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RESEARCH ARTICLE

Shifted baselines: Using the adaptive cycle to assess the post-tsunami mangrove social-ecological system recovery in the Nicobar Islands

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Abstract The 2004 tsunami and coastal subsidence resulted in 97% mangrove loss in the Nicobar Islands (India), leading to major social-ecological change. We assessed how the Nicobar mangrove social-ecological system (SES) responded to the 2004 event using the adaptive cycle (AC) framework. We describe the changes across AC phases (collapse-Ω, reorganisation-α, growth-r, and conservation-K) concerning various capital types (natural, built, human, social), connectedness and resilience. The subsidence and tsunami triggered a rapid collapse (Ω) in the mangrove SES, particularly depleting natural and built capitals. Despite declines in social and human capital, some knowledge and skills were retained within Nicobari communities. We suggest that locally managed interventions involving mangrove restoration are critical to escape the poverty trap caused by resource insufficiency hindering growth. The AC model helps visualise and describe temporal changes, preparing for recovery challenges. This approach is relevant to SESs beyond Nicobar, offering insights for sites confronting similar social-ecological dynamics and challenges.

Keywords Adaptive capacity · Coastal ecosystems · Environmental change · Indigenous communities · Resilience · 2004 Indian Ocean tsunami

Nehru Prabakaran and Meenakshi Poti are co-first authors.

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INTRODUCTION

Mangrove social-ecological systems

Mangrove social-ecological systems (SESs) are dynamic networks in intertidal zones along tropical, sub-tropical and warm temperate coastal areas (Mukherjee et al. 2014; Dahdouh-Guebas et al. 2021). Their unique transitional nature between terrestrial and marine ecosystems enables the ecological and social components of mangrove SESs to interact with neighbouring ecosystems such as coral reefs, seagrass beds, beaches and coastal terrestrial forests. Mangrove SESs are influenced by external factors beyond the confines of the mangrove forest, such as deforestation and sedimentation originating from other systems like inland forests and industrial agriculture (Yando et al. 2021).

Mangrove SESs provide critical ecosystem services, including provisioning (e.g. timber, charcoal, fisheries), regulating (e.g. coastal protective barriers, carbon sequestration) and cultural services (e.g. recreation, ethnobiological knowledge, spiritual significance) (Mukherjee et al. 2014). Diverse anthropogenic stressors contribute to the decline and degradation of mangrove SESs worldwide (Duke et al. 2014). Geographically varied, the main drivers of mangrove degradation are human-driven processes like aquaculture, agriculture conversion, urban development, pollution and climate change (Friess et al. 2019; Goldberg et al. 2020; Lovelock and Reef 2020). Natural disturbances, including cyclones, lightning strikes, storm surges and tsunamis, also contribute to mangrove degradation worldwide (Nehru and Balasubramanian 2018; Krauss and Osland 2020; Dahdouh-Guebas et al. 2022).

The 2004 Indian Ocean tsunami

The 26 December 2004 Indian Ocean tsunami, triggered by a 9.1 Mw Sumatra–Andaman earthquake, caused widespread devastation across countries such as India, Indonesia, Sri Lanka, Thailand, and Malaysia (Dahdouh-Guebas et al. 2005; Satake 2014). The Nicobar Islands, situated near the earthquake's epicentre, experienced high-intensity tsunami waves (exceeding 10 m height) and tectonic subsidence (Porwal et al. 2012). Subsidence levels varied across the islands, measuring 1.1 m in Car Nicobar and ranging from over 1.4 to 2.85 m in South and Central Nicobar (Rajendran et al. 2007; Ray and Acharyya 2011; Nehru and Balasubramanian 2018; see Fig. 2). Altered tidal flows due to coastal subsidence resulted in severe mangrove loss (97% mangrove vegetation loss in the archipelago), affecting biodiversity and the indigenous Nicobarese community (Nehru and Balasubramanian 2018). This event established shifted baselines for subsequent mangrove recolonisation and restoration (Dahdouh-Guebas and Cannicci 2021).

The 2004 seismic event presents a unique case for understanding how the SES responds to drastic environmental change, offering insights for disaster management. Using the adaptive cycle (AC) framework, this study explores the Nicobar mangrove SES's response to the 2004 coastal subsidence and tsunami. The AC is a conceptual framework that helps describe the temporal dynamics and resilience of changing social-ecological systems (Gunderson and Holling 2002; Gunderson et al. 2009). It aids in representing time series information, identifying critical time periods and areas, and visualising, organising and understanding the dynamics of complex adaptive systems (Zhang et al. 2021). By analysing and synthesising past events and responses, we assume that these learnings are valuable, despite the future being uncertain. The consideration of adaptive histories, past experiences, memory and knowledge regarding past conditions is important for mitigating vulnerabilities, planning and subsequently implementing effective strategies (Saini 2015a). Overlooking these factors may lead to unsustainable outcomes for recovery, further increasing susceptibility to future events (Perez-Orellana et al. 2020; Dade et al. 2022).

Theoretical framework: adaptive cycle (AC)

The adaptive cycle, originally depicted by Gunderson and Holling (2002) as an infinity-shaped loop, comprises four phases: growth or exploitation (*r*), conservation (*K*), collapse or release (Ω) and reorganisation (α) (Fig. 1). The AC is visualised within a three-dimensional space defined by (1) capital (natural, built, human and social capital), (2) connectedness or "the degree of connection between variables and internal controlling processes" (Perez-Orellana et al. 2020) and (3) resilience (refer to Table 1 for definitions). Disturbances exceeding stability thresholds trigger collapse (Ω), wherein many accumulated resources (e.g. vegetation and fauna) and their connectedness are rapidly lost. This is followed by a reorganisation phase (α) with high transformation potential as resources are not yet tightly connected. The growth (*r*) and conservation (*K*) phases involve resource accumulation, extraction and stability maintenance.

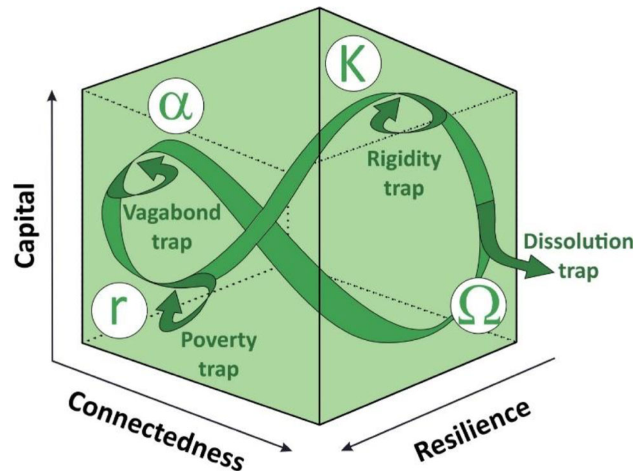

Fig. 1 Visualisation of the generic adaptive cycle in 3D including its phases, variables and traps (adapted from Dahdouh-Guebas et al. 2021)

Transitions between AC phases are not necessarily fixed, predictable or chronologically cyclic. Dahdouh-Guebas et al. (2021) demonstrate that the AC does not always follow the original infinite loop structure. Instead, systems can transition backward from *K* to *r*, move directly from r to Ω or revert from α to Ω. Moreover, systems may face challenges or get "trapped", limiting adaptability (Carpenter and Brock 2008). Four traps—lock-in, vagabond, poverty and rigidity—correspond to each phase, and identifying and understanding these traps is important for targeted interventions and for overcoming limitations in adapting to changing conditions or disturbances. Therefore, people involved with managing the SES must think creatively by planning new opportunities that enhance smoother transition between the AC phases (Chapin III et al. 2009).

This study uses the adaptive cycle perspective to describe, categorise and visualise the characteristics, transitions and traps of each phase in relation to capital, connectedness and resilience in the Nicobar mangrove SES. Understanding these patterns provides insights into challenges and opportunities during recovery, aiding informed decision-making for mangrove managers, especially in unique situations like those created by the 2004 tsunami

Table 1 Definitions of variables, phases and traps within the adaptive cycle

Adaptive cycle variables	
Capital	The resources or productive base of a social-ecological system. It includes natural, built, human and social capital (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)
Built 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)
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)
Social capital	Ability of groups of people to act collectively to solve problems (Chapin III et al. 2009)
Inclusive wealth	Total capital (natural, built, human and social) that makes up the productive base available to society (Dahdouh-Guebas et al. 2021)
Connectedness	"The relationships between system elements and processes, and the degree to which elements are dominated by external variability, or by relationships that mediate the influence of external variability" (Sundstrom and Allen 2019)
Resilience	The system's ability to reorganise and recover itself from a disturbance, by maintaining its "core function, structure, identity, and feedback" (Walker et al. 2004)
Adaptive cycle phases	
Conservation phase (K)	AC phase during which interactions among components of the system become more stable, specialised and interconnected (Chapin III et al. 2009)
Collapse or release phase (Q)	AC phase described by rapid change, transformation or collapse, reducing the structural complexity of a system (Chapin III et al. 2009). In this phase, connections between the elements constituting a SES in K-phase and the associated high capital are 'released' or lost
Reorganisation phase (α)	AC phase wherein the system gradually reorganises through the development of stabilising feedbacks that tend to sustain properties over time (Chapin III et al. 2009)
Growth phase (r)	AC phase during which environmental resources are incorporated into living organisms and policies become regularised (Chapin III et al. 2009)
Adaptive cycle traps	
Lock-in or dissolution trap in Q-phase	The inability to enter the renewal stage following collapse. Failure to get through the release or collapse phase results in a complete break of the system cycle (Allison and Hobbs 2004; Fath et al. 2015)
Vagabond trap in a phase	The inability to reorient the components of the system or to reconnect its nodes (Fath et al. 2015)
Poverty trap in r-phase	The loss of options to develop or deal with change due to insufficient resources or activation energy (Gunderson and Holling 2002; Chapin III et al. 2009)
Rigidity trap in K-phase	Excessively tight, rigid and inflexible connections that increase the resistance against changes and innovation, making it less resilient and more susceptible to external disturbances (Fath et al. 2015)

and subsidence in the Nicobar Islands. Furthermore, this paper illustrates the application of the AC framework proposed by Dahdouh-Guebas et al. (2021) for mangrove SESs, offering a sequential build-up from a two-dimensional (2-D) to a three-dimensional (3-D) view. Addressing a general gap in the literature, this paper explicitly shows the construction of the AC from a 2-D to 3-D view. The transition from a 2-D to a 3-D representation offers a comprehensive visualisation of how the three dimensions of the adaptive cycle (AC) interact over time.

STUDY CONTEXT

The Nicobar archipelago (or 'Nicobar'), located off the east coast of mainland India, consists of 21 islands (12 inhabited) spanning over 300 km, with a total land area of 1841 km^2 (Fig. 2). Clustered into northern, central and southern groups, the largest island is Great Nicobar (910 km^2), located around 200 km from the epicentre of the 2004 earthquake. Prone to high seismic activity, the islands have experienced seven major earthquakes (> 7 Mw) between 1847 and 1955, some of which caused land subsidence, uplift and tsunamis, however of lesser intensity than the most recent 2004 event (Rajendran et al. 2007).

The topography is flat, undulating and hilly, with the highest peak at 670 m in Great Nicobar. Positioned within the Sundaland global biodiversity hotspot (Myers et al. 2000), the islands feature diverse ecosystems, sandy beaches, mangroves and coral reefs (Prabakaran and Paramasivam 2014; Chandi et al. 2015). Approximately 90% of the land is covered by natural vegetation, including tropical

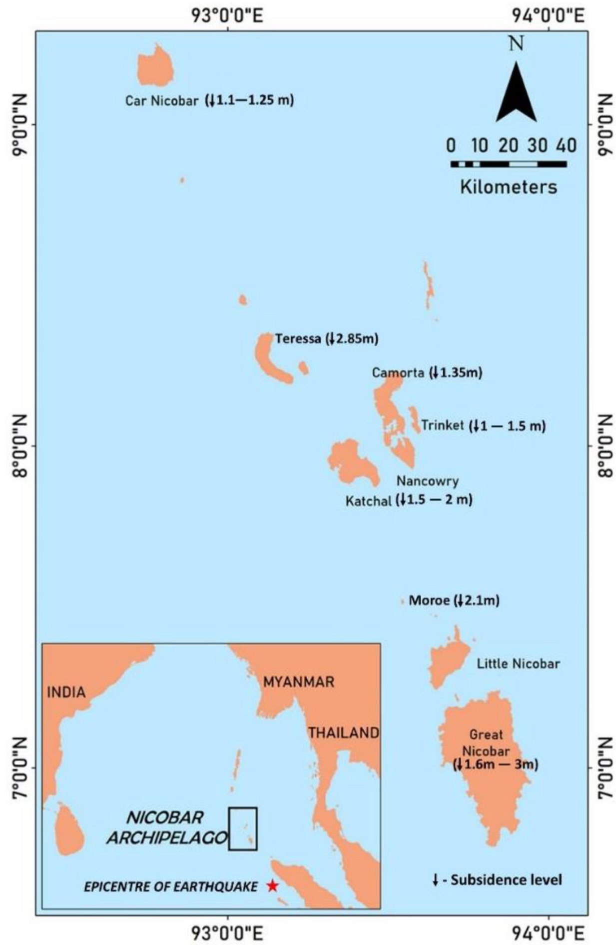

Fig. 2 A map of the study area showing the levels of subsidence across different islands in the Nicobar archipelago. The inset shows the location of the Nicobar archipelago and neighbouring territories

evergreen forests, mangroves and grasslands. The central and southern group of islands are more forested than the densely populated Car Nicobar and Chowra Islands (Chandi et al. 2015). The climate is hot and humid, with temperatures ranging from 22 to 32 °C and an annual average rainfall of 2650 mm (Kumar et al. 2012).

The Nicobar Islands, with a population of 37 000 people, are inhabited by two indigenous communities (Nicobarese and Shompen) and settlers from mainland India (settled from 1969 onwards) (Census of India 2011; Saini 2016). The Nicobarese, the primary inhabitants across all 12 inhabited islands, are predominantly coastal dwelling. The Shompen, a semi-nomadic tribe, reside in the forests of Great Nicobar Island (Chandi et al. 2015). This paper largely focuses on the indigenous Nicobarese community. The traditional Nicobarese economy is closely tied to the environment, with a focus on horticulture, coconut plantations, animal husbandry and fishing, and some engagement in trade with the mainland Indian market through dry coconut and betel nut trade (Singh et al. 2001; Chandi et al. 2015). A small proportion of islanders are employed as government servants or in private enterprises (Saini 2013).

Since 1956, the Nicobar Islands (officially part of 'Andaman and Nicobar Islands') have been a Union Territory of India (UT), governed directly by the central Government of India in New Delhi. Despite the absence of an autonomous government, the islands also have traditional governance structures based on kinship and personal networks (Chandi et al. 2015). Entry of outsiders is strictly regulated by the government, and the islands are largely protected under Tribal Reserves (Venkatanarayanan 2018).

MATERIALS AND METHODS

In this paper, we use the AC framework to qualitatively describe the impacts of the 2004 tsunami on the mangrove SESs of the Nicobar Islands. We categorise mangrove SES changes within the four AC phases, starting in 2004 with the coastal subsidence and tsunami driving the release or collapse event (Ω).

The description of the Nicobar mangrove SES AC is based on primary and secondary data from the following sources. First, we conducted a systematic literature review of English-written peer-reviewed literature on the Web of Science Core Collection and Scopus databases, using the search string "Mangrove* and Nicobar*" (details of the review process in Appendix S1). Through this review, we identified 29 relevant papers out of an initial pool of 225 articles focused on the Nicobar (selection criteria and article titles in Appendix S1). These articles primarily emphasise the ecological aspects of the mangrove SES (i.e. natural capital), with limited information on the social aspects. Second, to gather insights into the social aspects, we conducted an extensive review of literature by experts in sociology and socio-economics who have worked extensively on pre and post-tsunami socio-cultural changes in Nicobar (accessing their ResearchGate and Google Scholar pages—reviewed articles are listed in Appendix S1). Third, we formalised community observations based on personal interactions with the local community over the last 20 years which represents substantial knowledge and intuition about the system. Fourth, based on the lead author's fieldwork and recent publications, we used primary quantitative data on mangrove vegetation parameters (e.g. density, rate of vegetation increase, number of species) and remote sensing analysis of satellite data to understand mangrove recolonisation rates (Nehru and Balasubramanian 2011; Prabakaran and Paramasivam 2014; Nehru and Balasubramanian 2018; Prabakaran 2020; Prabakaran et al. 2021; Bayyana and Prabakaran in review; Table S2 shows the fieldwork duration spanning 55 months over a period of 15 years). Consequently, this paper provides a more detailed examination of natural capital due to the availability of more information compared to other capitals.

Drawing on extensive scientific and societal experiences, we integrated diverse knowledge to make informed professional judgements and assessments (Haas 2003). Information from the literature was categorised for each of the AC phases and the three AC axes—capital (natural, human, built and social), resilience and connectedness. We assigned high, low or intermediate values for each of the AC axes over a temporal scale (pre-2004 to 2020) (Fig. 3). We first depict time-related events in relation to each of the three AC axes: capital versus time (top horizontal graph), resilience versus time (left vertical graph) and connectedness versus time (right vertical graph). We then combine the AC axes—capital and resilience; and capital and connectedness—to create two graphs with 2 AC axes and with time axis information included in the curve itself (hereafter referred to as '2-D graphs'). In line with the original AC by Gunderson and Holling (2002), curves in the graphs represent time as a factor influencing change over the course of the AC. In other words, 'time' refers to the speed at which each phase progresses. For instance, in the horizontal graph of Fig. 3A, the period between 1995 and 2004 in the *K*-phase, where natural capital remains constant, corresponds to a stationary point in the top left and top right 2-D graphs. Conversely, the period between 2004 and 2005 in the Ω-phase, marked by a sudden drop in natural capital, aligns with a similar drop in the top left and top right 2-D graphs along the natural capital axis. This analysis applies similarly to the connectedness and resilience axes. Finally, we integrate all three AC axes into a single graph, with connectedness as the X-axis, capital as the Y-axis and resilience as the Z-axis (hereafter referred to as '3-D graphs'). The information from the 2-D graphs can be viewed inside the two panels of the 3-D cube, acting as "windows" of the cube. The numerical labels in the graphs (in black circles in Fig. 3) correspond to numbers enclosed in square brackets in the Results and Discussion section of the paper.

RESULTS AND DISCUSSION

The Nicobar mangrove socio-ecological system (SES) experienced catastrophic impacts from the 2004 subsidence and tsunami events of a scale rarely witnessed in human memory. Viewing these events as a trigger (collapse phase in the AC), we trace and hypothesise the adaptive cycle phases according to the capitals (natural, built, human and social capital), connectedness and resilience of the mangrove SES.

Conservation phase-K (pre-tsunami)

Before the tsunami, we hypothesise that the Nicobar mangrove SES was in the *K*-phase, characterised by high inclusive wealth—the total capital encompassing natural, built, human and social capitals—forming the productive base of the SES. The natural capital (environmental resources) of the mangrove SES was at its peak during the pre-tsunami period (Fig. 3A). Prior to the 2004 tsunami, the mangroves in the Nicobar archipelago remained largely undisturbed by human activity, covering a total area of 37 km^2 (Roy et al. 2005). The mangrove vegetation had an average canopy height exceeding 25 m, with *Rhizophora apiculata* along the seaward zones and *Bruguiera gymnorrhiza* and *Lumnitzera* spp. along the landward zones (IIRS 2003; Nehru and Balasubramanian 2018).

The built capital, comprising physical infrastructure and assets, was consistently low in the Nicobar archipelago (Fig. 3B). However, the resilience of the built capital in Nicobar mangrove SES was high because of community access to abundant natural resources from the terrestrial forest. Before the tsunami, the coastal dwelling indigenous Nicobarese community depended on mangrove resources for sustenance and shelter, with minimal dependence on the global market economy (Saini 2012). Economic self-sufficiency was achieved through copra (dehydrated coconut) production (Singh 2009). Most of their food requirements, including fish, crabs, bivalves, and shrimp, were primarily gathered from mangroves (Prabakaran 2021). The mangroves were extensively utilised as raw materials for traditional Nicobarese hut construction, utilising poles extracted from *Bruguiera gymnorrhiza* and 2018fronds of the *Nypa fruticans* palm for roof thatching (Chandi ; Prabakaran 2021) (Fig. S4). This well-established species-specific utility of the mangroves meant that connectedness was high pre-tsunami.

Human capital, encompassing knowledge and skills, was abundant pre-tsunami and primarily held by a select few, especially elders in the community (Engineer 2020) (Fig. 3C; Fig. S5). This knowledge included expertise in harvesting optimal construction poles, boat building, thatching roofs and hunting specific species like crabs, crocodiles, and turtles (Singh et al. 2001). The resilience associated with the human and social capitals was hypothesised to be intermediate, because the Nicobarese are a vulnerable community due to their small population, isolated nature, limited access to medical facilities and relatively recent exposure to settlers from mainland India (potential carriers of diseases new to the Nicobarese and the further erosion of traditional ecological knowledge (TEK) (Saini 2017; Engineer 2020).

Before the tsunami, the Nicobarese, characterised by strong social organisation, coordinated resource

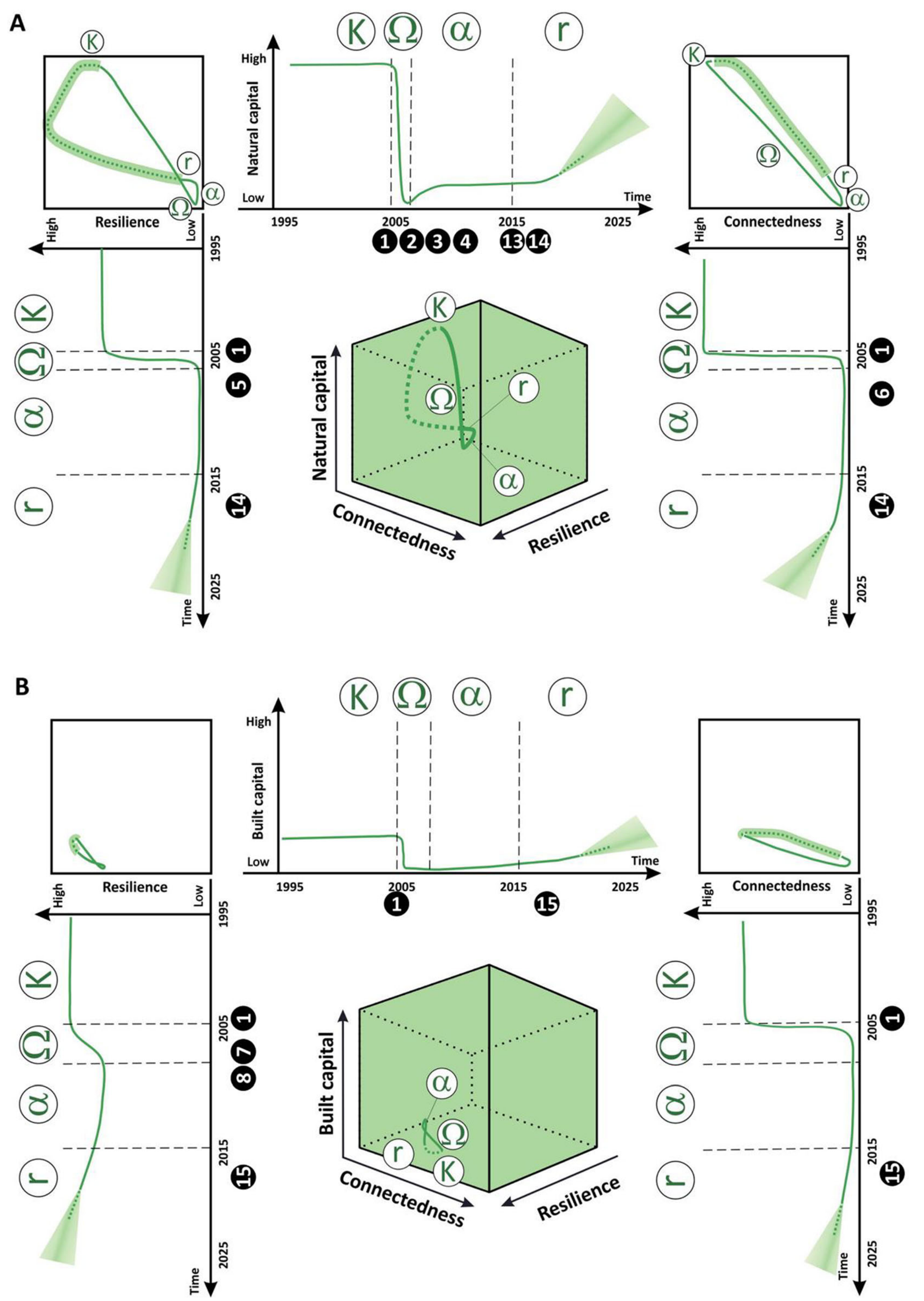

Fig. 3 Synthesised adaptive cycles based on the mangrove social-ecological systems: **A** natural capital; **B** built capital; **C** human capital; and **D** social capital in the Nicobar archipelago. Time-related events are first plotted in relation to each of the three AC axes: capital versus time (top horizontal graph), resilience versus time (left vertical graph) and connectedness versus time (right vertical graph). The 2-D graphs with 2 AC axes: capital and resilience (top left graph); and capital and connectedness (top right graph). The 3-D graph in the centre includes all 3 AC axes: resilience and connectedness as a function of capital. Labels with numbers indicate specific events of change and are highlighted in the main text in square brackets. The dotted lines in the curves and light green shading represent the uncertain future

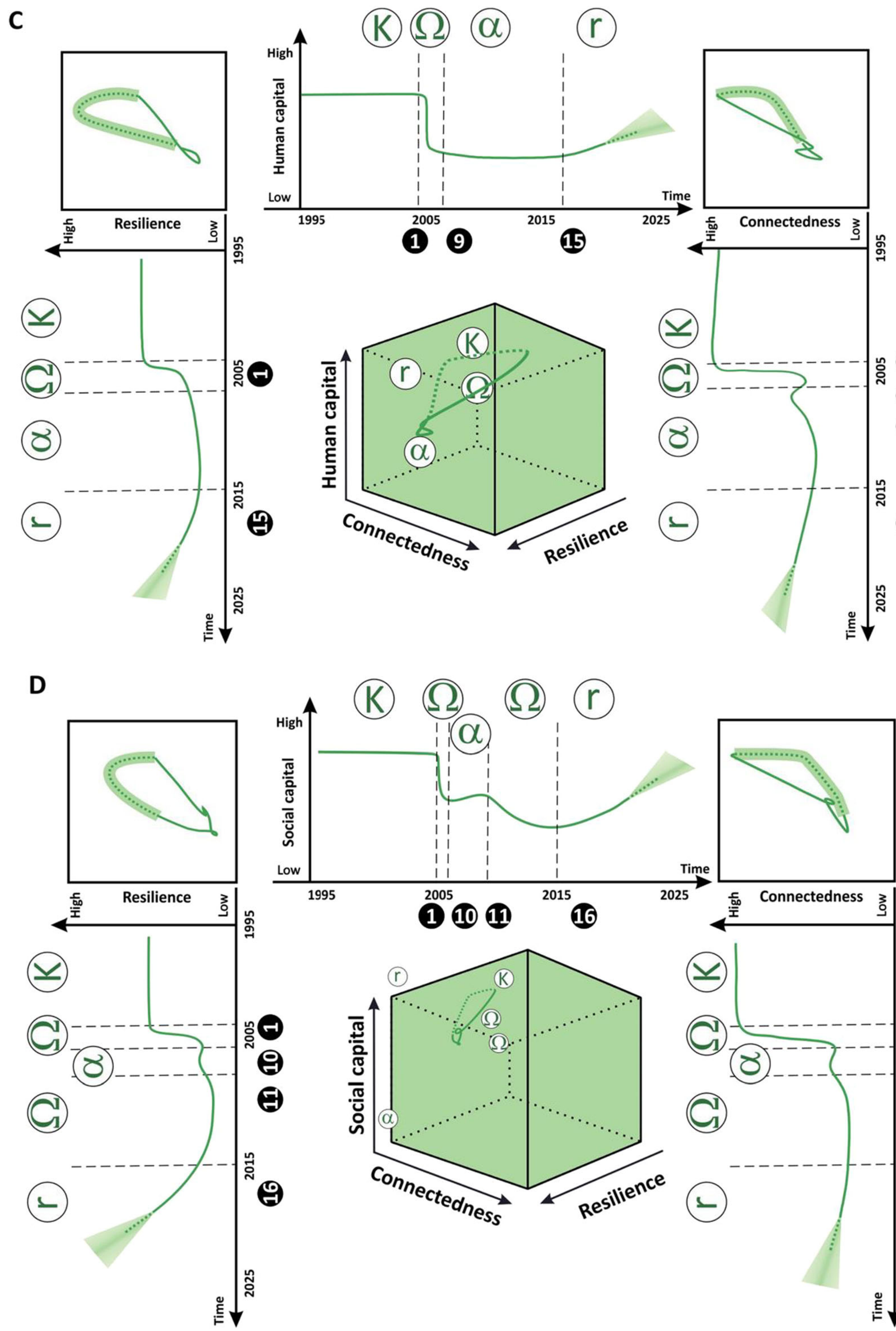

Fig. 3 continued

management and traditional knowledge, are inferred to have a high social capital (relationships, networks, and institutions; Fig. 3D). The Nicobarese elders, cognisant of resource conservation, established shared practices for managing natural resources, fostering a culture centred on environmental respect, communal living and mutual benefit (Singh 2003; Chandi et al. 2015). For example, in Car Nicobar Island, the Nicobarese practiced communal living and social cooperation through the "tuhet" system. In this arrangement, a large lineage group of extended family members resided in individual houses, either adjacent to the primary homestead or within horticultural gardens (Singh 2003). In a tuhet, all collected resources were considered family assets rather than individual possessions (Saini 2013). Although the Nicobarese were self-sufficient and had minimal interaction with the state/ administration, it does not imply that they were 'untouched' before the tsunami; rather, the rate of transition between 'tradition' and 'modernity' was constrained by their relative insular seclusion (Ramanujam et al. 2012).

In summary, the overall high resilience, connectedness and inclusive wealth of the Nicobar mangrove SES were characterised by the high mangrove species richness (21 species) representative for their biogeographical position, relatively undisturbed mangroves and highly coordinated social organisation among the Nicobarese (Fig. 4). We hypothesise that the SES demonstrated high connectivity and organisation in resource flows, with minimal room for innovation.

Collapse phase-Ω (subsidence and tsunami)

The tsunami (Allison and Hobbs 2004) and associated subsidence triggered a rapid collapse (Ω) of accumulated natural capital (mangrove vegetation, fishery resources, benthic diversity, above-ground biodiversity and soil nutrients), as illustrated by the steep declining curve (Fig. 3A). Subsidence and permanent seawater inundation led to the loss of approximately 97% of mangrove vegetation across the Nicobar Islands, with only isolated trees and a small forest patch surviving on Car Nicobar Island (Nehru and Balasubramanian 2018). Consequently, overall natural capital, connectedness and resilience remained low post-tsunami (Nehru and Balasubramanian 2018). Studies from Trinket Island and the Central Nicobar group of islands indicated that 67–68% of the mangroves were uprooted by the tsunami, while the remaining succumbed to the sudden increase in relative sea level due to subsidence (Ramachandran et al. 2005; Porwal et al. 2012; Prabakaran et al. 2021). Mangrove tree die-off mostly

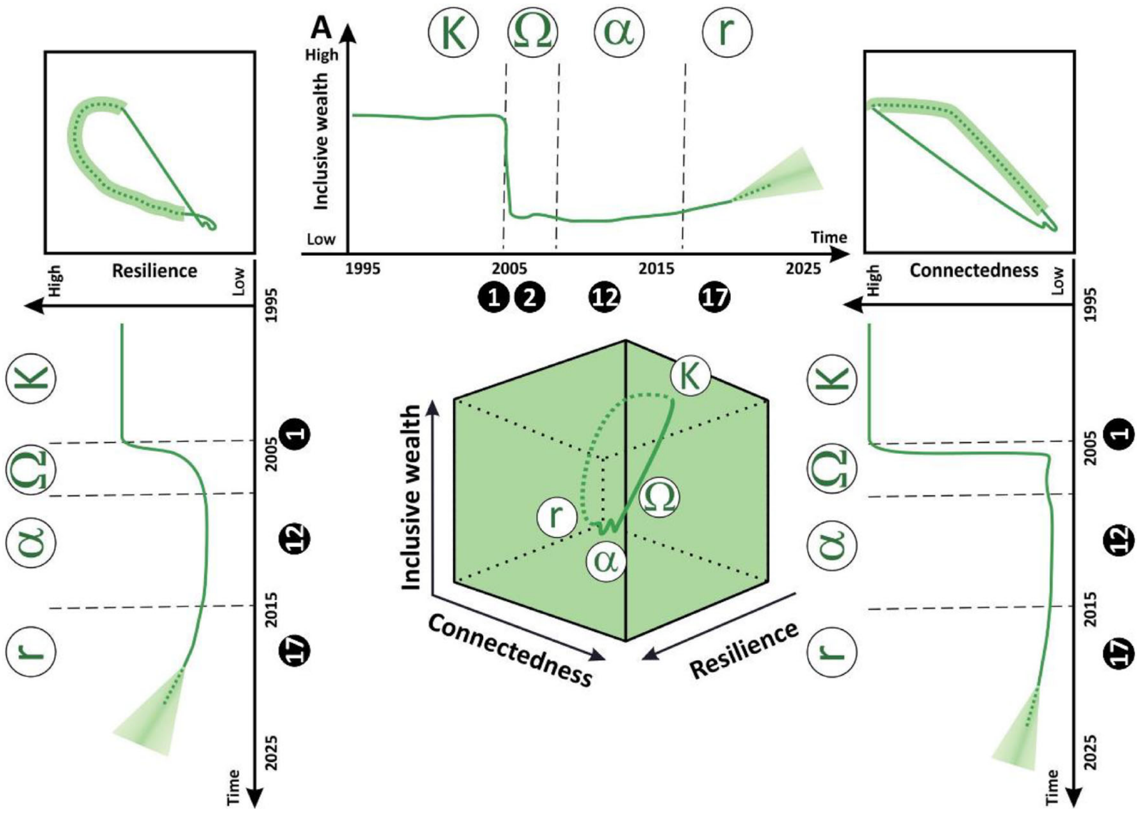

Fig. 4 Synthesised adaptive cycles based on the mangrove SES inclusive wealth (*i.e.* total capital) in the Nicobar archipelago. Time-related events are first plotted in relation to each of the three AC axes: capital versus time (top horizontal graph), resilience versus time (left vertical graph) and connectedness versus time (right vertical graph). The 2-D graphs with 2 AC axes: capital and resilience (top left graph); and capital and connectedness (top right graph). The 3-D graph in the centre includes all 3 AC axes: resilience and connectedness as a function of capital. Labels with numbers indicate specific events of change and are highlighted in the main text in square brackets. The dotted lines in the curves and light green shading represent the uncertain future. The system's ability to reorganise and recover itself from a disturbance, by maintaining its "core function, structure, identity and feedback (Dahdouh-Guebas et al. 2021)

lasted 2–3 months after the tsunami. A sudden increase in certain marine resources, such as milkfish, shrimp and bivalves (Sekhsaria 2009), contributed to a slight rise in natural capital (Balke et al. 2011) after the initial steep decline (Fig. 3A).

In addition to the loss of mangrove natural capital, the tsunami triggered the loss of 3480 human lives in Nicobar, destroyed more than 10 000 houses and damaged 5625 ha of cultivatable land (Porwal 2006 as cited in Ramanujam et al. 2012; Chandi et al. 2015). This meant that built capital, with only a few remaining trees, continued to remain very low (Allison and Hobbs 2004) (Fig. 3B). The connectedness required for producing the built capital declined drastically and reached its lowest point. The high human casualties, predominantly among the Nicobarese people, resulted in the sharp decline of TEK and, consequently, human capital (Allison and Hobbs 2004) (Fig. 3C). As Saini (2016) stated, "*the Nicobarese believe that after the tsunami, their society has moved backward and has reached a 'zero point' from where it must take a U-turn.*" The numerous human casualties, especially among the elders who make or transmit the rules and knowledge, and the loss of properties (*e.g.* land and coconut plantations) due to the tsunami and subsidence, have resulted in the sharp decline of social capital (Allison and Hobbs 2004) (Fig. 3D).

In summary, the loss of human life, land and resources resulted in resource scarcity—arguably to a scale that was never experienced by the Nicobarese before (Chandi et al. 2015; Saini 2015a). The tsunami caused a significant loss of accumulated resources (Allison and Hobbs 2004), with natural and built capitals nearly depleted. While social and human capitals declined with the decrease in the elders, some were retained in the form of knowledge and skill sharing mechanisms. All of this together contributed to an overall gradual decline in inclusive wealth, resilience and connectedness after the tsunami (Fig. 4).

Reorganisation phase-α

Despite substantial loss in natural capital, the system overcame the lock-in or dissolution trap in some sites and transitioned to the reorganisation phase (α) due to a few remaining trees and continuing propagule dispersal (Bosire et al. 2008) (Fig. 3A). Subsequently, mangroves slowly began re-establishing in the newly created intertidal areas that were previously terrestrial zones (Fig. S3). The mangrove colonisation in these new zones was initially slow, with a 3–20% increase in vegetation cover over 15 years (Prabakaran et al. 2021), marginally increasing natural capital. In some sites, seaward mangroves, particularly *Rhizophora* spp., are colonising the pre-tsunami landward mangrove zones, which were earlier dominated by *Bruguiera gymnorrhiza* and *Lumnitzera* spp. (Prabakaran 2020). Notably, in many sites, the subsidence of the flat terrestrial zone adjacent to the coast facilitated the creation of vast stretches of new intertidal zones with potential for mangrove colonisation (*e.g.* Great Nicobar). In contrast, smaller areas of new intertidal zone were created in the Central Nicobar group of islands due to their steeper coastal topography (Prabakaran 2021).

The α-phase lasted for around 10 years following the 2004 events (Fig. 3A). The slower developments during this phase can be attributed to the limited availability of propagules and the initial environmental conditions in the new intertidal zones, which were less conducive for mangrove establishment. The initial mangrove colonisers were largely propagules that survived the disturbance and immediately established at appropriate sites in the new intertidal zones. Changes in the soil substrate, previously terrestrial, likely occurred, eventually making the environment more conducive for mangrove growth (Carpenter and Brock 2008). However, resilience during the α-phase was relatively low (Census of India 2011) due to low species richness and tree density, making the system more vulnerable to further disturbance. With the almost complete loss of natural capital after the tsunami, connectedness rapidly decreased to its lowest value and remained low for over 10 years (Chandi 2018).

During the α-phase, there was a high potential for innovative responses, such as human-assisted ecosystem restoration, to facilitate faster reorganisation of the mangrove SES, leading the system to adapt to the changed conditions (Bosire et al. 2008). However, initial post-tsunami mangrove restoration efforts by the local Forest Department were less successful due to the drastic changes in intertidal topography, water currents and soil conditions. For example, the new intertidal zones were predominantly unsheltered from high wave action, contributing to excessive sediment run-off, which resulted in unsettled soil within these zones. Dahdouh-Guebas and Cannicci (2021) emphasised that the "shifted baselines" (new site conditions) need to be considered when planning rehabilitation and restoration efforts (R/R). Additionally, the viability of the propagules that were collected from the Andaman Islands is also questionable. Possibly, most of the propagules might have lost viability by the time they reached the planting sites in the Nicobar Islands because of inappropriate collection, storage, and transport conditions. The limitations in basic infrastructure in the remote islands, such as local transport and manpower, further intensified after the tsunami, making effective implementation of restoration projects challenging. All these conditions have likely contributed to the failure in the initial years of restoration. However, after 2010, some sites had better restoration results (Prabakaran 2021). This is probably because the soil properties may have improved over time and the propagules used were locally collected from the few established mother trees. Thus, despite the challenges, persistent efforts towards mangrove restoration by the Forest Department resulted in gradual success in a few selected sites across the Nicobar archipelago.

As mangrove resources became unavailable or scarce after the tsunami, there was a loss in built and human capitals. The loss in natural capital compelled the Nicobarese to reassess various aspects of their livelihood, diet, and subsistence practices (Ramanujam et al. 2012). After the tsunami, the resilience of built capital declined gradually (Chandi et al. 2015) compared to other forms of capital. This was because of the availability of resources from dead mangrove trees for construction purposes. Over time, the dead trees degraded and became no longer suitable for construction, further decreasing resilience (Chapin et al. 2009). Additionally, the elders who possessed TEK gradually declined due to natural death, reducing the chances of knowledge transfer to the younger generation (Saini 2017; Engineer 2020). These factors contributed to a further gradual decline in human capital (Dade et al. 2022).

As the Nicobarese community started regrouping immediately after the major disaster (Ramanujam et al. 2012; Chandi et al. 2015), social capital and its associated resilience and connectedness along with the connectedness of human capital slightly increased (Dahdouh-Guebas and Cannicci 2021) after the steep decline. However, as the Nicobarese adopted new livelihood options in the absence of traditional resources, emigration and adoption of modern lifestyles influenced by external aid (Saini 2014; Engineer 2020), there has been a further decline in social capital, resilience and connectedness (Dahdouh-Guebas et al. 2021). This sharp decline was due to the poorly managed aid system and social conflicts posing as a second collapse phase-Ω.

Post-tsunami aid distribution managed through the government disrupted social institutions among the Nicobarese (Singh 2009; Ramanujam et al. 2012). There was increased mobilisation for external aid, through monetary compensation and relocation of Nicobarese from their coastal homes to areas away from the coast (Engineer 2020). For example, the aid distribution system disregarded the tuhet system and divided these extended family units into nuclear families (Saini 2015b). The temporary resource flow from external sources highly degraded the values and rules of the social institution of Nicobarese, resulting in more social conflicts and reduced cooperation within the community (Singh 2009; Ramanujam et al. 2012; Saini 2013). Moreover, as the self-sustainable Nicobarese society became dependent on external resources and the breakdown in their community structure, their own rebuilding capacity or societal resilience declined drastically and persisted over a decade (Singh and Haas 2013; Chandi et al. 2015).

The introduction of modern material goods (*e.g.* alcohol and electronic devices such as mobile phones and televisions), free rations and amenities like education and electricity triggered major changes in the Nicobarese lifestyles (Ramanujam et al. 2012; Saini 2014; Engineer 2020). Consequently, the younger Nicobarese found little relevance in applying traditional or past practices in changed conditions, marked by resource scarcity and the introduction of globalised lifestyles (Engineer 2020). This period also saw the abandonment of traditional practices, such as fishing, hunting, and festival celebrations (Engineer 2020). However, in some cases, a few elders have passed on the knowledge to the next generation (Prabakaran 2021). Studies from other sites demonstrate that the sharing of knowledge and experiences related to past disasters play an important role in strengthening community resilience to the risks associated with tsunamis (*e.g.* Pisa 2024).

In summary, the inclusive wealth, overall resilience and connectedness of the mangrove SES remained low during the α-phase due to the almost complete loss of natural and built capitals after the tsunami (Dahdouh-Guebas et al. 2005) (Fig. 4). Additionally, this was exacerbated by disruption in human and social capitals because of the misaligned external aid distribution.

Growth phase-*r*

The establishment of the founder population of mangrove trees within a few years, coupled with the stabilisation of the new intertidal areas, suggests that the system successfully reconnected its elements after the disturbance, hence overcoming the vagabond trap and moving into the next AC growth (*r*) phase (Dahdouh-Guebas et al. 2022). The early r-phase is characterised by the risk of the poverty trap due to the loss of options to develop or to deal with change due to insufficient resources or activation energy (*cf.* Gunderson and Holling 2002; Chapin III et al. 2009), in this case unavailability of seed source (propagules). As the propagules made available by the initial colonisers were insufficient in the initial years (reproductive maturity among initial colonisers is observed to be almost 5–8 years), the natural capital in the r-phase started much lower. Although the natural capital slightly increased because of the regeneration of few isolated mangrove trees, there were not enough trees to improve the overall connectedness of the ecosystem. Connectedness encompasses both intra- and interspecific interactions. Furthermore, it extends to the interrelation between faunistic and microbiota elements with vegetation (Friess et al. 2019).

With due course of succession, the established trees ensured the continuous flow of propagules for regeneration in a stable habitat. Hence, the colonisation rates that were stagnant are swiftly increasing (Duke et al. 2014). In the initial 15–18 years after the tsunami, the natural capital and its connectedness has been increasing at a faster rate due to higher mangrove recruitment rates and a subsequent increase in vegetation cover in many sites (Prabakaran et al. 2021). For example, time series data from Kimios bay, Car Nicobar, suggest that the mangrove cover decreased from 66% immediately after the tsunami to 35% in 2007. However, the mangrove cover has recovered to 60% in 2014 and 75% in 2019 compared to the pre-tsunami estimates (Prabakaran et al. 2021). A recent estimate from 2019 shows that 14% (5.26 km^2) of mangrove cover has recovered, with approximately 20 km^2 available for further mangrove colonisation for the entire Nicobar Islands (Prabakaran, unpubl.). As the system is stabilising and the mangrove resources are becoming available, the resilience is increasing in recent years (Duke et al. 2014). The recent increase in mangrove vegetation is linked to the greater availability of propagules, originating from the few trees that effectively colonised the new intertidal zones. The ongoing and future colonisation processes heavily depend on these individuals, frequently resulting in the development of mono-dominant stands and ultimately strengthening connectedness within the system.

As of 2023, we hypothesise that most sites are in the early to mid r-phase with the increase in mangrove recruitment (Prabakaran et al. 2021; Thirumurugan et al. 2022) (Duke et al. 2014). These growth rates are determined by factors such as initial colonisation chances, species-specific traits of the initial coloniser, its colonisation vigour and the suitability of the site for growth of mangrove trees. For example, according to Prabakaran et al. (2021), (i) sites colonised by *Sonneratia* spp. or *Lumnitzera racemosa* showed better increase in vegetation cover and stem density than the sites initially colonised by *Bruguiera* spp. or *Rhizophora* spp. and (ii) sites with more new intertidal area at the landward zone that receive minimal tidal flooding (inundation class 4 and 5—Prabakaran, unpubl.) have better colonisation rates than sites with more area under the frequently inundated tidal regime. The high frequency of tidal flooding increases the susceptibility of propagules to wash away easily, potentially impacting their successful establishment in the seaward zones (Prabakaran et al. 2021). Conversely, in low inundation areas, propagules benefit from extended periods of no inundation for root initiation, leading to more effective anchoring. This logic aligns with the "windows of opportunity theory," which suggests that suitable conditions for establishment play a crucial role in determining successful colonisation (Balke et al. 2011).

The built and human capitals of the mangrove SES have been slowly increasing (Ellison et al. 2020) as mangrove resources become available due to mangrove recolonisation (Duke et al. 2014) (Prabakaran et al. 2021). Moreover, since they were provided houses through external aid, the necessity to exploit the dead mangrove trees did not arise. After the discontinuation of the aid system in 2010, the financial resources were soon used up (Saini 2014). With the growing population, termination of external aid and limited island resources, some people are blending traditional knowledge with modern practices and recognise the need for building traditional houses (Prabakaran 2021). For example, the Nicobarese have been incorporating materials intrinsic to their lifestyle, such as *Nypa fruticans* palm fronds, alongside modern building materials like tin (Chandi 2018; Prabakaran 2021). This demonstrates their adaptability to lifestyle changes while still preserving certain aspects of their tradition. Although employment in formal sectors increased post-tsunami, some Nicobarese still engage in fishing and pig-rearing to meet their livelihood needs (Engineer 2020). In some islands such as Chowra, communities are still practicing resource sharing mechanisms to deal with resource scarcity (Chandi et al. 2015). With mangrove resources gradually becoming available, social capital, connectedness and resilience gradually increased (Engineer 2020).

In summary, the recent rise in mangrove colonisation rates (natural capital) and the ongoing recovery of human and social capitals have led to a gradual increase in inclusive wealth and its associated overall connectedness and resilience (Fath et al. 2015) (Fig. 4). The low population density and the self-sustenance of the indigenous Nicobarese community contribute to the negligible anthropogenic pressure on the mangroves. The extraction of mangrove wood is negligible, with little impact on mangrove recovery (natural capital). Prospects of land reclamation of the new intertidal zones for development are discussed only for the east coast of Great Nicobar where mainland settlers inhabit (Saxena and Sekhsaria 2023). Otherwise, no anthropogenic constraint exists for the establishment of mangroves in the new intertidal zones.

Reflections on the future

The AC does not predict the future, but it offers a framework for understanding the changes that occurred in the past to better prepare and adapt for the future. It depicts potential futures in a range of schematic pathways, essentially guiding our approach to thinking about the future. From a natural capital perspective, the AC growth (r) phase may continue for at least 15–20 more years based on current growth rates (if we consider having 80–90% mangrove cover in the new intertidal zones as an end for the r-phase) (Prabakaran et al. 2021; Bayyana and Prabakaran in review). Considering pre-tsunami and current observations,

Table 2 Examples of quantifiable measurements and sources for factors describing natural, built, human and social capital

Measurement	Unit	Reference
Natural capital		
Biomass	Mg ha^{-1}	Wolswijk et al. 2022
Fish catch	kg	Zu Ermgassen et al. 2020
Built capital		
Infrastructure	SQM of concrete	Lucas et al. 2022
Charcoal	kg	Satyanarayana et al. 2021
Human capital		
Literacy	% of population	World Bank 2022
Education level	years of education	World Bank 2022
Social capital (refer to social network analysis—*e.g.* Dahdouh-Guebas et al. 2022)		
Social network degree centrality	Number of ties between stakeholders	Mafaziya Nijamdeen et al. 2023
Social network transitivity	Likelihood of two actors to have ties when a third actor has ties with each of them	Mafaziya Nijamdeen et al. 2023
Social network reciprocity	Proportion of mutual ties in the network	Lewis (2015)

we envision the conservation phase-*K* to be characterised by a well-established mangrove community with clear zonation patterns. This includes *Rhizophora* spp. and *Sonneratia alba* along the seaward zone and *Bruguiera* spp. along *with Sonneratia* spp., *Lumnitzera* spp. and *Nypa fruticans* in the landward zones. The canopy height is expected to reach 20–25 m and in some sites may exceed 30 m. However, it remains unclear if the entire mangrove SES will rebound to its pre-2004 state due to drastic changes in topography because of subsidence (shifted baselines), site-specific differences in recovery, availability of new upstream areas (terrestrial zone pre-tsunami) for colonisation and the influence of external factors. Although the impacts of climate change are not yet clearly documented in the Nicobar Islands, potential sea-level rise is anticipated to negatively affect mangroves in the new intertidal areas (Velmurugan et al. 2015).

In the Nicobar mangrove SES, where a regime shift occurred, two restoration approaches can be employed, either alone or in combination: (i) 'wait-and-see' (natural succession) allowing the ecosystem to develop naturally or (ii) intervention by managers through mangrove afforestation with suitable species to restore and sustain ecosystem services. However, the latter needs to be driven by local community needs and knowledge and not by state agencies, which may have different agendas in restoration projects (Ellison et al. 2020). As the post-tsunami mangrove recovery in Nicobar is confronted with shifted coastlines, ensuring the propagule availability of the right species in the new intertidal habitats (previously terrestrial areas) through management interventions becomes crucial to overcoming the poverty trap. This approach facilitates faster mangrove recovery (*r*-phase), addressing the challenges posed by shifted restoration baselines (Dahdouh-Guebas and Cannicci 2021).

From a social perspective, it is uncertain how population dynamics, economic changes and developmental activities will play a role in shaping future trajectories of the Nicobar mangrove SES. While challenging to predict, there are important lessons from the past that can be applied in the future. The post-tsunami response through external aid did not consider the existing norms and traditions of the Nicobarese context; instead, it exacerbated social conflicts and fostered dependency on external aid and modern lifestyles. Although societies naturally evolve with technology and developmental changes, sudden and profound events such as tsunamis can rapidly erode traditional knowledge and practices (Engineer 2020). We have no possibility to compare societal changes that would have occurred without the 2004 seismic events. However, we assume that these events have accelerated ongoing or expected societal processes and exacerbated their impacts. When responding to these changes, there is a need to ensure that social contexts are considered, without undermining existing social organisations, structures and distinct traditional knowledge systems of recipient communities (Saini 2015b). Although traditional knowledge was severely affected due to the loss of lives and external aid, some people have incorporated traditional practices and resource sharing to deal with challenges of resource scarcity. While this is the case in specific sites, it is yet to be seen how the Nicobarese will combine technological advancements and traditional knowledge to face future changes and disasters.

Study limitations

The application of the AC in this study has certain limitations. First, considering that we relied on qualitative information from literature and expert on-ground knowledge, there may be some subjective bias in how we hypothesised the levels of capitals, resilience and connectedness. This could be more robust by using quantitative information by identifying and measuring specific variables as indicated in Table 2. Second, the study focuses specifically on the Nicobar mangrove AC using the tsunami as a collapse event, not looking into other concurrent drivers of change at different time scales. Importantly, the delineation between ongoing change (development) versus point perturbation (tsunami) is not easy. To complement this, further studies can also use the Drivers-Pressures-State-Impact-Responses (DPSIR) framework to enhance understanding, especially when there are multiple drivers operating at different time scales (Quevedo et al. 2023). Third, the AC's weakness in determining system boundaries becomes challenging when multiple SESs interact. This could be addressed by adopting a panarchy approach, wherein multiple ACs at different scales are nested together (from small and fast to large and slow scales) and exhibit cross-scale interactions, as exemplified by Perez-Orellana et al. (2020).

While the AC framework is useful in depicting general long-term dynamics of SESs, it is not without its limitations. Nevertheless, it remains a valuable tool for guiding thinking about system change, offering a broad framework that serves as a starting point for further analysis and understanding of these complex and interconnected SESs.

CONCLUSION

Envisioning changes through an AC after a large-scale disturbance triggered by a natural disaster, such as the 2004 tsunami in the Nicobar archipelago, provides insights for mangrove SES recovery and management. In particular, understanding the various AC traps and their effects on each phase of SES recovery serves as an effective first step towards facilitating faster recovery through human intervention.

The process of learning from disasters and responding to them is ongoing, with no static answer. Understanding how mangrove ecosystems and local communities, such as the Nicobarese, respond to drastic changes and influence the recovering SES provides lessons on adaptive capacity. We observed that the natural capital demonstrated resilience and displayed a capacity for recovery. Conversely, the human factors (built, human and social capitals) did not recover as smoothly and underwent substantial changes, particularly marked by a significant loss of traditional ecological knowledge. Furthermore, when a system deviates from a typical recovery process due to external factors, like poorly aligned post-tsunami external aid causing a further reduction in social capital after a steep decline, it serves as an indicator of maladaptation. This information contributes to develop managerial strategies that account for the specific social context of the area. Failing to do so could significantly hinder the speed and effectiveness of the recovery process.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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