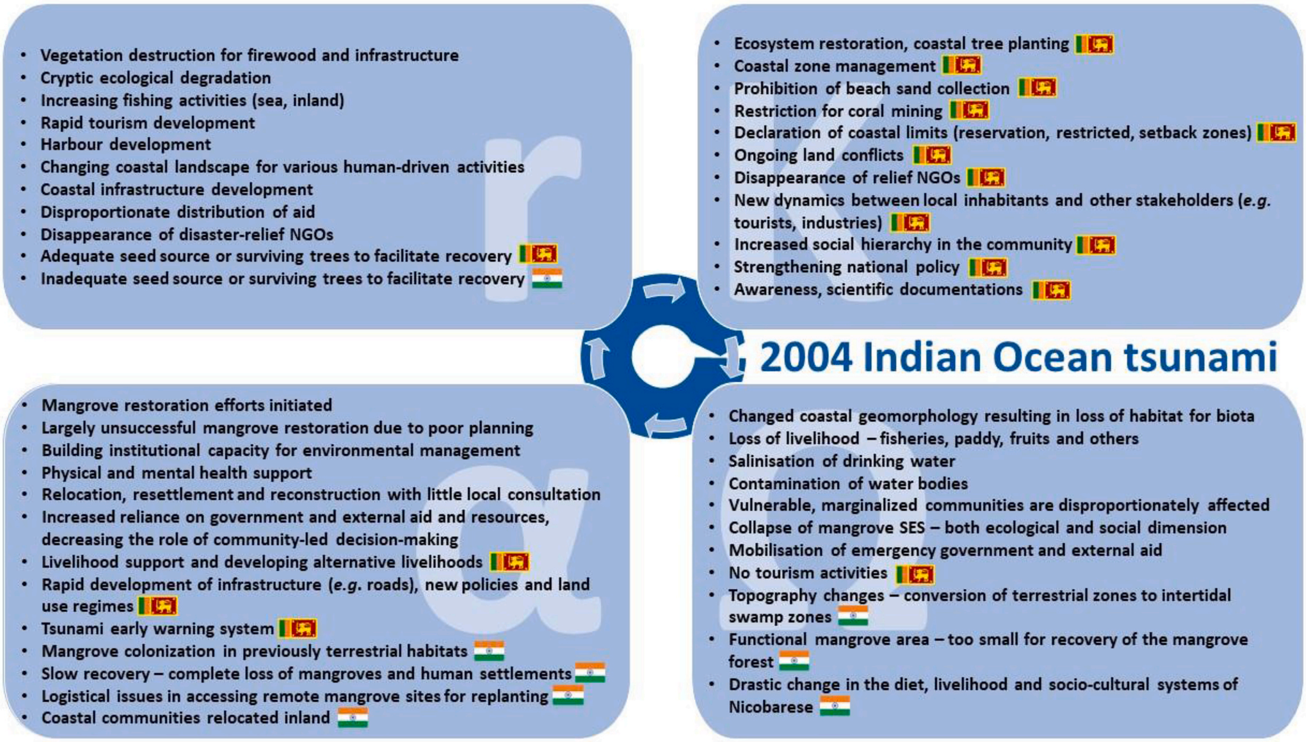


Fig. 2. Map showing the case study locations. Map of the Bay of Bengal and the Andaman Sea showing the locations of the case studies in Sri Lanka , the Nicobar Archipelago ②, and the Matang Mangrove Forest Reserve (MMFR) in Peninsular Malaysia ③. (A) View inside MMFR's Virgin Jungle Reserve, a forest in the protective zone that has not been disturbed for nearly 100 years and is in K phase (F.D.-G., June 2019). (B) Post-tsunami housing area for fishermen relocated away from the coast in Panama on Sri Lanka's east coast (F.D.-G., February 2006). (C) Complete loss of mangrove cover in Trinket Island (Nicobar Archipelago) due to the 2004 Indian Ocean tsunami, now stuck in a poverty trap with hardly any recolonization (N.P., November 2010). (D) Ongoing clear-cutting (Ω phase) in a 30 year-old coupe of the MMFR near Kuala Sepetang, Malaysia (F.D.-G., June 2019). Background extracted on 29/05/2020 from Google Earth; Image: Landsat/Copernicus 14 Dec. 2015; Data: SIO, NOAA, U.S. Navy, NGA, GEBCO.



- Vegetation destruction for firewood and infrastructure
- Cryptic ecological degradation
- Increasing fishing activities (sea, inland)
- Rapid tourism development
- Harbour development
- Changing coastal landscape for various human-driven activities
- Coastal infrastructure development
- Disproportionate distribution of aid
- Disappearance of disaster-relief NGOs
- Adequate seed source or surviving trees to facilitate recovery 🇱🇰
- Inadequate seed source or surviving trees to facilitate recovery 🇮🇳

- Ecosystem restoration, coastal tree planting 🇱🇰
- Coastal zone management 🇱🇰
- Prohibition of beach sand collection 🇱🇰
- Restriction for coral mining 🇱🇰
- Declaration of coastal limits (reservation, restricted, setback zones) 🇱🇰
- Ongoing land conflicts 🇱🇰
- Disappearance of relief NGOs 🇱🇰
- New dynamics between local inhabitants and other stakeholders (*e.g.* tourists, industries) 🇱🇰
- Increased social hierarchy in the community 🇱🇰
- Strengthening national policy 🇱🇰
- Awareness, scientific documentations 🇱🇰

- Mangrove restoration efforts initiated
- Largely unsuccessful mangrove restoration due to poor planning
- Building institutional capacity for environmental management
- Physical and mental health support
- Relocation, resettlement and reconstruction with little local consultation
- Increased reliance on government and external aid and resources, decreasing the role of community-led decision-making
- Livelihood support and developing alternative livelihoods 🇱🇰
- Rapid development of infrastructure (*e.g.* roads), new policies and land use regimes 🇱🇰
- Tsunami early warning system 🇱🇰
- Mangrove colonization in previously terrestrial habitats 🇮🇳
- Slow recovery – complete loss of mangroves and human settlements 🇮🇳
- Logistical issues in accessing remote mangrove sites for replanting 🇮🇳
- Coastal communities relocated inland 🇮🇳

- Changed coastal geomorphology resulting in loss of habitat for biota
- Loss of livelihood – fisheries, paddy, fruits and others
- Salinisation of drinking water
- Contamination of water bodies
- Vulnerable, marginalized communities are disproportionately affected
- Collapse of mangrove SES – both ecological and social dimension
- Mobilisation of emergency government and external aid
- No tourism activities 🇱🇰
- Topography changes – conversion of terrestrial zones to intertidal swamp zones 🇮🇳
- Functional mangrove area – too small for recovery of the mangrove forest 🇮🇳
- Drastic change in the diet, livelihood and socio-cultural systems of Nicobarese 🇮🇳

Fig. 3. Tsunami adaptive cycle. Four phases of the adaptive cycle indicating the key conditions or properties characterising the respective phases in the aftermath of the tsunami in Sri Lanka and Nicobar Archipelago (India). Absence of any flag indicates the point is valid in both countries; presence of one flags indicates the point is only valid for the respective country.

Table 1

Drivers able to trigger release or contribute to reorganisation, exploitation or conservation phases of the AC and SES variables that can be impacted by the driver. The Ω phase drivers serving as an exit point for the AC in which the SES was are indicated as intended (●) or unintended transformation (○). The SES variables listed are not meant to constitute an exhaustive list. The references do not form an exhaustive list either but serve as example of studies that did not involve the AC, but the reported variables of which can be framed into the AC heuristic according to the present paper. The peer-reviewed references can be found by the search string mentioned in the text AND (= Boolean operator) the driver term in bold. Grey literature references were added where relevant. The names of the variables have been taken from Ostrom (2009) and Vogt et al. (2015), or, if missing, proposed here. SES-ECO = Related ecosystems; SES-I = Interactions; SES-GS = Governance systems; SES-O = Outcomes; SES-RS = Resource systems; SES-RU = Resource units; SES-S = Social, economic and political settings; SES-U = Users.

Phase of the adaptive cycle	Drivers of system change	Examples of SES variables that can be impacted by the change	Reference examples
Release (Ω)			
disturbance/collapse (hours-days) creating an opportunity for change	Mangrove conversion to **aquaculture**, agriculture or (non-mangrove) silviculture. ●	**SES-RS**: clarity of system boundaries (*e.g.* fragmentation, fringing mangroves burnt to expand paddy cultivation) **SES-RS**: storage characteristics (*e.g.* loss of C stock) **SES-RU**: economic value **SES-GS**: property-rights systems (*e.g.* change of power relations) **SES-U**: importance of resource **SES-I**: lobbying activities **SES-RU**: growth or replacement rate (*e.g.* tree death) **SES-RU**: interaction among resource units (*e.g.* barriers block water exchange and dispersal of propagules) **SES-ECO**: pollution patterns (*e.g.* agricultural effluents in mangrove)	Foell et al. (1999), Orchard (2014), Richards and Friess (2016), Arifanti et al. (2019)
	River diversion (**hydrology**), construction of highways, **roads**, pavements	**SES-RS**: predictability of system dynamics (*e.g.* siltation) **SES-RU**: interaction among resource units (*e.g.* reduced connectivity between mangrove patches)	Dahdouh-Guebas et al. (2005a), Lewis III (2005), Spalding et al. (2010), UNEP et al. (2014), Hayashi et al. (2019)
	Subsidence or **uplift** ○	**SES-RU**: Resource unit mobility (*e.g.* tree death in areas not appropriately inundated)	Ray and Acharyya (2011), Nehru and Balasubramanian (2018)
	Ocean surges (from **tsunami** or **cyclone**/hurricane origin)	**SES-RS**: clarity of system boundaries (*e.g.* decreased/damaged fringing mangroves) **SES-RS**: size of resource system	Badola and Hussein (2005), Dahdouh-Guebas et al. (2005b), Danielsen et al. (2005), Tanaka et al. (2006), Jayatissa et al. (2016)
	Wind (from cyclone/**typhoon**/**hurricane** origin)	**SES-RS**: clarity of system boundaries **SES-RU**: growth or replacement rate (*e.g.* tree death, defoliation, windthrow of fringing mangroves)	Fritz and Blount (2007), Vogt et al. (2012), Villamayor et al. (2016)
	Frequent **flood** events	**SES-RS**: clarity of system boundaries (*e.g.* soil erosion in frontal/creek-ward mangrove fringes)	Mathiventhan and Jayasingam (2014)
	Lightning strikes	**SES-RU**: growth or replacement rate (*e.g.* electrocution (and possible death) of biota)	Aldrie Amir (2012), Pers. obs.
	Sea-level rise	**SES-RS**: productivity of system **SES-RU**: growth or replacement rate (*e.g.* frontal mangrove mortality) **SES-RS**: clarity of system boundaries (*e.g.* landward extension or coastal squeeze (depending on topography, salinity & sediment)	Gilman et al. (2006), Gilman et al. (2007, 2008), Ellison (2015), Lovelock et al. (2015)
	Waste accumulation and **pollution**	**SES-RU**: growth or replacement rate (*e.g.* death of biota) **SES-I**: conflicts among users **SES-ECO**: pollution patterns	Cannicci et al. (2009), Spalding et al. (2010), Pehna Lopes et al. (2011), UNEP (2014)
	Selective **cutting**, over-exploitation	**SES-RU**: economic value (*e.g.* dominance shift from preferred to less preferred species, local extinction and impairment of new recruitment of economically important species) **SES-RU**: growth or replacement rate **SES-I**: harvesting levels of diverse users	Walters (2005a,b)
	Security issues from illegal or harmful activities (*e.g.* aquaculture, poaching, encroachment, production of illegal substances, *etc.*)	**SES-RU**: economic value **SES-I**: conflicts among users **SES-ECO**: pollution patterns	pers. obs.
Reorganisation (α)			
	Residual trees, **dispersal**, **recruitment**, changed frequency and duration of **inundation** and **flooding**, soil seed bank	**SES-RS**: productivity of system (*e.g.* degradation of existing mangrove patches, colonization of new areas by seedlings, recruitment of new faunal species and larvae) **SES-RS**: equilibrium properties	Dahdouh-Guebas and Koedam (2002), Lewis III (2005), Ragionieri et al. (2015), Van der Stocken et al. (2019), Cannicci et al. (2019)
	Increased **CO_2**	**SES-RS**: productivity of system (*e.g.* increased productivity) **SES-RS**: storage characteristics	Farnsworth et al. (1996)
	Replanting, **regeneration**	**SES-RS**: storage characteristics **SES-I**: investment activities (*e.g.* aided seedling establishment)	Goessens et al. (2014), Sillanpäa et al. (2017)
	Abandoned **shrimp ponds**	**SES-RU**: growth or replacement rate (*e.g.* natural regeneration in some places) **SES-RS**: productivity of system	Stevenson et al. (1999), Arifanti et al. (2019)

(*continued on next page*)

Table 1 (*continued*)

Phase of the adaptive cycle	Drivers of system change	Examples of SES variables that can be impacted by the change	Reference examples
		SES-RS: storage characteristics **SES-U**: history of use	
Exploitation (r) growth (decades), insensitivity to potential agents of disturbance, or high level of resilience	Propagule availability, potential **habitats**, **competition** for **spatial** and food resources **Land tenure**, ownership	**SES-RS**: predictability of system dynamics (*e.g.* rejuvenation, degradation of existing mangrove patches or colonization of new areas by seedlings) **SES-GS**: property-rights systems (*e.g.* private areas delimited and fenced) **SES-U**: history of users	Fontalvo-Herazo et al. (2011), Ragionieri et al. (2015), Nehru and Balasubramanian (2018), Cannicci et al. (2019) Lovelock and Brown (2019)
Conservation (K) steady-state with specialized and complex interactions	Plant-animal **interactions** (tree-**crab** interactions)	**SES-RS**: productivity of system (*e.g.* decreased rejuvenation due to propagule predation) **SES-RU**: interaction among resource units (brachyurophily and brachyurochory pollination and seed dispersal by crabs) **SES-RU**: spatial and temporal distribution	Pers. obs., Clarke and Kerrigan (2002), Fratini et al. (2005),
	Protection and (co-)- **management** through policies, lower perturbation regime	**SES-RS**: productivity of system **SES-RU**: growth or replacement rate (*e.g.* sustained natural regeneration of mangroves) **SES-GS**: operational rules **SES-GS**: monitoring and sanctioning processes	Tompkins and Adger (2004), Sillanpää et al. (2017), Trzaska et al. (2018)
	Regularised uses of mangroves (timbers, NTFPs, fisheries, **recreation**, *etc.*)	**SES-S**: government resource policies **SES-GS**: operational rules **SES-RS**: predictability of system dynamics (predictable mangrove utilisation at various spatial and temporal scales) **SES-U**: importance of resource	Spalding et al. (2010), UNEP (2014), Spalding and Parrett (2019)
	Alternative for mangrove uses	**SES-S**: government resource policies **SES-GS**: operational rules **SES-U**: importance of resource (*e.g.* less reliance on mangrove products)	Omodei-Zorini et al. (2004), Nfotabong-Atheull et al. (2011), Badola et al. (2012)
	Replanting schemes (mono and poly-specific), **replanted** mangroves, **nursery**	**SES-RS**: size of the resource system (*e.g.* increasing mangrove cover) **SES-RS**: productivity of the resource (*e.g.* secondary floristic succession) **SES-RU**: resource unit mobility **SES-ECO**: flows into and out of focal SES (*e.g.* faunistic recruitment)	Huxham et al. (2004), Kirui et al. (2008), Mathiventhan and Jayasingam (2016)
	Awareness of local people	**SES-I**: information sharing among users (*e.g.* building adaptive capacity)	Bosire et al. (2008), Ramalanjaona (2011), Das (2013), Trzaska et al. (2018)
	Monitoring, **assessment**	**SES-GS**: monitoring and sanctioning processes (*e.g.* early warning systems)	Ramalanjaona (2011), Mackenzie et al. (2016), Bunting et al. (2018)

Following Ostrom's terminology, the set-up and the dynamics of the SES-RS (*e.g.* the equilibrium properties and the productivity) and the SES-GS (*e.g.* network structures) change throughout the various stages of the AC.

Before applying the AC to the complex adaptive mangrove system, we take wildfires in terrestrial forests as a relatively straightforward example to illustrate the AC phases. Throughout the Ω phase (hours to weeks) triggered by a wildfire, we can expect a surface or canopy fire, tree mortality, decreases in productivity, increasing runoff to streams, a loss of confidence in fire management, the collapse of various types of tourism, a loss of livelihoods, forced migration and displacement, and the establishment of disaster relief-oriented NGOs or state-initiatives (Chapin III et al., 2009; Lidskog et al., 2019). Capacity, resilience and connectedness are then at their lowest values possible.

In the α phase, lasting months to years, new seedlings are recruited, new government policies for forest management are proposed and adopted, and livelihoods are changed, for instance from natural resource extraction to the service sector in nearby towns. At this point, the system is prone to the poverty trap, if there is a lack of social or ecological resources for example (*e.g.* ideas or nutrients). However, the α phase may also benefit from the legacy stored in intact neighbouring forests, from which resources such as seeds or functional guilds of animals can be recruited (Fig. B2 in Appendix B).

What follows is the incorporation of environmental resources into living organisms, and the high moisture content and low biomass of young trees reducing fire hazards, among this SES's ecological properties. Also among a SES's social features we find government policies becoming accepted, implemented and more readily enforced. In addition, NGOs that focus on post-disaster reconstruction and rehabilitation grow amidst constant changes in activities and personnel (if an NGO cannot cope with this it may disappear or change its mission), and even changes in land tenure. All these ecological and social SES properties may last decades and characterize the r phase. (Chapin III et al., 2009; Oloruntoba, 2013).

Finally, the K phase, in which most SESs typically spend nearly all of their time, is characterised by plant-mycorrhizae interactions and predictable patterns of recreation, hunting and harvesting. Governments and other organisations also become less flexible in their responses to changes in the economic or social climate. Therefore, we find increased levels of interconnectedness and rigidity within and between both natural/biological and human/socio-political/legal connections (Oloruntoba, 2013). Such a forest is in a 'rigidity trap' and cannot change by endogenous processes but may be highly vulnerable to external disturbance by catastrophic wildfire (Carpenter and Brock, 2008).

Gunderson and Holling's (2002) AC is a metaphor (heuristic) for system dynamics that extends the traditional successional logistic curve (r → K) to include the collapse and reorganisation phases (Holling, 1986; Fath et al., 2015). As mentioned above, a key parameter by which to assess and understand ACs is resilience.

The AC provides a framework to describe, understand and predict how disturbances in SESs drive disruption, reorganisation and renewal (Holling, 1986; Chapin III et al., 2009). A disturbed system can be sustained by having a sufficient degree of resilience to return to a similar system state that existed before the disturbance (Lucas et al., 2020). The disturbed system may also tip into an alternative (stable) state (Holmgrem and Scheffer, 2001; Scheffer et al., 2001). In case the system has a high degree of transformability it may shift regimes (*cf.* Cavanaugh et al., 2019). Transformability is the capacity of a system to reconceptualise and create a fundamentally new system with different characteristics (Walker et al., 2004).

2. The adaptive cycle in practice: what challenges can it (not) take on?

The AC heuristic is a thoroughly tested mechanism, both empirically and theoretically, that has significantly improved the current understanding of the behaviour of ecosystems and SESs on different spatio-temporal scales (Burkhard et al., 2011; Sundstrom and Allen, 2019). This makes the AC of great potential for structuring meaningful policies for management to ensure long-term sustainability of SESs and its constituent components such as SES-RS, SES-RU, SES-GS and SES-U (Ostrom, 2009; Salvia and Quaranta, 2015).

The hypothetical approaches based on the AC principles can provide insights on the trajectories of multiple ecosystem services in different management regimes (Burkhard et al., 2011). Similarly, systematic approaches using empirical data (qualitative and quantitative) have been useful tools to assess the connectedness, potential, functionality and capacity of SESs in terms of social, natural, and economic capitals in current, historic and prehistoric systems (Abel et al., 2006; Thompson and Turck, 2009; Daedlow et al., 2011; Salvia and Quaranta, 2015). Adaptive management practices that consider regional factors can greatly improve the resilience of ecosystems and landscapes (*cf.* Vandebroek et al., 2020). The AC can also capture complex human behaviour as 'enculturated' and 'enearthed', co-evolving with socio-cultural and biophysical contexts (Schill et al., 2019).

The outcomes of the actions that the actors (individuals, groups and organisations) or SES-U take to confront a complex environment are unpredictable (Hollnagel et al., 2011; Fath et al., 2015). In the process of adaptative management, people and organisations consistently need to adjust their activities. This in turn requires time, resources and information, all of which are usually restricted. Therefore, it is conceivable that the performance of such adjustment is variable and could even be unexpected, leading to undesirable outcomes (Hollnagel et al., 2011). Though the AC heuristic is a thoroughly tested mechanism, developing an adaptive system is complex and such a system may fail (Hollnagel et al., 2011).

Woods and Branlat (2011) propose that maladaptation can fall under three basic patterns. First is *"decompensation"* (*i.e.* when disturbances and/or challenges arise faster than the responses, the capacity to adapt is exhausted). Second is *"working at cross-purposes"* (*i.e.* the failure to coordinate different groups at different tiers). Third is *"getting stuck in outdated behaviours"* (*i.e.* overconfidence on past successes). For instance, there are findings showing that the availability of adaptation options may vary and could even be insufficient, which will affect the adaptation capacity (Abel et al., 2006; Goulden et al., 2013). These examples demonstrate the *"decompensation"* pattern of maladaptation. Another example of limitation has been seen in the case of German recreational fisheries where maladaptation could occur due to patterns of *"working at cross-purposes"* (Daedlow et al., 2011). This study highlighted the fact that the AC model could need adjustment, and for this case, the inclusion of *"intergroup relation"* theory helped the adaptation processes (Daedlow et al., 2011).

A case reported in the Solomon Islands shows that the adaptation to sustain overall resilience of a system (*e.g.* globalisation and land-tenure) may cause the system to be more vulnerable to low-probability hazards (*e.g.* tsunamis) and may require negotiation of trade-offs (Lauer et al., 2013). The AC can greatly improve the understanding, the steering, and the management of such specified and general system resilience.

Nevertheless, some authors point to the limitations of the AC heuristic. Resilience thinking is presented as apolitical, lacking focus on power relations, and insufficiently focused on human vulnerability (Mikulewicz, 2019). Olsson et al. (2015) highlight issues regarding the extreme difficulty of measuring the different elements of resilience and the AC using the same standards and point to the risk of disciplinary tensions between social and natural scientists. Challenges include the acknowledgement of heterogeneous values, interests and power of social actors, the anticipation of changes, the adjustment of policy goals, and the inclusion of all effects (Faber and Alkemade, 2011; Hoque et al., 2017). In light of this, Burkhard et al. (2011) suggest a modification of the AC which is explored in detail by Fath et al. (2015) highlighting key features for success through each stage.

Gotts (2007) questions the link between connectedness and resilience in the AC. Abel et al. (2006) did not support the proposition that the four AC phases tend to be sequential, nor that Ω events are preceded by reduced resilience. Why we do not aim to downplay any of these criticisms? In fact, we will show later than we agree with some of these critics. However, we believe that the AC heuristic offers a simplified common terminology and approach to better understand the dynamics of SESs and we will discuss later the flexibility needed to interpret it in a local context.

3. Methodology

Relying on over 300 years of combined expertise of our authorship, we tabulated examples of drivers of change in mangrove ecosystems and classified them within the four phases of the AC (Table 1). Then, we reviewed the mangrove literature of the past 25 years (post-1995) by searching the term 'mangrove' in Web of Science® by Title, Abstract or

Table 2
A comparison of the characteristics of the adaptive cycle phases in the mangrove SESs of Sri Lanka and the Nicobar Islands, following the 2004 Indian Ocean tsunami.

Adaptive cycle phase	Sri Lanka	Nicobar Islands
Release (Ω)	• The maximum height of the tsunami waves was 6.8 m (Shibayama et al., 2005) • 78% of mangroves were lost in the eastern region of Sri Lanka (Patel et al., 2014) • Around 30,000 deaths and 500,000 people displaced; 65% of the coastline was affected (Nishikiori et al., 2006; Mulligan and Shaw, 2007) • More than 130,000 houses affected, of which more than 99,000 were completely destroyed (Sri Lanka, 2005) • 150,000 people lost their primary source of livelihood particularly in fisheries (Jayasuriya et al., 2006)	• Wave height reached up to 10 m (https://earthobservatory.nasa.gov/images/14404/earthquake-spawns-tsunamis; Sankaran, 2005) • 1.1 m–3 m of subsidence resulted in extensive land loss across coastal areas • More than 60% of mangrove forests were permanently lost due to land submergence (Porwal et al., 2012) • 97% of mangrove cover disappeared (Nehru and Balasubramanian, 2018) • More than 3500 human casualties; the southern Nicobar group of islands lost nearly 40% of inhabitants (Sankaran, 2005; Singh, 2009) • Many villages were submerged and four islands (Kondul, Pilo Milo, Trinket and Bombuka) were abandoned • The high dependency of coastal dwelling indigenous communities (Nicobarese) on mangroves and other natural resources was broken (Patankar et al., 2015), Singh et al., 2018)
Reorganisation (α)	• Mangrove conservationists proposed to establish an operational center to provide necessary advice for mangrove planting • Technical guidelines for the mangrove practitioners provided by the state universities • Suitability maps showing the most appropriate places for mangrove restoration/rehabilitation prepared by the Ministry of Environment and Wildlife Resources • Despite the above three points, very few replanting projects were run through the operational center and suitability maps were not optimally used • Numerous mangrove replantation projects initiated • 1000–1,200ha of mangroves replanted (Kodikara et al., 2017) • 100 m no-built buffer zone imposed without consultation with locals created stress and conflict. People were unable to access the coastal forests (Uyangoda, 2005) • Skills and knowledge transferred to help establish new forms of livelihoods along the coast (Mulligan and Shaw, 2007) • Relocation of both tsunami and war victims (Fernando, 2010) (see Fig. 2B) • Sri Lanka is now identified as the first country to officially protect all its remaining mangrove forests and has embarked on an ambitious plan to restore 10,000ha of wetland including mangrove forests, during the United Nations Decade of Ecosystem Restoration	• Partial mangrove colonization at the submerged habitats that were terrestrial zones prior to the tsunami • Initial colonization was mostly by the surviving mangrove propagules. Also, restoration projects were implemented at few sites • The soil substratum and unstable tidal regime in the new inter-tidal habitats hindered immediate regeneration of mangroves (Fig. 2C) • The self-sustaining indigenous communities became dependent on the outside world, through government and private aid for livelihood until 2009 (Singh, 2009) • For many Nicobarese, it was a first life experience of receiving aid from government and the outside world • The local economy changed to a complex, cash-intensive system and social conflicts increased (Saini, 2013) • The Nicobarese were provided housing away from coasts by the government • The aid system led to socio-cultural changes (Saini, 2013). For example, the communal living of extended families changed into small nuclear families • There were changes in diet preferences, with increased dependence on supplies from the outside world • Raising new coconut plantations, commercial fishing and working for daily wages on construction projects provided some livelihood. • Nicobarese started building new canoes and boats for travelling between islands
Exploitation (r)	• Continuation of mangrove restoration projects • Assistance from NGOs for basic needs (Shaw, 2014) • Restoration of major pipelines, electricity lines, roads, bridges in tsunami-affected areas (UNICEF, 2009) • Local and international tourism opportunities for coastal communities were (re)established in tsunami-affected areas (Robinson and Jarvie, 2008)	• The initial naturally regenerated/planted mangroves attained reproductive maturity in around five years, acting as seed sources for further colonization, *i.e.* activation energy of the exploitation phase (Fath et al., 2015) • The soil substratum and tidal regime stabilized in the new habitats allowing the proliferation of mangroves, a process that took almost 10 years at many sites • Initial phase of mangrove colonization was relatively slow due to unstable conditions (*e.g.* soil substratum and tidal regime) and the lack of propagules – most of the sites had no surviving mangroves nearby • 24% of the potential area for mangrove colonization currently vegetated. However, 76% remains unvegetated (unpublished). • Nicobarese resettled in the previously abandoned islands and villages on their own, mainly after 2009 when most of the aid stopped. By 2019, although the number of households in such islands had increased this number is still incomparable to that of the pre-tsunami era • Gradual increase in the utilisation of mangrove resources (*e.g.* for construction poles and food resources like crabs, oysters, fish *etc.*) and coconut plantation yields • Construction of traditional houses using natural resources (mangrove poles, *Nypa* leaves for thatch roofing) on the rise • Harvesting and export of mangrove crab *Scylla serrata* (Forsskål, 1775) mostly after 2015 providing new livelihood options
Conservation (K)	• Less than 10% survival in more than 75% of the mangrove plantations; only about 200–220ha of mangrove planting was successful (Kodikara et al., 2017) • The urban situation became 'build back faster' rather than 'build back better (Kennedy et al., 2008) • Disappearance of relief NGOs (Hertzberg, 2015) • Pollution of coasts (Jayapala et al., 2019) • Land tenure impeded as poor people could not prove their land ownership (Arunatilake, 2018) • Establishment of policies on conservation and sustainable utilisation of mangrove ecosystems • Establishment of guidelines on expansion and rehabilitation of mangrove areas • Establishment of Mangrove Ecosystems and Livelihoods Action Group (MELAG), Commonwealth Blue Charter	Not applicable. We presume that the mangrove systems in the Nicobar Islands are still in the AC's exploitation phase r

Keyword fields (Author Keywords and KeyWords Plus), in combination with the keywords indicated in Table 1 in the same search fields, to provide but a few literature examples reporting the tabulated drivers. In addition, known examples from our experience were added where relevant. In addition, we included in Table 1 the SES variables (as defined by Ostrom, 2009) that can be affected by the drivers and that operate at various spatial and temporal scales.

Next, we identified two mangrove case studies from our authorship's joint expertise from which we could synthesise current or future phases of the AC starting from drivers triggering a clear release event. These are the 2004 Indian Ocean tsunami, focused on Sri Lanka and the Nicobar Archipelago (part of the Union Territory of Andaman and Nicobar Islands, India), and the cyclic silviculture practices in Malaysia's Matang Mangrove Forest Reserve (hereafter referred to as 'MMFR'), the world's longest-managed mangrove forest, as evidenced by written Forest Department documents (Fig. 2).

Those two case studies were supported by (i) peer-reviewed literature, (ii) grey literature to which the authors had access through institutional contacts, and, above all, (iii) the hands-on societal and scientific experience of the authors in the respective sites for nearly 20 years. The scientific experience employed a suite of systematic and consolidated participatory methods such as face-to-face interviews, semi-structured interviews and questionnaires, focus group discussions, the nominal group technique, Q-methodology, the Delphi technique, Participatory Rural Appraisals, social network analysis and multi-criteria decision analysis (Mukherjee et al., 2018). The methods used were often embedded in a conceptual framework such as Drivers–Pressures–State–Impact–Responses (DPSIR, Nassl and Löffler, 2015), Rights–Responsibilities–Revenues–Relationships (4Rs, Dubois, 1998), or the SES framework by Ostrom (2009). Finally, the research projects in which the authors were involved were interdisciplinary and results were cross-checked with ecological methods from field ecology, vegetation science, biodiversity studies, and remote sensing (Dahdouh-Guebas and Koedam, 2008).

The societal experience includes local ecological knowledge, practiced traditional lifestyles, personal observations and perceptions of change, and forest management practices, among others. Both the scientific and societal experience enabled the authors to aggregate various types of knowledge, uncertainty and heuristics while making sound professional judgements (*cf.* Haas, 2003).

4. Results and discussion

4.1. Case study 1: the 2004 Indian Ocean tsunami in Sri Lanka and India's Nicobar Archipelago

The Indian Ocean tsunami of 26 December 2004 was one of the worst disasters in modern history, responsible for immense destruction and loss of lives and livelihood. The response to the tsunami was overwhelming. According to Jayasuriya and McCawley (2008), approximately ten billion USD was raised in the aftermath of the disaster, making it the largest ever mobilisation of emergency aid.

The eastern and southern coasts of Sri Lanka were some of the most heavily impacted during this tsunami event (Table 2), with substantial inundation extended inland by as much as 2–3 km in some places (Liu et al., 2005; Wijetunge, 2006). The Nicobar Archipelago, in addition to receiving high intensity tsunami waves resulting from its geographic proximity to the earthquake epicentre, was also heavily impacted by tectonic subsidence that ranged from 1.1 m to 3 m (Nehru and Balasubramanian, 2018). Both countries' SESs had to cope with and adapt to the new conditions after the tsunami (SES-S), differing in interactions (SES-Is) and outcomes (SES-Os) based on their local contexts. Actions were implemented to recover social and ecological (mangrove) systems by various means from government and from national and international agencies (SES-GSs).

In pre-tsunami Sri Lanka, 33% of the total inhabitants were involved in diverse livelihoods involving coastal ecosystems (SES-Us). The tsunami resulted in a high number of deaths and displacements (Table 2) in the coastal areas (Nishikiori et al., 2006; Mulligan and Shaw, 2007). Sri Lanka was already vulnerable (prone to release), as the country was in the middle of a 25-year civil war between the government and the Liberation Tigers of Tamil Eelam (LTTE) in the northern and eastern districts (SES-Ss). The catastrophe acted as an amplifying feedback, further destabilising the coastal SESs. The tsunami disproportionately affected the conflict areas and the people who had already been victimized by the civil war (Beardsley and McQuinn, 2009), thus weakening the capacity to recover. Soon after the tsunami, emergency aid was provided to the victims around the country and rehabilitation measures were implemented (SES-GSs).

There is not enough evidence to prove whether or not the aid from international NGOs was distributed equally in the war-affected areas that were also affected by tsunami (Bauman et al., 2006; Fauci et al., 2012). Government relief and reconstruction schemes had little or no coordination or consultation with other agencies (Wanasinghe, 2004; Mulligan and Shaw, 2007). With the increasing reliance on government and external aid, there was little room for the role of human and social capital in the local communities. The emphasis was on rehabilitating the built capital of the SES. There was rapid development of infrastructure, new policies and land use regimes on a socio-economic and ecological scale. This led to the relocation and rebuilding of villages (Fig. 2B) for the victims of the war and tsunami (Näsström and Mattsson, 2011; Buultjens et al., 2016) (SES-O). This reorganisation in the SES led to stabilising the system ($\alpha \rightarrow r$).

Sri Lanka has become the first country in the world to protect all its mangroves by legislation irrespective of land tenure (Seacology, 2016) (SES-GS). New coastal development policies and property right rules set out by the government departments (SES-GS) created conflicts among coastal villagers (SES-U). These land conflicts are still ongoing. No-build zones were imposed along the coast where people were unable to prove their land tenure (SES-RS) due to the loss of evidence during the tsunami and war (Uyangoda, 2005; Bastian, 2005). However, the Land Reclamation Department of Sri Lanka has been actively involved in resolving land tenure issues, including communities subject to path dependence (their livelihoods coupled to coastal resources since generations). Moreover, Sri Lanka's Survey Department has launched an operation to confirm the boundaries of major land use types. Appropriate implementation of government policies and support from local government and non-governmental organisations (social capital) are essential for the sustainability of mangrove SESs in Sri Lanka. The evolution of the mangrove's SES in Sri Lanka closely adheres to the attributes of the different phases of the AC model (Table 2).

Unlike Sri Lanka, the Nicobar Archipelago is not well connected with the outside world. The islands are predominantly inhabited by the two indigenous communities (Nicobarese and Shompens), and a few settlers from mainland India (SES-Us). Except the east coast of Great Nicobar Island, the rest of the archipelago is a tribal reserve, where entry by outsiders is tightly regulated by the government (SES-S). Prior to the tsunami, the life of indigenous people in the Nicobar Islands, numbering about 30,000 which equated to 20 persons per km^2, was self-sustaining and highly dependent on natural resources available such as mangroves

(Singh et al., 2018).

The tsunami triggered a collapse of the mangrove ecosystem (SES-RS) (Nehru and Balasubramanian, 2018) and a disintegration of the socio-economy and culture of the Nicobarese (SES-Us) (Singh et al., 2018). Moreover, the subsidence-related land drowning in Nicobar completely changed the topography of the archipelago (SES-RS) (*e.g.* intertidal zones became permanently inundated, and terrestrial zones turned to intertidal zones). This resulted in the permanent inundation of around 60% of mangrove habitat, decreasing mangrove cover by 97% (SES-RU) (Nehru and Balasubramanian 2018). By contrast, in Sri Lanka, the intensity of tsunami damage was comparatively less as there was no tectonic subsidence and therefore no land drowning. The estimated loss of mangrove cover in Sri Lanka was not well-documented at the country level although approximately 65% of the coast was highly affected (Department of Census and Statistics, 2015).

According to Fath et al. (2015), if a release phase exceeds the critical threshold of a system, it will lead the α → r transition of the adaptive cycle towards a new regime, where the structure, function and feedbacks are based on a new set of rules. The effects of the tsunami were probably facilitating the evolution of a new regime different from the pre-tsunami conditions. For example, the mangrove habitats and species diversity have changed significantly, allowing new species to dominate. Additionally, a drastic change in the diet, livelihood and socio-cultural systems of Nicobarese has led to a new way of life. Therefore, the temporal scale in each phase of the AC of the Nicobar Islands might take longer than that of Sri Lanka. Also, temporal scales may not be uniform across the different sites within the two regions.

In both regions severe damage was inflicted on coastal communities and their environment, in AC terms (Fig. 3), suggesting the following narratives per AC phase:

Release (Ω). Release/collapse was triggered throughout a wide array of natural, social, economic, management and governance-related processes (SES-S) (Table 2). Areas where mangrove forests and other coastal vegetation were present offered protection and remained significantly less damaged compared to areas where human impacts had resulted in (qualitative) functional degradation more than in (a quantitative) reduction of mangrove forest area (Dahdouh-Guebas et al., 2005a; Danielsen et al., 2005) (SES-RU). The latter implies that fostering conservation of extensive mangrove areas is not enough. If the 'functionality' (here used as a synonym for 'capital', 'potential' or 'capacity') of these forests is jeopardised by cryptic ecological degradation, even large forest areas are unlikely to provide specific socio-ecological functions and goods and services, such as coastal protection (Appendix A. A2). The same is true if mangroves are unable to regenerate on a site after the disruption. In this context Satyanarayana et al. (2017) investigated the island-wide coastal vulnerability of Sri Lanka to future ocean surges. This revealed the importance of sand dunes and beach vegetation in addition to or instead of mangroves.

Like other complex systems, mangrove SESs lose resilience as they develop a higher degree of self-organisation (Allison and Hobbs, 2004). A way to illustrate this is by referring to mangrove-dependent villages which had thinned or cleared much of the surrounding mangroves prior to the tsunami for diverse purposes, such as firewood collection, brush piles (for traditional Sri Lankan fish-aggregating devices) or the establishment of shrimp ponds. While this is a release in itself, in some cases it benefitted from the 'Remember' process in situations of panarchy (Appendix B. Fig. B2). This means that thanks to adjacent forest patches from which propagules and seeds may be recruited, the AC may have quickly re-looped into a new K phase, running through the reorganisation (α) and exploitation (r) stages faster than expected or skipping them altogether. However, at a certain point, the remaining area of functional mangroves (*i.e.* not affected by exploitation or degradation) had become too small to cope with the intensity of this additional driver of system change (*i.e.* the tsunami itself). Therefore, forests and the human settlements within and beyond them were devastated by the height and strength of the waves. In some areas the tsunami left fewer trees than needed to have a healthy and functional ecosystem or to re-establish a new forest, resulting in a collapse of both human settlements and mangrove forest (Table 2). Confidence in coastal management was lost, disaster relief NGOs and projects started appearing in large numbers, some communities moved inland while others changed their occupation.

Reorganisation (α). The reorganisation phase was characterised by the rearranging of previous elements of the SES, such as remaining life forms (natural capital), infrastructure (built capital), the relocation (Fig. 2B) and rehabilitation of tsunami victims (human capital). In Sri Lanka, this phase was shorter. National plans for coastal development rapidly emerged. This included the establishment of a no-build zone 100 m in from the coast, gazettement of new protected areas along the coast and demarcation of lands for coastal reserves. Some of the affected villages were rebuilt, copying the previous structure and organisation, whereas others reconceptualised their infrastructure (*e.g.* building dykes, walls, or leaving vacant spaces on the ocean-side of their development, none of which were nature-based solutions) in case of a future tsunami. This was supported by the acceptance and implementation of the aforementioned policies (Mathiventhan, 2013). Marginal and politically invisible minority communities were unable to get benefits or voice their land related issues (Ruwanpura, 2009; Uyangoda, 2005; Telford and Cosgrave, 2007). The tsunami also allowed people to experiment with new forms of livelihoods in the coastal zone (Birkmann, 2011).

Natural post-tsunami secondary succession of the vegetation resulted in massive recruitment of less functional herbaceous mangrove associate species that were unable to fulfil the same coastal protection function as mangrove trees (Dahdouh-Guebas et al., 2005b). Likewise, failed planting by institutions that did not apply scientific rehabilitation protocols ended up spending a lot of money in vain (*cf.* Lewis III, 2005; Kodikara et al., 2017; López-Portillo et al., 2017). Unlike in Sri Lanka, the α phase in the Nicobar Archipelago was quite long due to the complete loss of mangrove vegetation by the permanent submergence of the mangrove zone due to tectonic subsidence (Nehru and Balasubramanian, 2018). The magnitude of the tsunami and its tragic impacts allowed little time for planning and many planting failures occurred in the subsequent recovery phase, as they also failed in Sri Lanka. This highlighted the need to rethink how better planning mechanisms could have prevented such failures. To cite but three examples, two from Sri Lanka and one from the Nicobar Islands:

- Risvol (2006) concluded that, "*The experiences and observations from the aftermath of the tsunami illustrate an emphasis on rebuilding physical damages. Such a response reflects a two-fold problem which provides lessons for future disaster recovery: firstly, while focusing on physical assets, it is necessary to simultaneously strengthen local institutions, in order to achieve equity in the recovery process. Secondly, attempts to return to the pre-disaster scenario of narrow livelihood options should be reconsidered, and rather adapt to new situations in order to promote development in the affected communities*".
- Kodikara et al. (2017) reported that, "54% of planting attempts resulted in complete failure [0% survival] and roughly 40% of the sites chosen for planting had [almost] no success [1–10% survival] (survival rate of saplings after 5 years). Of the 14 sites that had some

recruitment, 50% (i.e. 7 sites) had survival rates of less than 10%. These figures are of grave concern given that 13 million USD were invested in such planting efforts". The success rate of 8 year-old mangrove plantations along the eastern coast of Sri Lanka was 0.1% (Mathiventhan and Jayasingam, 2016).

- According to Singh and Hass (2013), ignoring the socio-cultural organisations of Nicobarese (the dominant indigenous community in Nicobar Islands) during the distribution of aid and rehabilitation programmes have led to a "complex disaster", which "refers to a state that has become more vulnerable than it was prior to the disaster itself, as a consequence of inappropriate human interventions leading to (a) a breakdown of institutional structures and thus a loss of reorganizing capacity, (b) failure of the society to maintain its material and energetic metabolism with its environment, and (c) creation of dependence on higher systems for continuous resource flows for its survival."

Exploitation (r). The resource availability, activation energy and driving force are critical to rebuild the system to a pre-disturbed condition or to build a new system, and avoid the poverty trap (Fath et al., 2015). Availability of adequate seed sources to repopulate the destroyed areas or suitable leadership to act as a catalyst to mobilise the social capital and create stabilising feedbacks, could serve as activation energy in this phase. In many sites in Sri Lanka, there were enough surviving trees so transition to the exploitation phase was relatively fast compared to the Nicobar Islands where the mangrove forests declined by 97% after the tsunami. A recent study in a tsunami affected area in the Nicobar Archipelago found an increase of 42% mangrove cover (natural capital) in 15 years when surviving mangrove patches (activation energy) were found nearby. Meanwhile, a site without any surviving vegetation or seed source has managed to increase the vegetated area by only 2.5% (Prabakaran & Bayyana, unpublished data).

The resulting lack of a seed bank or residual trees for succession at the new intertidal areas formed along the new coastline made any 'Remember' (facilitated rapid recovery) process impossible (Fig. 2C, Fig. B2C in Appendix B). In some cases, the establishment of new mangrove trees was observed, but in other cases the cryptic (hidden) ecological degradation trend continued with vegetation dominated by species other than those that were dominant prior to the disaster (Dahdouh-Guebas et al., 2005a,b). Once the relief phase was over, many disaster relief NGOs either disappeared or had to consciously transform into NGOs focusing on alternative livelihoods for fisherfolk. Initially NGOs did not have local knowledge and experience, and in their mission to spend the funds in haste, ended up disregarding local circumstances and community needs (Jayasuriya et al., 2006). Cost escalations that produced funding gaps combined with institutional and procedural bottlenecks hindered the distribution of available tsunami funds in Sri Lanka (Jayasuriya and McCawley, 2008).

Conservation (K). The new dynamics of villagers and other stakeholders (*e.g.* tourists, visiting fishermen, industries, decision-makers, *etc.*) becomes ever more predictable. While some stakeholders may be affected by legacies creating path dependence (*i.e.* they are affected by past events, in this case the tsunami that has laid the foundations for future social-ecological dynamics decades after the event), for other stakeholders there has been such a turn-over of the population living along the coast that their collective memory has "forgotten" the disaster of the tsunami. They need to be continually reminded of the potential risks associated with living on the coast or the risks of destroying the natural capital. In the K-phase we expect stakeholders to be less flexible in their responses to changes in ecological, social, economic and political settings (SES-S). Government measures to re-arrange land use or establish policies that deal with the new setup, may play a major role in the system's development, *i.e.* conservation. In Sri Lanka, the openhearted community spirit of people just after the tsunami soon converted to self-interest and social hierarchy (Fauci et al., 2012; Fernando and Hilhorst, 2006). Development activities started to slow down along the coast as they were impeded by land scarcity. Many land titles were under dispute (Fletcher et al., 2005; Uyangoda, 2005; Telford and Cosgrave, 2007; Ruwanpura, 2009; Arunatilake, 2018). In total, 30% of the households in Galle and 70% of the households in Batticaloa needed more than two years to recover from the tsunami, if they did at all, due to changing livelihoods, poverty and war (Birkmann and Fernando, 2008).

4.2. Case study 2: cyclic silviculture in Matang Mangrove Forest Reserve in Malaysia

The Matang Mangrove Forest Reserve (MMFR) in Peninsular Malaysia is well known for being the world's longest-managed mangrove forest (documented by written forestry archives since 1902) for pole and charcoal production from *Rhizophora apiculata* Bl. and *Rhizophora mucronata* Lamk. stands. It is managed by the Perak Forest Department (SES-GS) for the sale and export of poles and charcoal (SES-S). MMFR's silvicultural management uses a patchwork of 2.2 ha concessions or coupes (SES-RS/SES-RU), each coupe of a different age, operated on 30-year rotation cycles with two thinning events at 15 and 20 years after clear-felling. For each coupe reaching 30 years of age, the clear-felling involves clearing of the entire forest coupe, after which subsequent forest growth within the coupe takes place through a combination of natural regeneration and/or replanting depending on site conditions (Ariffin and Mustafa, 2013; Goessens et al., 2014; Otero et al. 2018; Otero et al., 2019; Lucas et al., 2020). In this context, as many as 70 pole contractors (for the thinning) and 144 charcoal contractors (for the clear-cutting), along with several hundred locals hired by the contractors, depend on the MMFR for their income generation and livelihood (SES-U). Even more depend on the ecosystem processes and functions, and on the goods and services provided by the mangrove ecosystem (SES-RS) (Appendix A. A1 and A2).

The MMFR has a total area of 40,288 ha and is divided into four different administrative zones: the protective, the productive, the restrictive productive and the unproductive zone. The productive and restrictive productive zones are under silvicultural management and are the only areas where wood extraction occurs. The protective zones (Fig. 2A), such as those registered under 'old-growth forest' or 'Virgin Jungle Reserve' (hereafter referred to as 'VJR') are composed of diverse mangrove genera including, but not limited to, *Avicennia*, *Sonneratia*, *Bruguiera* and *Rhizophora*. Patches of dryland forest exist within the protective zones (SES-ECO). The unproductive zones are represented by lakes and infrastructure areas, including villages, charcoal kilns and administrative buildings. (Otero et al., 2019).

To exemplify the use of the AC in the MMFR, we will focus on three levels: the AC reflecting what happens ecologically within a single forest coupe in a productive and a protective zone; the AC reflecting what happens ecologically in the entire MMFR; and the AC representing the wider MMFR SES. Each of these will be framed in a historic context looking at one AC axis at a time (Fig. 4 and Supplementary Material) and as a synthesised representation combining AC axes (Fig. 5). Analysing

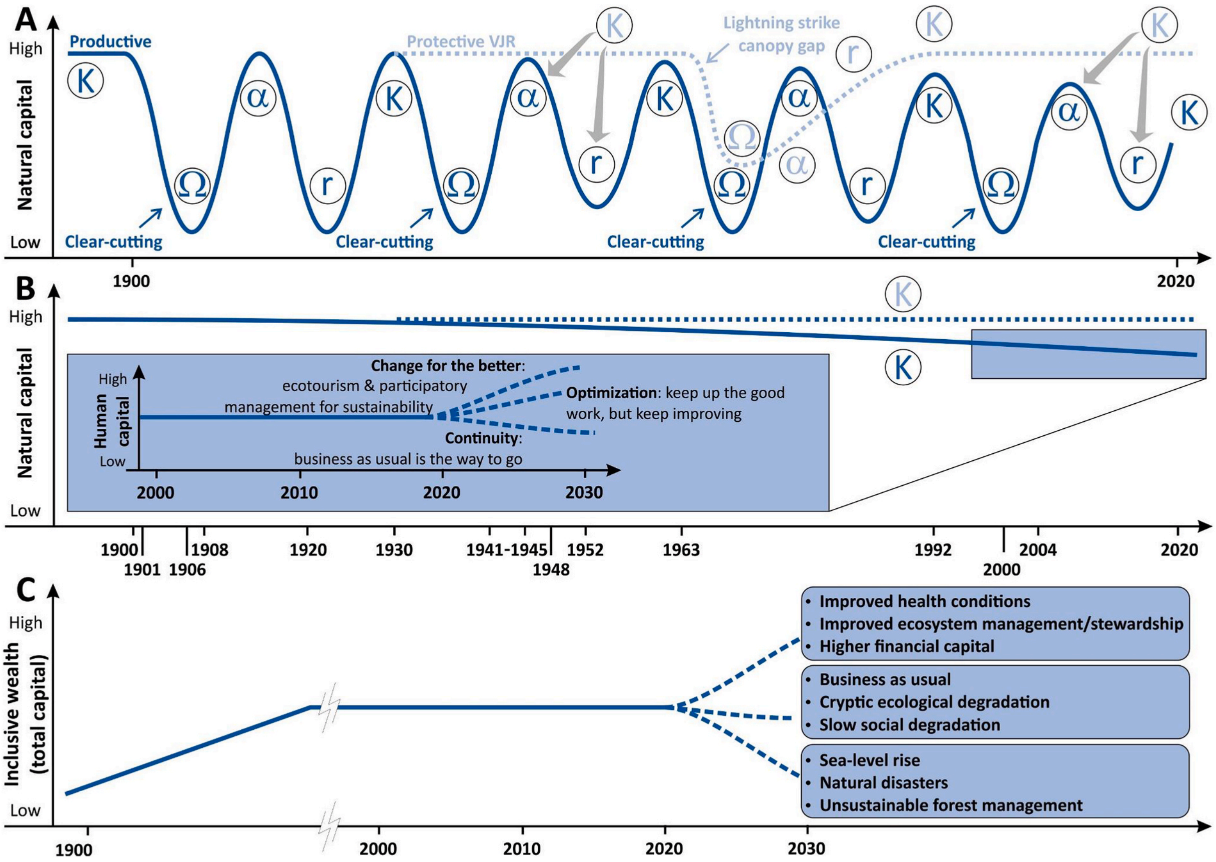


Fig. 4. Silviculture adaptive cycle in a historical context. Adaptive cycle suggested for the Matang Mangrove Forest Reserve displaying partial or total capital in function of time (in contrast to Fig. B1 in Appendix B this is one-dimensional view with time on the X-axis). Historic events on the X-axis are detailed in Supplementary Material. (A) AC within the focal scale of a single forest coupe with emphasis on natural capital. In contrast to clear-cutting events thinning events and their associated losses in natural capital are not shown but are discussed in the text. (B) AC within the entire MMFR with emphasis on natural capital on the focal scale of all coupes together. The inset shows current/future management scenario's *sensu* Hugé et al. (2016) in terms of human capital. (C). AC of the entire MMFR SES and surrounding communities incl. the tertiary service sector in villages, with possible scenarios for achieving higher inclusive wealth (N.B. the 20th century section of the X-axis is interrupted to allocate more detail to the 21st century section). Refer to Section 4.2 for detailed explanations. Refer to Fig. B1 in Appendix B for the theoretical background. Full lines: productive zone; Dotted lines: protective zone such as the VJR; Dashed lines: forecasted scenarios.

the AC using these differential spatial limits enables us to show how small-scale adaptive cycles embedded in our focal scale interact with each other (*cf.* Fig. B2 in Appendix B). Please note that all encircled numbers refer to Fig. 5, which was not repeated each time to avoid disrupting the text flow.

4.2.1. *The adaptive cycle of a single forest coupe*

Starting with the clear-cutting in the productive zone, the forest in K phase (Figs. 2A and 4A) collapses into the Ω phase, in which natural capital is essentially destroyed (Fig. 2D), and basic processes and functions such as primary productivity are halted (cf. Appendix A. A1). In contrast to the above-mentioned examples of wildfire or tsunami disasters, this release phase is planned and strengthens confidence and trust in the management rather than weakening it. In fact, as leisure and educational visitors continue to visit clear-cut areas, eco-tourism persists even in those areas. As natural capital (trees) is converted into built capital (charcoal), and as human capital (education) is sustained, the inclusive wealth of the SES stays relatively stable. However, some natural capital is lost as fauna such as macrobenthos and birds lose their habitat, which otherwise would have created spatial niche dimensions (Appendix A. A1). Macrobenthos will face a shift in community structure and composition. From previous studies carried out in Indo-Pacific mangroves, it is reasonable to assume, for resident microbenthic organisms, a change from litter-feeding towards macrobenthos-feeding crabs (Cannicci et al., 2009), and from species less tolerant to dehydration to more tolerant ones (Cannicci et al., 2018). Birds on the other hand, will be forced to move (temporarily) away, limiting their role in import and export of C-compounds and non C-resources, higher tropic transfers, *etc.* at least temporarily (Tab. A1 in Appendix A). It has been demonstrated that all avifaunal functional guilds are represented in MMFR coupes aged over 17 years (Sleutel, 2016). Considering that these results were obtained after the first thinning event, avifaunal recolonization by all functional guilds probably occurs earlier than that.

The α phase typically lasts 2 years – the period after which regeneration is aided by planting in the event of insufficient natural regeneration (*cf.* vagabond trap). Note that in the α phase the capital peak is lower in productive ❶ as opposed to protective zones ❷ (Fig. 5A and B). The recruitment of propagules and seeds in the α phase is an excellent example of how panarchy works in patchy, managed ecosystems (see Section 4.2.2). We believe that the capacity of the entire SES in the α phase remains relatively low due to the management regime aimed at harvesting tall trees ❶, because a young forest is "quite useless" for charcoal production. Neither the natural capital (the trees) nor the built capital (the charcoal) reaches its maximum capacity at this stage. However, with the increase of natural capital invested in tree growth, a slow variable, the potential of the SES increases steadily throughout the early α and r phases. Small losses in capital, resilience and connectedness in the late r phase coincide with thinning events related to mangrove pole trade ❸ (Fig. 5A and B).

In the K phase, the capacity of the system is at its maximum and resilience at its minimum (Figs. 4A and 5A), which follows resilience theory in the AC (Gunderson and Holling, 2002). However, the

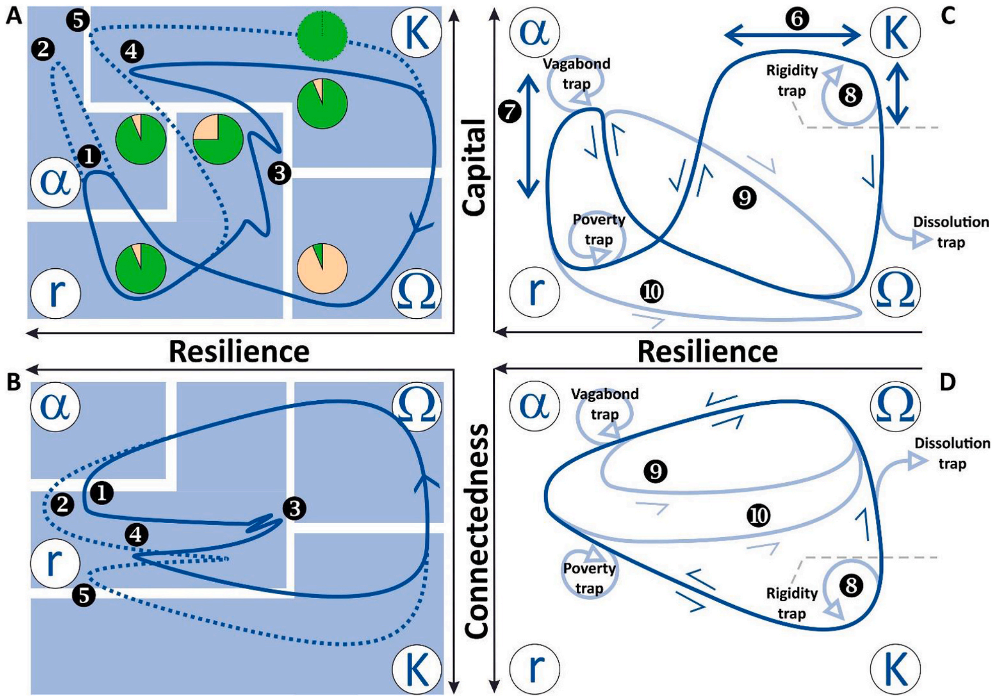


Fig. 5. Synthesised adaptive cycles. (A and B) Adaptive cycle suggested for the Matang Mangrove Forest Reserve, displayed as two coupled two-dimensional views with both capital (A) and connectedness (B) as a function of resilience, in productive zones (full lines) and protective zones (dotted lines). Pie charts indicate the proportional distribution between natural capital (in green) and built/human capital (in orange) in the productive zones; one pie chart per phase and two for the r phase (one corresponding to the early r phase and one to the thinning events). The pie chart in dotted lines corresponds to the K phase of the protective zone. The arrows in A and B indicate the "normal" direction of the AC. The blue panes in A and B attempt to visualise the time the AC spends in each phase (the blue panes correspond to 2D views of a 3D space: the larger the 3D space, the more time the AC spends in that phase). Refer to Fig. B1 in Appendix B for the theoretical background. (C and D) The same views as A and B for a generic AC indicating the possible traps. The one-way arrows show the 'expected' direction of the AC, but the double arrows in opposing directions emphasise that the AC can move back and forth. Encircled numbers refer to detailed explanations in Section 4.2. Line styles in AC and pie charts as in Fig. 4.

resistance component of resilience (see Section 1.1) is very strong due to the steady-state resource management. The broken-circle aspect of the AC in Fig. 5B was drawn to hypothesise an entrance into the K phase at a much higher resilience than usually displayed in ACs. The maximum capital and resilience in the K phase are nevertheless lower in productive □ as opposed to protective zones ❺ (Fig. 5A and B). The strong resistance component of resilience is evidenced by the monospecific nature of the coupes aimed at maximising yield. Other factors contributing to a very strong resistance are the historic MMFR objective, the single equilibrium state of the coupes, the managerial reduction of variability and the overall protection of current management goals (Chapin III et al., 2009; Hugé et al., 2016). This makes each coupe in K phase largely unresponsive to change and prone to the rigidity trap (see Section 1.3), increasing its vulnerability. Such steady-state resource management is fundamentally different to resilience-based stewardship in which the SES-GS might manage a forest for fundamental SES properties, with variability, diversity and even disturbances being fostered. Furthermore, SES-Us must work together to define goals and sustain multiple potential (stable) states and future options (Chapin III et al., 2009).

A final observation is that 15 and 20 years after clear-cutting the coupes are thinned and therefore lose some natural capital ❸ (Fig. 5A and B). At that moment the AC is in r phase, but it is debatable whether thinning results in a new Ω phase. If it does, it corroborates the view of Walker et al. (2004) that the AC can move from r directly into Ω phase (Fig. 5C). Alternatively, thinning can just incur a loss of capital within the r phase. However, even a loss in inclusive wealth can be debated, as the natural capital (the trees) lost from the system is converted into built capital (the charcoal), which may be considered as a stabilising feedback mechanism (Fig. 5).

The AC of the protective zone is very different. The VJRs have not been disturbed since approx. the 1920s, resulting in the report of 26 mangrove species (Khamis et al., 2005), an additional 30 dryland forest species (Wong, 2005), and total plant richness of up to 70 species (Khamis et al., 2005). This higher diversity, plus the probable functional redundancy of species resulting from 2 to 4 congeneric species for major and minor mangrove genera such as *Avicennia*, *Barringtonia*, *Bruguiera*, *Rhizophora* and *Sonneratia*, should lead to a higher resilience of protective as opposed to productive zones in the α ❷ and K phase ❺ (Fig. 5A and B). At this point, we recall that the AC is a heuristic that should be flexible and is to be interpreted in a local context. The resilience in some SESs can remain high in the K phase and should be considered flexible ❻ (Fig. 5C). Likewise, the maximum of the capital peak in the α phase ❼ (Fig. 5C) depends on the SES. In this particular situation, we believe that the resilience in the K phase is not necessarily low and may result from the forest's legacy (❹ and ❺ in Fig. 5A and B and ❻ in Fig. 5C). The latter is based on efficient processes and functions related to trophic and non-trophic resources as well as to non-resource components (Appendix A. A1). High resilience preceding the Ω phase was also observed in cattle and wildlife ranching SESs in Zimbabwe, and in an Aboriginal hunter-gatherer SES and a wool-bearing sheep pastoral SES in Australia (Abel et al., 2006).

4.2.2. *The adaptive cycle of the entire Matang Mangrove Forest Reserve*

Looking at the entire MMFR and at the interactions between two coupes, we can well exemplify panarchy and self-organisation. As indicated in Section 1.3 a SES is to be regarded as being composed of several subunits that all have their own AC. Hence, in a mangrove under silviculture management such as in MMFR each forest coupe is in a different stage of its own AC. The entire system can thus be seen as being composed of different ACs stacked behind one another as indicated in Fig. B2 (Appendix B). Because of the patchwork of coupes in the entire MMFR, the focal clear-cut coupes are often surrounded by older productive coupes or even protective old-growth stands (Lucas et al., 2020) that are in a larger, slower AC somewhere between the r and far K phases (Figs. 2D and 4A). By drawing on their legacies, these mature mangrove stands facilitate the α and r phases of the adjacent clear-cut coupe (*i.e.* the panarchy Remember arrows in Fig. B2 in Appendix B and Fig. 4A), for instance by providing propagules that can re-seed clear-cut patches (Otero et al., 2020). Where such cross-scale panarchy facilitation exists, the r phases of the productive zones experience a smaller drop in natural capital (grey 'Remember' arrows in Fig. 4A). This largely prevents the system from getting stuck in a poverty trap due to a deficiency of nutrients or of ecosystem processes and functions (Appendix A. A1). Stabilising feedbacks between two adjacent coupes operate at significantly different time scales (more than a decade apart). The focal clear-cut coupe benefits from the adjacent mature coupe as described above, and by the time this adjacent coupe will be ready for harvest (K→Ω) the focal coupe will be mature (K phase) and be able to facilitate the recovery of its neighbouring clear-cut coupe. This is an example of temporal self-organisation which is aided by the spatial patchwork of coupes (SES-GS). However, the first essential condition for these stabilising feedbacks to occur is the presence of a relatively undisturbed hydrological connectivity between the coupes (Bosire et al., 2008; Van der Stocken et al., 2019).

Since MMFR has been managed for over 100 years (Ismail et al., 2005; Wong, 2005), the ecological capacity is seemingly steady at the scale of the entire MMFR. While we currently disclaim any causal relationships between natural capital (production) and the years of historic events (Fig. 4B and Supplementary Material), we suggest future research to investigate this in detail. For now we can confidently conclude that as long as there is production, the MMFR is in an almost continuous K phase, albeit with gradual decrease of natural capital over time in the productive as opposed to the protective zone ❹ (Figs. 4B and 5A,B). This can be evidenced from vegetation data (Goessens et al., 2014), remote sensing data (Ibharim et al., 2015), theoretical modelling (Fontalvo-Herazo et al., 2011), and information obtained from local managers (Harry Yong, pers. comm., June 2019) and can be considered a form of cryptic ecological degradation *sensu* Dahdouh-Guebas et al. (2005a).

Other hidden problems include the negative effect that the steady-state resource management of monospecific stands has on avifauna (see Section 4.2.1). In spite of all functional guilds being present (Section 4.2.1), there is a lower avifaunal species richness in the productive zones as opposed to the protective zones (Sleutel, 2016). Whereas birds are probably less linked to specific mangrove trees, the links between mangrove trees and crabs are much stronger (Sivasothi, 2000; Dahdouh-Guebas et al., 2002; Ng et al., 2015). Therefore, we expect the same for patterns of macrobenthos between different-aged stands, with a lower richness in arboreal crab fauna in younger coupes, for instance (Sivasothi, 2000; Lee et al., 2015; Ng et al., 2015). This is subject to in-depth research in forests with stands of different ages. Such stands can not only be found in forest coupes in the productive zone, but also in canopy gaps recovering from lightning strikes in protective zones.

Both clear-cutting and lightning strikes are drivers of change, potentially causing the AC to enter the Ω phase (Fig. 4A, Tab. A2 in Appendix A). Clear-cut coupes are at least 22,000 m^2 (Otero et al., 2019) and the process of clear-cutting undeniably triggers release. However, lightning-induced canopy gaps range between 390 m^2 and 5112 m^2 (Aldrie Amir, 2012) and may be small enough to rely on the forest's legacy and cope with such disturbances in r and K phases, provided the system is not in a poverty trap (Fig. 5C and D) or rigidity trap ❽ (Fig. 5C and D). The rigidity trap is built up during the K phase. Small scale disturbance below the threshold indicated by the dashed grey line in Fig. 5C and D (*cf.* K_{lim} in Fath et al., 2015) may leave the system to bounce back. If the rigidity is too high, this threshold may shift and the AC may collapse from K→Ω ❽ (Fig. 5C and D). In this context we highlight that in just the same way as MMFR is composed of coupes, a coupe may be seen as a patchwork of sub-coupes. When no lightning strikes affect the coupe the ACs of these sub-coupes are all synchronised. However, when a sub-coupe is struck by lightning, we can recognise the same panarchy interactions with the unaffected sub-coupes. Note also that lightning gaps occurring in the productive zone suffer the combined impacts of harvesting and thinning legacies, as well as lightning. In younger coupes this may lead to the vagabond trap (Fig. 5C and D).

Finally, Note also the α→Ω ❾ and r→Ω shortcuts ❿ (Fig. 5C and D). The latter may happen when a first natural disaster (*e.g.* a tsunami in year 1) is closely followed by a second one (*e.g.* a pathogen outbreak in year 3) giving the system no chance at all to have moved into the K phase.

4.2.3. *The adaptive cycle of the wider Matang Mangrove Forest Reserve social-ecological system*

The social components at coupe level (Section 4.2.1) or at the level of the entire MMFR (Section 4.2.2) foster a continuation of the current K phase, which is characterized by a seemingly stable (but slowly degrading) single-resource management aimed at producing timber and charcoal. However, when considering the wider MMFR SES involving all stakeholders (SES-Us), *i.e.* workers involved in charcoal production (tree cutters, boat drivers, pole bearers, fire monitors, charcoal packagers, lorry drivers, supervisors), fishermen and fishmongers involved in fish, shrimp and cockle fisheries, restaurant owners, shopkeepers and ecotourism employees (Martínez-Espinosa et al., 2020), we get more insight into the AC of the entire SES.

A first point of importance is that, while present, none of the mangrove disservices (Appendix A. A3) have been reported to influence the AC. Due to asymmetries in social power some actors have power over others, creating distributional inequities (Ingalls and Stedman, 2016). This differential power distribution among key stakeholders can be obscured by the relative consensus on the way ahead regarding the management of the system as a whole (Hugé et al., 2016).

The dominance of conservative (as in: maintaining current management practices) stances among key stakeholders carries the danger of a rigidity trap, a situation in which the system cannot innovate anymore and gets 'stuck' in the current management regime despite the shortcomings that become ever-more visible and impactful (Fig. 4C). Avoiding the rigidity trap requires to prepare for different future scenarios.

At present, we do not see any signs of a dissolution trap for single coupes or for the MMFR as a whole. A heightened awareness and preparedness to exogenous factors which may influence the system is necessary to maintain the overall resilience of the MMFR SES. The most likely causes for an unintented transformation might come from a total collapse of the social properties (*e.g.* public health-related, as highlighted by Vandebroek et al., 2020), a total collapse of international trade and/or charcoal demand, or a total collapse of the ecological properties (*e.g.* large scale natural hazard destroying the entire MMFR) (Fig. 4C). We recall at this point that Fath et al. (2015) highlighted that the ingredients to avoid the dissolution, vagabond, poverty and rigidity traps come from all four phases of the AC.

5. The adaptive cycle as a persuasive narrative to re-frame mangrove management for policymakers

In order to assess the power of the AC heuristic (*cf.* Angeler et al., 2015) we call upon mangrove scientists from the basic, applied, social and human sciences to join forces in a global exercise to fit a diverse array of empirical data from numerous case studies from all continents with mangroves to the AC. This initiative would feed the framework presented in this paper. To the best of our knowledge this has never been published in mangrove-focused peer-reviewed papers, which makes it currently very difficult to analyse all aspects of change in a mangrove SES. In fact, a search of the Web of Science® using ‘mangrove’ and ‘adaptive cycle’ as keywords in title, abstract and keyword fields generated 26 results (search done on 21/05/2020) but all of these papers investigated the life ‘cycle’ or tidal ‘cycle’ in combination with ‘adaptive’ metabolism, ‘adaptive’ capabilities of species, ‘adaptive’ significance *etc.* Not a single paper dealt with the AC *sensu* Gunderson and Holling (2002), Gunderson & Pritchard Jr. (2002), Chapin III et al. (2009), and Gunderson et al. (2009) among many others. However, unpublished literature such as conference presentations (*e.g.* Abuchahla and Schaeffer-Novelli, 2016) and MSc. theses (*e.g.* Jonsson, 2017) exist and we aim at including them in the meta-analysis endeavour which we all request.

We maintain that an analysis or meta-analysis of these data through the AC heuristic will encourage mangrove scientists to synthesise data into cyclic patterns, and *vice versa* inspire researchers who discover cyclic patterns (*cf.* Cintrón et al., 1978; Cavanaugh et al., 2019) to frame them within an AC.

In order to do so we created an online platform where scientists are briefly introduced to the core idea of a SES and are invited to identify which of their datasets can fit into the four phases of the AC heuristic. The URL of the platform is: http://www.ulb.ac.be/sciences/biocomplexity/research/AC_mangrove.html.

This will in turn aid scientific, management and governance stakeholders to understand a SES as dynamic and as complex as mangroves, with stakeholders having various (mutual) relationships at risk, such as the reciprocal links between SES-Us and SES-GSs in the tsunami case study or the trade-offs between natural and built capital in the mangrove silviculture case study. It will also help interactive adaptive planning and identification of priorities for management and governance for uncertain futures.

CRediT author contributions

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Glossary

Adaptive capacity (synonymous with adaptability): Capacity of human actors, both individuals and groups, to respond to, create and shape variability and change in the state of a system. (Chapin III et al., 2009)

Amplifying feedback (synonymous with positive feedback): Feedback that augments changes in process rates and tends to destabilize a system. It occurs when two interacting components cause one another to change in the same direction. (Chapin III et al., 2009)

Built capital (synonymous with manufactured capital): The physical means of production beyond that which occurs in nature (*e.g.* tools, clothing, shelter, dams and factories). (Chapin III et al., 2009)

Capital: The human, manufactured and natural assets or productive base of a social-ecological system, including natural capital, built capital, human capital and social capital. (Chapin III et al., 2009). Some authors use this term as synonymous with ‘potential’ but in our opinion ‘potential’ denotes capital that has not been used yet.

Complex adaptive system: System whose components interact in ways that cause the system to adjust (*i.e.* “adapt”) in response to changes in conditions. (Chapin III et al., 2009)

Conservation (K) phase: Phase of an adaptive cycle during which interactions among components of the system become more specialized and interconnected. (modified from Chapin III et al., 2009)

Connectedness: The tightness of coupling among the system elements and controlling variables that determine the system’s ability to modulate external variability. (modified from Gotts, 2007)

C**ryptic ecological degradation**: functional ecological degradation that involves a qualitative decline of typical, stenotopic, vulnerable, valuable and functional species that is masked by a quantitative increase of less typical, eurytopic, disturbance-resistant, less valuable and less functional species. In a more general context, it is a qualitative ecological and socio-economic degradation of one ecosystem component that is masked by an easily detectable quantitative *status quo* or even increase of another. (modified from Dahdouh-Guebas et al., 2005a; 2005b)

Dissolution trap: Failure to survive the adaptive cycle’s release (Ω) phase resulting in a complete break of the system cycle. (Fath et al., 2015)

Exploitation (r) phase (synonymous with growth phase): Phase of the adaptive cycle during which environmental resources are incorporated into living organisms, and policies become regularized. (Chapin III et al., 2009)

Fast variable: Variable that responds sensitively to daily, seasonal, and interannual variation in exogenous or endogenous conditions. (Chapin III et al., 2009)

Inclusive wealth (of a system): Total capital (natural, manufactured, human and social) that constitutes the productive base available to society. (Chapin III et al., 2009)

Heuristic: A thinking strategy that enables quick, efficient judgment (Meyers and Twenge, 2019). Heuristics are frugal - that is, they ignore part of the information. Unlike statistical optimization procedures, heuristics do not try to optimise (*i.e.* find the best solution), but rather satisfice (*i.e.* find a good enough solution). (Gigerenzer, 2008)

Human capital: Ability of people to accomplish their goals given their skills at hand, which can be increased through various forms of learning. (Chapin III et al., 2009)

Latitude (in resilience): [A three-dimensional representation of] The maximum amount a system can be changed before losing its ability to recover. (Walker et al., 2004)

Legacy: Stored past experiences of the dynamics of social-ecological systems. (Chapin III et al., 2009)

Natural capital: Non-renewable and renewable natural resources that support the production of goods and services on which society depends. (Chapin III et al., 2009)

Panarchy: Mosaics of nested subsystems that are at different stages of their adaptive cycles, with moments of interaction across scales. (Chapin III et al., 2009)

Path dependence: Effects of historical legacies on the future trajectory of a system, or more narrowly, the co-evolution of institutions and social-ecological conditions in a particular historical context. (Chapin III et al., 2009)

Poverty trap: Situation in which a system cannot access enough activation energy [in the r phase] to reach a state where positive feedbacks drive growth internally. (Fath et al., 2015)

Precariousness (in resilience): [A three-dimensional representation of] How close the current state of the system is to a limit or threshold. (Walker et al., 2004)

Release (Ω) phase (synonymous to collapse phase): Phase of an adaptive cycle that radically and rapidly reduces the structural complexity of a system. (Chapin III et al., 2009)

Remember (in adaptive cycle): Facilitation of renewal and reorganisation by drawing on the memory (*cf.* legacy) that has been accumulated and stored in a larger, slower cycle. (Berkes et al., 2003)

Reorganisation (α) phase (synonymous to renewal phase): Phase of an adaptive cycle in which the system gradually reorganises through the development of stabilising feedbacks that tend to sustain properties over time. (modified from Chapin III et al., 2009)

Resilience: The capacity of a system to absorb disturbance and reorganise while undergoing change so as to retain its essential core function, structure, identity and feedback [loops]. Resilience contains four aspects: Latitude, Resistance, Precariousness and Panarchy. (modified from Walker et al., 2004)

Resistance (in resilience): The ease or difficulty of changing the system; how “resistant” it is to being changed. (Walker et al., 2004)

Revolt (in adaptive cycle): The connection between scales that can cause a critical change in one adaptive cycle to cascade up to a stage in a larger and slower one. (Berkes et al., 2003)

Rigidity trap: A situation in which a system becomes so refined in its processes [in the K phase] that there is little room for further innovation or change. (modified from Fath et al., 2015)

Self-organisation: The development of system structure or function as a result of stabilising feedbacks among system components. (modified from Chapin III et al., 2009)

Slow variables: Variables that strongly influence social-ecological systems but remain relatively constant over years and decades. (Chapin III et al., 2009)

Social capital: Ability of groups of people to act collectively to solve problems. (Chapin III et al., 2009)

Stabilising feedback (synonymous with negative feedback): Feedback that tends to reduce fluctuations in process rates, although if extreme, can induce chaotic fluctuations. A stabilising feedback occurs when two interacting components cause one another to change in opposite directions. (Chapin III et al., 2009).

Transformability: The capacity to create a fundamentally new system when ecological, economic or social (including political) conditions make the existing system untenable. This can be done by introducing new components and ways of making a living, thereby changing the state variables, and often the scale, that define the system. (Walker et al., 2004)

Vagabond trap: Inability to reorient the components of the system or to reconnect its nodes [in the α phase]. (Fath et al., 2015)

Vulnerability: Degree to which a system is likely to experience harm due to exposure to a specified hazard or stress. (Chapin III et al., 2009)

Appendix A. Mangrove ecosystem process and functions, goods and services and disservices

Table A1

Ecosystem processes and functions of mangroves in four categories (shaded in grey): trophic processes and functions, processes and functions regarding non-trophic nutritional resources, functions regarding other resources, and non-resource functions, most of which would be categorised as SES-RS or SES-RU (Fig. 1). For each process and function, one or more examples are given and for each example one or more literature references are provided in a non-exhaustive way (See Appendix A). All examples are part of the natural capital that constitutes the productive base of a SES. Finally, it is indicated whether the example constitutes a slow or fast SES variable.

Ecosystem processes and function depending on biota	Example	Reference example(s)	Type of variable
Trophic functions			
primary productivity	mangrove trees	Rivera-Monroy et al. (2019)	fast
	diatoms	Costa-Boddeker et al. (2017)	fast
	phytoplankton	Bouillon and Dehairs (2000), Chew et al. (2012)	fast
	cyanobacteria	Holguin et al. (2001), Granek and Ruttenberg (2008)	fast
	seagrasses	Twilley et al. (1992), Sheaves (2005), Sheaves et al. (2006)	fast
herbivory *sensu lato*	snails	Plaziat (1984), Fratini et al. (2004)	fast
	crabs	Cannicci et al. (1996a, 1996b), Dahdouh-Guebas et al. (1998), Feller and Chamberlain (2007)	fast
	caterpillars	Duke (2002)	fast
	leaf miners	Chen et al. (2017)	fast
	ants	Jenoh et al. (2016)	fast
	terrestrial herbivores	Thompson and Rog (2019)	fast
	plant parasites	Orozco et al. (1990)	fast
higher trophic transfers (‘carnivory’)	cuttlefish	Farid Dahdouh-Guebas (Pers. obs. in Gazi Bay, Kenya)	fast
	crabs	Cannicci et al. (1998), Alberts-Hubatsch et al. (2016)	fast
	spiders	Soriano (2006)	fast
	snakes	Das (2013), pers. obs.by multiple co-authors in different countries	fast
	fish	Nagelkerken et al. (2015)	fast
	primates	Saroyo et al. (2017)	fast
	cats	Thaung et al. (2018)	fast
	birds	Sodhi et al. (1997)	fast
	ants	Offenberg (2004), Tang et al. (2019)	fast
DOM breakdown and remobilisation of nutrients (*e.g.* feeding pellets, exuviae)	bacteria	Bouillon et al. (2004)	fast
	fungi	Sarma and Hyde (2001), Jones and Pang (2012)	fast
	monitor lizard	Pers. obs. in Kenya, Sri Lanka, Malaysia, *etc.*	fast
	crabs	Lee (1997)	fast
import and export of C-compounds from the system specifically effectuated by organisms (thus connecting systems)	larval stages of mangrove biota	Sheaves et al. (2012), Skov et al. (2005)	fast
	migratory animals	Hill (1994)	fast
	mangrove trees	Van der Stocken et al. (2018)	fast
Functions regarding non-trophic nutritional resources			
nitrogen fixation	cyanobacteria	Kyaruzi et al. (2003)	fast
	other bacteria	Goncalves Reis et al. (2017)	fast
nitrogen mobilisation into the biota (nitrogen uptake)	crabs	Chen and Gu (2017)	fast
phosphorus mobilisation into the biota (phosphorus mobilisation and uptake)	micro-organisms	Thatoi et al. (2013)	fast
mobilisation of other limiting elements into the biota (Si, K,…)	crabs	Chen and Gu (2017)	fast
import and export of non C-resources from the system specifically effectuated by organisms (thus connecting systems)	larval stages of mangrove biota	Sheaves et al. (2012), Skov et al. (2005)	fast
	migratory animals	Hill (1994)	fast
	mangrove wood	Wolswijk et al. (2020)	fast
Functions regarding other resources			
creation of spatial niche dimensions (*e.g.* substrate for epiphytes, root complex as refuge areas)	mangrove trees	Bishop et al. (2012), Hayasaka et al. (2012)	slow
	mud lobster	Dahdouh-Guebas et al. (2011)	fast

(*continued on next page*)

Table A1 (*continued*)

Ecosystem processes and function depending on biota	Example	Reference example(s)	Type of variable
	algae	Steinke et al. (2003)	fast
	acari	Pfingstl et al. (2020)	fast
	mudskipper	Macnae (1968)	fast
	leaf rollers	Cannicci et al. (2008)	fast
	crabs (burrows)	Ridd (1996), Gillikin et al. (2001), Vannini et al. (2003); Stieglitz et al. (2013)	fast
	corals	Yates et al. (2014)	slow/fast
Oxygenation	mangrove trees	Marchand et al. (2003)	slow
	crabs	Koch and Nordhaus (2010)	fast
	mud lobster	Hossain et al. (2019)	fast
	mudskipper	Aguilar et al. (2000)	fast
light attenuation (resource decrease)	trees	Smith III (1992)	fast
	herbaceous and suffruticose mangrove species (fern, *Acanthus*, …)	Dahdouh-Guebas et al. (2005c)	fast
freshwater collection, dew delivery	mangrove leaf buds	Cannicci et al. (1996a, 1996b)	fast
	mangrove tree trunk crevices	Catesby and McKillup (1998), Nowak (2008)	fast
	canopy	Lovelock et al. (2017)	fast
Non-resource functions			
Pollination	bats	Stewart and Dudash (2017)	fast
	birds	Wee et al. (2015)	fast
	butterflies	Raju & Kumar, (2016)	fast
	honeybees	Hermansen et al. (2014)	fast
	other insects	Sánchez-Núñez and Mancera-Pineda (2012)	fast
diaspore dispersal	crabs	Sousa et al. (2007)	fast
	other animals	Marcos César de Oliveira Santos (Pers. obs.)	fast
Bioturbation	crabs	Thongtham and Kristensen (2003), Kristensen and Alongi (2006), Kristensen (2008), Penha-Lopes et al. (2010), Bartolini et al. (2011)	fast
	mud lobster	Dahdouh-Guebas et al. (2011), Sarker et al. (2020)	fast
	shrimp	Sarker et al. (2020)	fast
shading and temperature buffering (general physicochemical setting through cooling by canopy)	trees	Vannini et al. (1997), Seghers (2014)	slow
siltation and geomorphological processes incl. wave and current attenuation or their effects	trees	Dahdouh-Guebas et al. (2005b), Adame et al. (2010)	slow/fast
	seagrasses	Guannel et al. (2016)	slow/fast
fragmentation, shredding and displacement/redistribution of matter (organic and inorganic)	crabs	Guest et al. (2006)	fast
	ants	Pers. obs. by multiple co-authors in different countries	fast
salinity and pH buffering	vegetation	Sippo et al. (2016)	fast

Table A2

Ecosystem goods and services from mangroves in four categories (shaded in grey): wood products, NTFPs, abiotic raw materials, and services, most of which would be categorised as SES-U (Fig. 1). For each good or service one or more examples are given, and for each example one or more literature references are provided in a non-exhaustive way (See Appendix A). The SES productive base that each example is part of, is given as N = natural capital, B = built capital, H = human capital, S = social capital. Finally, it is indicated whether the example constitutes a slow or fast SES variable.

Ecosystem goods & services	Example	Reference example(s)	Type of capital	Type of variable
Wood products				
Construction wood/timber	Construction wood *sensu lato*	Palacios and Cantera (2017)	N,B	slow
	Roof beams	Dahdouh-Guebas et al. (2000)	N	slow
Fuelwood	Firewood *sensu lato*	Walters (2005a,b), Nfotabong Atheull et al. (2009)	N	slow
	Charcoal	Estoque et al. (2018)	B	fast
Other wood products	fishing material	Gallup et al. (2020)	N,B	slow
	furniture and other objects made out of wood	Dahdouh-Guebas et al. (2000)	B	slow
	paper and fibres	Al-Maruf and Sarwar (2015)	B	fast
Non-timber forest products (NTFPs)				
Chemical substances of medicinal or other interest	Medication	Bandaranayake (1998, 2002)	N	slow/fast
	tannins and dyes	Dahdouh-Guebas et al. (2006a)	N	slow/fast
	Ointments	Walters et al. (2008)	N,B	slow/fast
	Insecticides	Dahdouh-Guebas et al. (2000)	N	slow/fast
	Fertilizer	Morton (1965)	N	slow/fast
	fish poison	Dahdouh-Guebas et al. (2006a)	N	slow/fast
Food and drinks	fruit juice	Jayatissa et al. (2006)	B	fast
	cakes and pastries	MAP (2006)	B	slow/fast
	Marmalade	Jayatissa et al. (2006)	B	slow/fast
	ice cream	Jayatissa et al. (2006)	B	slow/fast
	tea	Hernández-Cornejo et al. (2005)	B	slow/fast
	alcohol	Rasco (2010)	N	slow/fast
	vegetables	MAP (2006)	N	slow/fast
	salad	UNEP (2014)	N	slow/fast
	fodder	Dahdouh-Guebas et al. (2006b)	N	slow/fast

(*continued on next page*)

Table A2 (*continued*)

Ecosystem goods & services	Example	Reference example(s)	Type of capital	Type of variable
Abiotic raw materials				
Soil extraction	sand (mining)	Nfotabong Atheull et al. (2011)	N	slow
	lime/coral stone	Scales et al. (2018)	N	slow
other goods and services				
Fishing/hunting	fishing area	Lee et al. (2014)	N	slow
	hunting area	McNally et al. (2016)	N	slow
Animal rearing	livestock browsing	Kokwaro (1985), Dahdouh-Guebas et al. (2006b), Hoppe-Speer et al. (2015)	N	slow/fast
	beekeeping	Frank et al. (2017)	N,B	fast
	aquaculture	Richards and Friess (2016)	N,B,H	fast
Protection of lives and properties	coastal protection against ocean surges	Hochard et al. (2019)	N	slow
	protection against erosion	Krauss et al. (2003)	N	slow
	refuge from other people/authorities	Mastaller (1997), Satyanarayana et al. (2013)	N,S	fast
Enjoyment	(eco)tourism	Avau et al. (2011), Spalding and Parrett (2019)	H	fast
	social media	Spalding and Parrett (2019)	H,S	fast
	scenic/decorative plants	Himes-Cornell et al. (2018)	N	fast
Socio-cultural services	Spirituality/existentiality	Mastaller (1997), Uddin et al. (2013), Friess (2016)	H,S	slow
	Heritage	Uddin et al. (2013), Cormier-Salem (2017), Vandebroek et al. (2020)	H,S	slow
	Education	Rosa and Di Maio (2018)	H	slow/fast

Table A3

Mangrove ecosystem disservices in five categories (shaded in grey): health-related, safety and security-related, leisure and recreation-related, and material mangrove disservices *sensu* Vaz et al. (2017) and Friess et al. (2020), and perceived mangrove disservices which we believe to be inaccurate, ambiguous or *in se* harmless to humans. Most of these would be categorised as SES-U and be subject to SES-S (Fig. 1) For each disservice one or more examples are given (elaborated from Friess et al., 2020) and for each example one or more literature references in a non-exhaustive way are provided (See Appendix A). It is indicated whether the example constitutes a slow or fast SES variable.

Disservices	Example	Reference example(s)	Type of variable
Health-related mangrove disservices			
Diseases caused by Protozoans	malaria transferred by mosquitos	Friess (2016)	fast
Viral diseases	Mayaro, Chikungunya, Zika and West Nile virus transferred by mosquitos	Ali et al. (2019)	fast
Bacterial diseases	cholera, often adhering to chitinous or mucilaginous organisms such as plankton, shrimps and blue green algae	Neogi et al. (2012), Rebaudet et al. (2013)	fast
Fungal diseases	Lethargic crab disease causing mass mortality in *Ucides cordatus* (an important food source) by the ascomycete *Exophiala cancerae*	Seyedmousavi et al. (2018), Simith and Diele (2008)	fast
Diseases caused by other organisms	toxic dinoflagellates, cyanobacteria, algae *sensu lato*, *etc.* and their vectors (*e.g.* molluscs)	Guidi-Rontani et al. (2014), Grizzle et al. (2018), Duran-Riveroll et al. (2019)	fast
Safety and security-related mangrove disservices			
Danger of water	drowning, damage to equipment	Von Rosenberg (1867)	slow/fast
Danger of water/Risk of injury	floating debris	Cochard et al. (2008, 2011)	slow
Risk of injury	roots with razor-sharp oysters	Friess et al. (2020)	slow
	Blind-your-eye mangrove *Excoecaria agallocha* L.	Chan et al. (2018)	slow
Conflicts with wild animals	crocodiles, tigers, snakes, *etc.*	Badola et al. (2012), Das (2013), Naha et al. (2016)	slow
Danger of losing way	root labyrinth in all directions	Friess (2016)	slow/fast
Dangerous people	dangerous indigenous communities	Mastaller (1997)	slow/fast
Leisure and recreation-related mangrove disservices			
Reduction, disruption, or inhibition of recreational interactions with nature	Obstructed landscape/seascape view	Friess (2016), Friess et al. (2020)	slow/fast
Reduction in recreational access	Ecosystem components that reduce recreational opportunities due to perceived or actual disservices (see other disservice categories)	Friess et al. (2020)	slow/fast
Material mangrove disservices			
Danger of salt	damage to equipment	Personal experience	slow/fast
Physical damage to built infrastructure or equipment caused by ecosystem components	damage by crabs, monkeys, *etc.*	Dahdouh-Guebas et al. (1997)	fast
Perceived mangrove disservices (inaccurate, ambiguous or *in se* harmless to humans)			
Fear of dangerous people	legacy of indigenous communities that once were dangerous, or that were perceived as aggressive	Mastaller (1997), Friess (2016)	slow/fast
Bad smell	source of putrid exhalations	Darwin (1839)	slow
Sounds	shrimp-borne clicking sounds	Staaterman et al. (2017), Friess et al. (2020)	slow
Dirty	reluctance to walk through muddy waters and soils	Jayatissa et al. (2002)	slow
Unappealing	"dark", "gloomy", "fetid", "dismal"	Friess (2016), Friess et al. (2020)	slow
Impenetrable forest	root labyrinth	Friess (2016)	slow
Uninhabitable forest	place for punishment and exile	Expedition Robinson (a.k.a. Survivor) International reality game show	slow

(*continued on next page*)

Table A3 (*continued*)

Disservices	Example	Reference example(s)	Type of variable
Landward mangrove extension (into terrestrial/inhabited/cultivated areas)	bad omen for sea-level rise	Unpublished data from Kenya	slow

Appendix B. The adaptive cycle and its cross-scale interactions (panarchy)

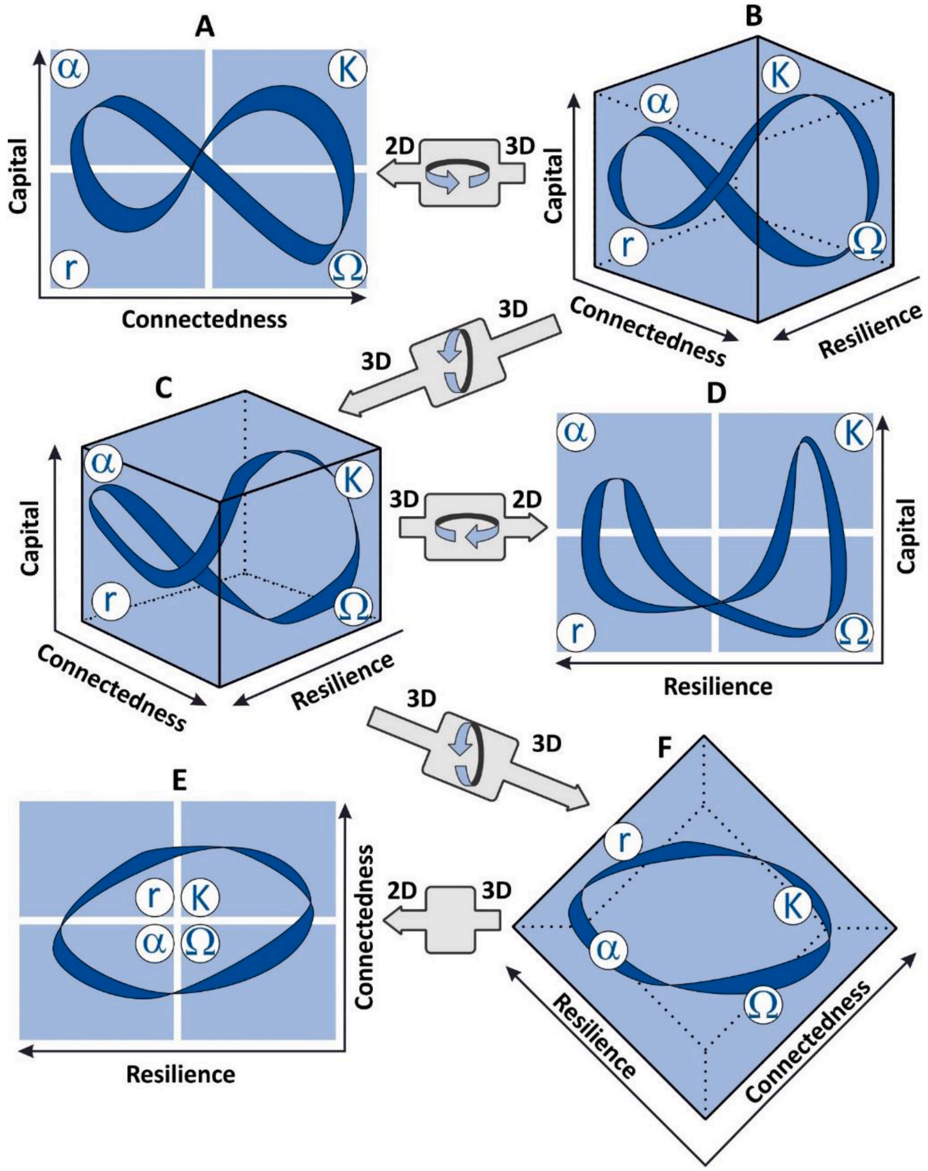

Fig. B1. The adaptive cycle. Representation of the AC in two and three dimensions with capital (also named 'potential', '(functional) capacity' or 'inclusive wealth'), connectedness and resilience as axes. The most common representation of the AC is the infinity-like, figure of eight shape in 2D with connectedness as the X-axis and capital as the Y-axis (A). However, this is but a 2D representation of the 3D cube that also includes resilience as the Z-axis (B). By rotating this cube from a side-view to a bird's-eye-view (C) one can begin to see the 3D pattern of the AC, which now has a U-shape. By rotating the cube clockwise and viewing it from the side one can see the 2D view with resilience as the X-axis and capital still as the Y-axis (D). By rotating the cube further upward one can get a 3D bottom-view with resilience and connectedness as axes (F) and capital as depth (axis not shown). The latter is also given in 2D (E), in which the AC has become a circle. The 'infinity', 'U' and 'circle' shapes representing the AC viewed from different angles will be used again in Fig. B2 in Appendix B without their axes. In part, adapted from Holling et al. (2002). The phases of the AC symbolised as follows: Ω: Release (collapse), α: Reorganisation (renewal), r: Exploitation (growth), K: Conservation. See Glossary for definition of terms.

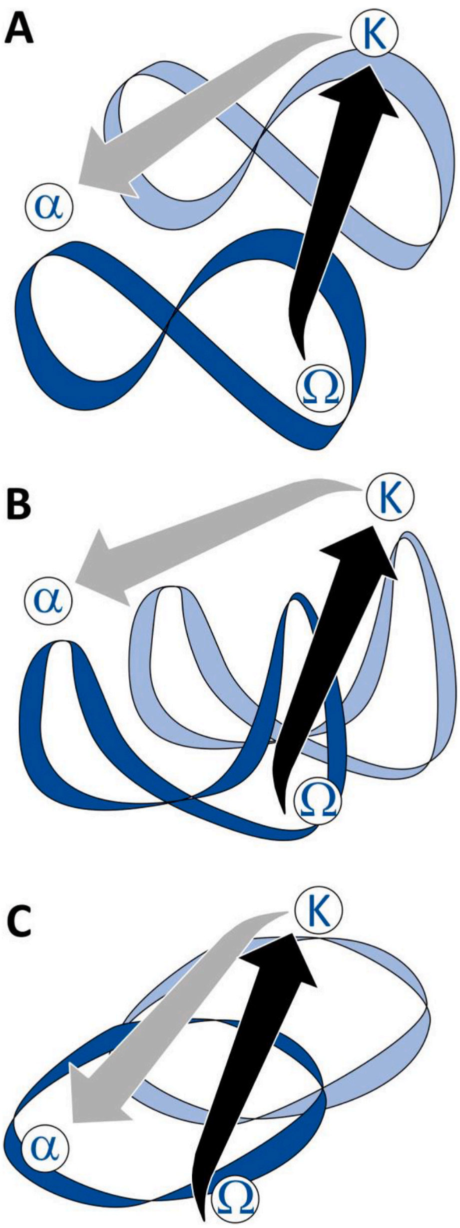

Fig. B2. Panarchy. A SES is to be regarded as being composed of several subunits that all have their own AC, here shown for the three 2D views discussed in Fig. B1 in Appendix B (axes not shown), with the connectedness vs. capital (A), resilience vs. capital (B), and resilience vs. connectedness (C). When release (Ω-phase) is triggered in the focal AC (in dark blue), the disruption may cascade (revolt) to the (slower) K-phase of the neighbouring AC (black arrow). Inversely, non-affected ACs in a (slower) K-phase, may help affected ACs reorganise. This is shown by a 'Remember' (grey) arrow with the dark blue AC being the focal one. In part adapted from Holling et al. (2002).

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2020.106942.

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