Title: Conceptualizing ecosystem degradation using mangrove forests as a model system

Authors: Erik S. Yando[a, b*], Taylor M. Sloey [a, c], Farid Dahdouh-Guebas [d, e, f], Kerrylee Rogers [g], Guilherme M.O. Abuchahla [h], Stefano Cannicci [i, j], Steven W.J. Canty [k, l, m], Tim C. Jennerjahn [h, n], Danielle E. Ogurcak [o], Janine B. Adams [p], Rod M. Connolly [q, r], Karen Diele [s], Shing Yip Lee [f, t], Jennifer K. Rowntree [m], Sahadev Sharma [u], Kyle C. Cavanaugh [v], Nicole Cormier [w], Ilka C. Feller[x], Sara Fratini[j,f], Xiaoguang Ouyang[t], Alison K.S. Wee[y,z], Daniel A. Friess[b,aa,f]

Affiliations:

[a] Department of Biological Sciences, Old Dominion University, Norfolk, VA, USA

[b] Department of Geography, National University of Singapore, Singapore

[c] Division of Sciences, Yale-NUS College, Singapore

[d] Systems Ecology and Resource Management Research Unit, Department of Organism Biology, Université Libre de Bruxelles - ULB, Av. F.D. Roosevelt 50, CPi 264/1, 1050, Brussels, Belgium [e] Ecology & Biodiversity, Laboratory of Plant Biology and Nature Management, Biology Department, Vrije Universiteit Brussel - VUB, Pleinlaan 2, VUB-APNA-WE, 1050, Brussels, Belgium

[f] Mangrove Specialist Group (MSG)- Species Survival Commission (SSC), International Union for the Conservation of Nature (IUCN)

[g] School of Earth, Atmospheric and Life Sciences, University of Wollongong, Australia [h] Leibniz Centre for Tropical Marine Research, Fahrenheitstrasse 6, 28359 Bremen, Germany

[i] Swire Institute of Marine Science and Division for Ecology and Biodiversity, The University of Hong Kong, Hong Kong, Hong Kong SAR, China

[j] Department of Biology, University of Florence, via Madonna del Piano 6, I-50019 Sesto Fiorentino, Italy

[k] Smithsonian Marine Station, Fort Pierce, FL 34949, USA

[l] Working Land and Seascapes, Conservation Commons, Smithsonian Institution, DC 20013, USA

[m] Ecology and Environment Research Centre, Department of Natural Sciences, Faculty of Science and Engineering, Manchester Metropolitan University, Chester St, Manchester M1 5GD, UK

[n] Faculty of Geoscience, University of Bremen, Klagenfurter Strasse, Bremen, Germany.

[o] Institute of Environment, Florida International University, Miami, FL, USA

[p] Department of Botany, Institute for Coastal and Marine Research, Nelson Mandela University, PO Box 77000, Port Elizabeth, South Africa

[q] Coastal and Marine Research Centre, Griffith University, Gold Coast, Queensland, Australia

[r] Australian Rivers Institute – Coast & Estuaries, School of Environment and Science, Griffith University, Gold Coast, Queensland, Australia

[s] School of Applied Sciences, Edinburgh Napier University, Edinburgh, UK

[t] Simon F.S. Li Marine Science Laboratory, School of Life Sciences, The Chinese University of Hong Kong, Shatin, Hong Kong SAR, China

[u] Institute of Ocean and Earth Sciences, Universiti Malaya, Kuala Lumpur, Malaysia

[v] Department of Geography, University of California, Los Angeles, CA, USA

[w] Department of Earth and Environmental Sciences, Macquarie University, Sydney, NSW, Australia

[x] Smithsonian Environmental Research Center, Edgewater, MD, USA

[y] School of Environmental and Geographical Sciences, University of Nottingham Malaysia, Semenyih 43500, Malaysia

[z] Guangxi Key Laboratory of Forest Ecology and Conservation, College of Forestry, Guangxi University, Nanning, Guangxi, China

[aa] Centre for Nature-based Climate Solutions, National University of Singapore, Singapore

* Corresponding author at: Dept. of Biological Sciences, Physical Sciences Building, Old Dominion University, Norfolk, VA 23529, USA. E-mail address: eyando@odu.edu (E.S. Yando).

Keywords: Anthropogenic, Degradation, Function, Management, Mangrove, Structure

Abstract*:*

The status and potential degradation of an ecosystem is often difficult to identify, quantify, and characterize. Multiple, concurrent drivers of degradation may interact and have cumulative and confounding effects, making mitigation and rehabilitation actions challenging to achieve. Ecosystem status assessments generally emphasize areal change (gains/losses) as a primary indicator; however, this over-simplifies complex ecosystem dynamics and ignores metrics that would better assess ecosystem quality. Consideration of multiple indicators is necessary to characterize and/or anticipate ecosystem degradation and appropriately identify factors causing changes. We utilize mangrove forests as a model system due to their distribution across a wide range of geographic settings, their position in the inherently dynamic coastal zone, and the multiple natural and anthropogenic pressures they face. We present a conceptual framework to: i) examine drivers of ecosystem degradation and characterize system status, and ii) delineate the roles of biogeographic and geomorphic variability, site history and typology, and references. A complementary workflow is proposed for implementing the conceptual framework. We demonstrate the universal applicability of our conceptual framework through a series of case studies that represent locations with differing drivers of degradation and biogeographic and geomorphic conditions. Our conceptual framework facilitates scientists, conservation practitioners, and other stakeholders in considering multiple aspects of ecosystems to better assess system status and holistically evaluate degradation. This is achieved by critically evaluating suitable comparisons and relevant elements in assessing a site to understand potential actions or the outcome of previously implemented management strategies.

1. Introduction:

Many of the world's ecosystems are experiencing rapid declines in extent and habitat quality, and the direct and indirect drivers of this change have accelerated over the last 50 years (IPBES, 2019). Climate change has increased in importance as a driver of habitat loss and degradation, with negative impacts on biodiversity and ecosystem ser- vice provision seen across terrestrial (e.g., Nolan et al., 2018), coastal, and marine systems (e.g., Smale et al., 2019). Different drivers of habitat loss and degradation have combined to cause an ongoing biodiversity crisis (WWF, 2020).

Ecosystem degradation can be difficult to identify and quantify (Thompson et al., 2013) as changes may be subtle and vary across spatial and temporal scales (Turschwell et al., 2020). Impacts of degradation can also vary across structural and functional attributes and are often site-specific in nature. Isolating anthropogenic contributions to degradation from natural variation further complicates efforts to address degradation as human impacts are pervasive and have affected almost every ecological system (Kennedy et al., 2019). Despite these challenges, conceptualizing degradation and identifying its various contributors is essential to elucidate key drivers, mitigate further impacts, and improve ecosystem condition (Ghazoul et al., 2015).

Definitions of degradation often lack consistency, whether in the general ecological literature (Hobbs, 2016) or in ecosystem-specific studies. Degradation definitions commonly cover broad themes of ecosystem structure, function, service, and/or resilience. Definitions aligning with ecosystem structure and function tend to relate to local reductions in biodiversity or ecosystem integrity (Bosire et al., 2008; Ghazoul et al., 2015). Ecosystem service-based definitions focus on the reduction in ecosystem benefits to humans (Anderies and Hegmon, 2011; Schwerdtner Máñez et al., 2014; Ghazoul et al., 2015; Scales et al., 2018) or alterations in service provision (Burkhard and Maes, 2017). Finally, resilience-linked definitions use changes in status of key theoretical resilience concepts such as redundancy, sensitivity, and/or vulnerability (Hamilton and Snedaker, 1984; Peterson et al., 1998; Adger, 2005; Gilman et al., 2008; Cannicci et al., 2021), leading to a definition of degradation that highlights alterations in key linkages and ecosystem integrity over time (Clewell and Aronson, 2013). Most definitions focus on only one aspect of degradation, with an example of an exception being Moberg and Rönnbäck (2003) who explicitly linked degradation to a reduction in ecosystem structure, function, and resilience. Importantly, definitions of degradation frequently do not refer to a baseline or reference condition and therefore make degradation difficult to assess. For the purpose of this manuscript, we define degradation as the loss of diversity, structure, function, and/or resilience, beyond the limits of natural variation within a given system due to anthropogenic drivers or the influence of anthropogenic activities on natural drivers.

Using mangrove forests as a model (eco)system to better understand and conceptualize ecological degradation, we present a conceptual framework to: i) examine drivers of ecosystem degradation and system status, and ii) characterize the roles of biogeographic and geomorphic variability, site history and typology, and references. We also provide a complementary workflow for implementing the conceptual framework. Additionally, we demonstrate the adaptability of the conceptual framework by applying it to a set of case studies from diverse bio- geomorphic and climatic settings where mangrove forests are experiencing different types and levels of impacts. Our framework provides a comprehensive examination of indicators that can be used to identify and quantify key degradation drivers and specific stressors in a variety of contexts based on location, resources, and available data. Finally, we place this conceptual framework into context in terms of how it may inform management considerations and address site specific concerns and nuances that exist with system monitoring, restoration, or conservation efforts. While we use the mangrove ecosystem to illustrate our concept, we anticipate that our framework can be readily adopted and modified for application in other ecosystems.

2. Mangrove forests as a model ecosystem to understand degradation

Mangroves are a model system to examine the applicability of a broad conceptual framework of degradation because of the inherently dynamic and diverse biophysical conditions where they exist. Man- groves are found across a range of climatic gradients from the tropics to sub-tropical and temperate regions (Osland et al., 2017) and across multiple geomorphic settings that experience different sediment loads and hydrodynamic forcings, from deltas and estuaries to carbonate atoll settings (Worthington et al., 2020). Mangroves also show substantial differences in species diversity across local environmental gradients and biogeographic regions (Duke et al., 1998; Lee, 2008). Finally, man- groves experience a range of natural processes and anthropogenic pressures that operate at different spatial and temporal scales.

Mangroves are threatened worldwide by deforestation, land use changes, climate change, and multiple other stressors. Although conservation efforts have helped to slow deforestation rates (Friess et al., 2020), mangroves continue to be lost globally at 0.13% per year (Goldberg et al., 2020). A focus on habitat quantity and efforts to reduce deforestation are welcome, but neglect the quality of remaining or rehabilitated patches (Lee et al., 2019). Areal loss is relatively straightforward to map and quantify, but stressors such as over- utilization (Scales et al., 2018) and pollution (Deng et al., 2021; Luo et al., 2021) can lead to cryptic degradation (Dahdouh-Guebas et al., 2005) or habitat fragmentation of mangrove forests (Bryan-Brown et al., 2020), without necessarily causing loss of extent. The effects of degra- dation are numerous, and in mangrove ecosystems may include changes in vegetation density, community composition, genetic diversity, the abundance and diversity of key faunal species, shifts in ecosystem functions, and losses of key ecosystem services (Cannicci et al., 2009; Bartolini et al., 2011; Penha-Lopes et al., 2011). Degradation also re- duces mangrove ecosystem resilience, making them more vulnerable to disturbances (Lovelock et al., 2009). The need to provide comparable, reference-based measurements of multiple metrics is imperative for conservation, restoration, and management actions.

3. Conceptualizing ecological degradation

The proposed Degradation Indicator Framework (Fig. 1) identifies drivers of degradation using sets of indicators that represent potential stressors, while also defining system status with a focus on ecosystem structure, function, and services (sensu Costanza et al., 2017) (see all components defined in Drivers and System Status subsections below). By considering both drivers and system status, this framework provides an objective overview of degradation and overall system status. We conceptualize each system through a compilation of indicators of relevant drivers of degradation and overall ecosystem status along a condition gradient based on reference locations/conditions (hereafter reference). References are spatial, temporal, or idealized to identify changes in degradation and system status of a given study location (see more in 3.3 Reference selection and data confidence subsection below). The Degradation Indicator Framework allows for the assessment of degradation using multiple drivers in an adaptable structure. Its purpose is to: i) provide a tool to visualize the drivers of degradation and the relative state of associated indicators, ii) highlight current structure, function, and services of the ecosystem in relation to average reference values, iii) emphasize the importance of site-specific drivers and indicators, and iv) deliver an adaptable tool to meet the needs of users based on their site-specific objectives and limitations (e.g., access to data, budget restrictions, etc.) for conservation and management actions. The combination of drivers of degradation and overall system status affords the ability to comprehensively assess a given system. This is done by considering crucial relevant factors in each system, or in a set of systems, moving beyond areal losses and starting to assess quality when evaluating degradation, restoration, or general ecosystem monitoring.

3.1. Drivers

Drivers of degradation can broadly be broken down into two key categories: anthropogenic or natural. In our framework, anthropogenic drivers are further categorized into stressor types: resource extraction, pollution, reclamation/land use, hydrologic modification, global climate change, and miscellaneous (modified from Bakhtiyari et al., 2019; Ellison and Farnsworth, 1996), while natural drivers of degradation may be further categorized into stressor types: extreme weather and extreme hydrological/geological events (e.g., hurricanes, earthquakes). Within each of these stressor types exists specific stressors that can cause a change in a given parameter or process that may potentially impact the health and/or productivity of the ecosystem. Finally, indicators are thereby measurable metrics that are directly responsive to each specific stressor (see Bakhtiyari et al., 2019 for examples) (e.g., Driver = Anthropogenic ➔ Stressor Type = Resource Extraction ➔ Specific Stressor = Logging ➔ Indicator = Number of Trees Extracted).

To ensure a comprehensive understanding of degradation, assessments of ecosystems should ideally incorporate indicators within each of the categories and stressor types, but representation (i.e., number of indicators within each category) may be adjusted depending on avail- able resources and relative importance. It is also possible that some categories or stressor types may not be included due to lack of information or an inability to quantify, but a consideration of each is needed to provide an understanding of a given system's degradation status while also identifying knowledge gaps.

With discrete, short duration stressors, such as high winds and storm surge that accompany hurricanes/cyclones, recovery from impact is often observed (Ellison and Farnsworth, 1996), unless impacts are severe, delaying recovery or pushing systems into a new stable state (Holling, 1973). Chronic drivers of degradation, such as urbanization, may impact hydrological and geomorphological processes resulting in alteration of system integrity (e.g., changing sedimentation regimes, water quality, storm water discharge, and surface and groundwater flow rates) (Lee et al., 2006) and may never return to their original state. Synergisms between drivers, and their associated stressors, operating at different spatial and temporal scales can result in ecosystem state changes outside the natural range of variation (Côté et al., 2016; Dahdouh-Guebas et al., 2021; Figs. 2 & 3).

Negative impacts on ecosystems are often the result of a combination of stressors and their additive, synergistic, or antagonistic interactions (Côté et al., 2016). Distinguishing the origin of specific stressors as entirely natural or anthropogenic is difficult given global climate change and other anthropogenic influences (e.g., hurricanes/cyclones, although natural, have increased in frequency and intensity with anthropogenic climate change) (Hegerl and Zwiers, 2011; Bindoff et al., 2013), although efforts to distinguish natural versus anthropogenic influences continue to improve (Eyring et al., in press). Consequently, natural events can serve as tipping points in mangroves already stressed by other drivers of degradation (Lewis et al., 2016). The impacts of one driver may exacerbate the impacts of other drivers (positive feedbacks) or lead to a cascade of effects (see 4.2 Temporal/ spatial scale and natural variation) (Fig. 3). Similarly, extremes in the variation of natural controls, such as geologic events (earthquakes, tsunamis, isostatic adjustments) or extreme weather events (cyclones, freezes, heatwaves, droughts, floods, lightning strikes) can lead to degradation, particularly in combination with anthropogenic disturbances (Jennerjahn et al., 2017).

3.2. System status

System status captures the overall state of a particular study site at a given point in time relative to a reference. System status is further broken down into status categories: structure, function, and ecosystem service. The feature types within each status category are as follows: abiotic and biotic for structure; biological, chemical, and physical for function (de Groot et al., 2002); and provisioning, regulating, and cultural for ecosystem services (Costanza et al., 2017). Structure is all abiotic and biotic elements and components of an ecosystem. Functions are important for maintaining the ecosystem, its biodiversity, and contributing to the goods and services provided by the ecosystem (de Groot et al., 2002). Ecosystem services refer to the benefits that specific ecosystem functions provide to human populations (Costanza et al., 2017).

Within each of these feature types, specific features should be selected that are site appropriate. Abiotic specific features might include soil type, hydrology, and water quality, whereas biotic specific features may include genetic diversity, species richness, forest structure, and soil biota. Growth and reproduction rates, nutrient cycling, and sedimentation rates are respectively examples of biological, chemical, and physical specific features. Specific features for ecosystem services could include climate regulation (regulating), food provision (provisioning), and tourism (cultural). Finally, similar to indicators of degradation, indicators of system status should be measurable metrics that are directly responsive to each specific feature (e.g. Status Category = Structure ➔ Feature Type = Biotic ➔ Specific Feature = Forest Structure ➔ Indicator = Basal Area). Inclusion of indicators across all feature types should be considered to ensure a comprehensive understanding of system status, but representation may differ depending on available re- sources and relative importance.

3.3. Reference selection and data confidence

To assess whether degradation is outside the expected range of natural variability, indicators selected for each portion of the Degradation Indicator Framework (e.g., drivers and system status) should be compared to values of a reference where the same indicator can be quantified. Here we define a reference as undisturbed locations or time periods to which direct evaluation of natural ecosystem structure, composition, function, and services may be compared (after Kaufmann et al., 1994). References serve as points that are within the range of natural variation and should be appropriate for the area being assessed (Davy-Bowker and Clarke, 2015). Selection of an appropriate reference is crucial for defining and measuring ecosystem degradation (reviewed by Kaufmann et al., 1998; Stoddard et al., 2006). In mangrove ecosystems this involves accounting for biogeography (Spalding et al., 2007), geomorphology (Thom, 1984; Woodroffe, 1992), and forest types (Lugo and Snedaker, 1974) (see 4.1 Biogeographic and geomorphic setting and forest typology below). References should also be temporally and spatially appropriate (see 4.2 Temporal / spatial scale and natural variation) with data collected prior to and during the assessment period to account for natural variation, if possible. The combination of both spatial and temporal reference types allows for a higher level of certainty and for the cross validation of possible changes to the reference site. This may not always be possible, and references may need to be either spatial or temporal depending on the source of degradation and data limitations. For example, if a specific stressor occurs at a large scale (e.g., regionally or globally) it may not allow for an appropriate spatial reference, thus a temporal reference may be best suited. Alternatively, if specific stressors are localized (e.g., point source) and/or access to temporal data is limited, then a spatial reference may be a better option. In circumstances where neither spatial nor temporal references are achievable, we suggest idealized references – indicator values derived from the literature of other mangrove systems strategically selected based on geomorphic, biogeographic, temporal, and spatial features. Additional or alternative considerations may be needed when applying the Degradation Indicator Framework to other ecosystems. Regardless, it is critical that a reference is selected to allow for comparisons and appropriate assessment.

Selected indicator values should be determined in both the study site and the reference(s). Indicators may be measured at the locations in question via on the ground sampling or remote sensing, extrapolated, or ascertained using expert opinion or local knowledge. Confidence in indicators must be critically evaluated by users depending on the site and the metric. For example, direct measures within the site would likely be considered high confidence, whereas determining an indicator value through conjecture would likely be considered low confidence. The Degradation Indicator Framework displays levels of confidence of each indicator for both the reference site(s) and the study site with high confidence (black), medium confidence (gray), and low confidence (white). This visual representation highlights both areas for improvement and provides a direct, comparison of confidence for the reference and study site.

4. Considerations for the assessment of degradation

To comprehensively assess degradation, system status, and select appropriate indicators, one must consider the geomorphology, biogeography, and typology of a system, while also fully appreciating both temporal and spatial scales and natural variation. While the mangrove ecosystem is used as an example to illustrate this point, we recognize that additional physical and socio-ecological features may also be relevant to other systems, and the framework presented here should be adapted to their use (see 6 Management implications of the degradation framework).

4.1. Biogeographic and geomorphic settings and forest typology

Biogeography and geomorphology provide context to assessing and understanding any system. For example, globally mangroves are distributed along low-energy coastlines in the tropics, sub-tropics, and some temperate regions, with >90% of extant mangroves found along humid-tropical coasts (Osland et al., 2017). Their latitudinal limits vary according to climate, coastal setting, suitable habitats, and ability to disperse. Climate influenced limits are related to both air and local sea water temperature (Duke et al., 1998; Quisthoudt et al., 2012), occurrence, severity, and duration of freezes (Duke et al., 1998; Osland et al., 2013; Cavanaugh et al., 2014), and/or precipitation (Osland et al., 2017; Adame et al., 2020). Propagule dispersal and suitable habitat are pre- requisites for mangrove establishment success, and also limits latitudinal extent (Duke et al., 1998; Raw et al., 2019). Tree species diversity not only decreases at higher latitudes, but also shows longitudinal differences with the center of diversity in Southeast Asia and a sharp decline in the Atlantic and Eastern Pacific region (Duke et al., 1998). Significant taxonomical, functional, and structural differences exist between the Indo-Western Pacific and Atlantic-East Pacific and they must be considered in any comparisons, conservation, or management activities (Ellison, 2000; Lee et al., 2014).

The geomorphological setting is also important in understanding vulnerability and ecosystem specific features. In coastal ecosystems such as mangrove forests, hydrodynamic and geomorphic processes will affect their establishment and long-term stability of the ecosystem. In mangrove ecosystems, the geomorphic setting is also a key boundary condition that controls multiple aspects of mangrove forest structure, species diversity, ecological function, and ecosystem service provision (Ewel et al., 1998; Rovai et al., 2018).

Several typologies exist to describe the setting of mangrove forests. Lugo and Snedaker (1974), with modifications by Ewel et al. (1998), provide the baseline for ecological typologies by categorizing mangroves as fringe (less diverse, pioneer species, stress tolerant), riverine (highly diverse, functionally/structurally complex), and basin forests (less diverse, limited growth, hypersaline/hypoxic environments). Thom (1984), and later Woodroffe (1992), provide a more geo- morphologically focused typology for mangroves: river delta, tidal estuary, lagoon, and carbonate reef. Twilley et al. (1999) synthesize these ecological and geomorphological typologies in a multi-spatial frame- work with a hierarchical status that provides context to any mangrove system. Recently, Worthington et al. (2020) developed a global categorization of the world's mangrove forests as deltas, estuaries, lagoons, or open coast sites of either terrigenous or carbonate origin. Finally, tidal ranges and inundation levels are also critical in assessing mangrove dominated shorelines as differences can result in considerably different rates of colonization and regeneration, types of microhabitats, and a range of abiotic influences (Tomlinson, 2016). All these factors need to be considered to adequately select appropriate reference locations and categorize both drivers of degradation and overall system status when considering ecosystem conservation, restoration, or management actions.

4.2. Temporal/spatial scale and natural variation

Establishment and survival of an ecosystem is dependent upon fac- tors that vary spatially and temporally, especially in mangroves (Twilley et al., 1999; Rogers and Krauss, 2019). Variation in factors influencing survival and overall distribution can lead to considerable degradation, particularly when anthropogenic stressors are compounded by natural cyclic perturbations and processes operating over larger temporal and spatial scales.

Numerous studies have described the hierarchy of factors influencing mangrove establishment and persistence. Processes need to be distinguished at relevant scales: global, regional, estuarine, or intertidal (Duke et al., 1998). Spatial and temporal considerations provide context to variation in forest structure and function, while geomorphic setting, forest type, and specific processes will change within individual forests along a range of temporal scales (e.g., 1 hour to 1000s of years) (Twilley et al., 1999). The proposal of four observational levels (Schaeffer-Novelli et al., 2000) provides perspective for disturbance at the site functional level (<0.1 ha), the patch level (0.1–100 ha), the mangrove setting (10–100 km), and the domain or segment level (500–1000 km). Rogers and Krauss (2019) conceptualized how both spatial and temporal variation in multiple processes operate and impact mangrove forests (Fig. 2). This explicitly recognizes that processes influencing ecosystems interact, causing both negative and positive feedbacks and leading to a myriad of end results. Understanding the compounding effect of these processes and whether they are conducive to stability or degradation is critical in determining how ecosystems respond, especially when considering management action or intervention.

The timescale over which disturbance processes in ecological systems occur have been described using the press and pulse framework (Bender et al., 1984). Chronic stressors operating over longer timescales, and often larger spatial scales, are regarded to be presses, whereas acute extreme events operating over shorter timescales, and most often smaller spatial scales, are considered pulses. Mangroves, like most ecosystems, can respond and adapt to presses when their magnitude, rise) (Woodroffe et al., 2016). The adaptive capacity of mangroves becomes exhausted when multiple pulse events are compounded with chronic presses (e.g., extreme weather, rapid sea-level changes) (reviewed by Sippo et al., 2018). The capacity of some ecosystems to remain resilient in the face of low intensity perturbations is high, but degradation and eventual loss will occur when cumulative intensity exceeds their ability to adapt or recover (conceptualized in Fig. 3). Identifying the multiple factors contributing to degradation, and the timescales over which they operate, is crucial to address degradation through feasible management strategies.

5. An actionable framework for quantifying degradation

Based on the key considerations of degradation outlined above, we propose a workflow for actionable implementation of the Degradation Indicator Framework (Fig. 4). This workflow is formatted to be adaptive and accommodate diverse users, with various levels of monitoring capabilities and historical data. Each site's unique features (biogeography, typology, climate, and site history – as described above) should be considered when identifying a system's status, the influential drivers of potential degradation, and when selecting the appropriate indicators to measure ecosystem response to those drivers. Each step of this work- flow, particularly the selection of indicators and references, can be revisited should more information become available.

We applied the workflow process for the Degradation Indicator Framework to generate site specific assessment for six mangrove forests from around the globe (Fig. 5). Case study sites include: Canal de Santos (Brazil) (Fig. 5a), Mngazana Estuary (South-Africa) (Fig. 5b), Segara Anakan Lagoon (Indonesia) (Fig. 5c), Mikindani (Kenya) (Fig. A.1), Galle Unawatuna (Sri Lanka) (Fig. A.2), and Matang Mangrove Reserve (Malaysia) (Fig. A.3). These study sites represent a range of conditions, potential sources of degradation, biogeographic and geomorphic set- tings, and demonstrate the use of various references and indicator confidence. For a full analysis of indicators, reference sites, and site- specific citations see Table A.1.

5.1. Brazil- Canal de Santos, São Paulo

The Canal de Santos mangrove forest in São Paulo state was compared to a spatial reference forest in Ilha do Cardoso, Cananéia, 200 km to the south, to allow for suitable data comparisons and avoid other degraded sites nearby. Despite the distance between them, both systems belong to the same geomorphic setting. Canal de Santos is characterized as a microtidal estuarine forest with a mountainous rainforest- dominated hinterland. Canal de Santos has suffered considerable physical modification through the construction of industrial complexes, ports, roads, and railways since the first half of the 20th Century. The main drivers of degradation were identified as industrial and domestic pollution and land reclamation. The core indicators of degradation were identified as water and sediment pollution as well as loss of forest area. Despite these indicators of degradation, the study site still maintains similar tree biomass as the reference site. Data for the reference were taken from individual field and remote sensing studies focusing on sites within these two areas. At Canal de Santos 85.7% of indicators are in the yellow or red category (Fig. 5a).

5.2. South Africa- Mngazana Estuary, Eastern Cape

A temporal reference via aerial photographs from the 1930s and a spatial reference from mangroves in adjacent estuaries provide a com- bination of references for the mangroves at Mngazana Estuary. Mngazana Estuary is described as a wave dominated, temperate/sub-tropical system with a permanently open ocean connection and three mangrove species. Harvesting of trees for wood products has resulted in decreased mangrove forest area and changed the size class structure as indicated by measurements in harvested and non-harvested plots. Mangrove cover is patchy due to canopy removal, salinization, and limited propagule establishment due to hydrologic changes. Other recorded impacts include footpaths, cattle browsing, trampling, multiple watershed im- pacts, sediment input, and disturbance from surrounding agricultural activities. The mangroves can be described as heavily impacted with 87% of the indicators in either yellow or red categories (Fig. 5b).

5.3. Indonesia-Segara Anakan Lagoon, Java

The Segara Anakan Lagoon on the island of Java was compared to a temporal reference to assess its system status and potential for degradation (Fig. 5c). The Segara Anakan area is a microtidal, estuarine lagoon with 15 mangrove species in a 20 km lagoon along the south coast of central Java with a large salinity gradient due to both riverine and oceanic influences. The resources of the lagoon and its mangrove forest have long sustained the livelihoods of a dense local population nearby. The lagoon's size rapidly decreased in the late 20th century due to increased sediment input from erosion after land use change. Despite higher sediment inputs providing additional substrate for mangrove colonization, net mangrove forest area decreased largely due to agricultural conversion (rice). Changing environmental conditions, logging, and artisanal fisheries further led to a decrease in abundance and species numbers of the flora and benthic fauna altering community composition. This site's poor status and high levels of degradation (47% red, 53% yellow, 0% green) have been well characterized with high confidence (black) in all indicators and metrics measured over time.

5.4. Kenya- Mikindani, Mombasa

Mikindani, located near the major East-African Port of Mombasa, was compared to two spatial reference mangrove sites near Gazi Bay (ca. 45 km South) and Mida Creek (ca. 100 km North) with all sites having been subject to considerable scientific inquiry. Mikindani is a peri- urban, macrotidal, fringing mangrove forest in a shallow bay system with ten mangrove species. Land-use change, land reclamation, and agricultural impacts are all drivers of degradation in this system, despite the fact that multiple nearby communities rely on it for a range of ecosystem services. Domestic sewage and watershed land use change are core stressors as this forest receives excessive amounts of domestic sewage from the adjacent inhabited hills. The need for rehabilitation and action is highly evident with 85% of indicators listed as red after the comprehensive assessment (Fig. A.1).

5.5. Sri Lanka- Galle-Unawatuna

The relatively small mangrove patch of Galle-Unawatuna, located within a tourist area, was compared to a temporal reference from the 1950s. Galle is a microtidal, basin mangrove forest with 10 mangrove species and a mosaic of vegetation across the microtopographic land- scape. Over 30 years of ecological field studies, remote sensing, and participatory approaches with local stakeholders highlight how this forest has been influenced by the development of roads, dams, and industry. 92% of indicators are listed as either red or yellow in our assessment highlighting both the degradation of this system, but also that some components appear to be resilient to disturbance (Fig. A.2).

5.6. Malaysia-Matang Mangrove Forest reserve

Matang Mangrove Forest Reserve is a heavily managed mangrove forest since its founding in 1902. For this analysis a forest patch in the productive zone of the mangrove forest was compared to a nearby spatial reference in the protective zone. Matang Mangrove Forest is a mesotidal system with a combination of riverine and tide-dominated stands and ~26 mangrove species. The relatively high proportion of indicators assessed as green (44%, Fig. 5f) is likely due to the 30-year harvesting cycles with largely un-disturbed growth (except for two phases of thinning) resulting in conditions within the reference variation. Yet, 39% of indicators examined were red, including biodiversity, nutrient cycling, and soil carbon loss resulting from clear-cutting. This assessment corroborates other recent literature (Goessens et al., 2014; Aziz et al., 2015) and highlights the declining production and associated risk for degradation (Fig. A.2).

6. Management implications of the degradation framework

Ecological monitoring is used to detect environmental change driven by a wide variety of factors (e.g., stochastic processes, successional trends, cyclic variation, or direct/indirect anthropogenic activities). To effectively detect and measure changes to make informed management decisions, it is imperative to gain an understanding of the current status of a system relative to a reference (spatial and/or temporal) and an understanding of relevant drivers of degradation. The Degradation Indicator Framework and associated workflow we present here can be applied by managers or researchers as part of a larger assessment framework to 1) evaluate the current status of a particular system relative to a reference system and 2) identify key drivers of potential degradation by considering a comprehensive suite of factors and stressors. The Degradation Indicator Framework and complementary workflow explicitly use a broad suite of indicators to facilitate an expansive assessment of ecosystem structure, function, and ecosystem services, which provides a more pertinent perspective than, for example, areal cover alone. Importantly, all specific indicators within each cate- gory are measurable, have a transparent scientific basis, and are clearly linked to their particular degradation stressor or system status feature. This suite of indicators can then be used to inform appropriate management or conservation action (McQuatters-Gollop et al., 2019). For example, this framework and workflow could be used to assess the current status of a system and be applied repeatedly to understand how management and or restoration activities have helped to improve overall ecosystem structure, processes, and services and how actions have reduced specific drivers of degradation. Furthermore, it allows for a comparable and actionable decision support workflow to revisit areas of special concern or areas that require additional attention.

The presented Degradation Indicator Framework and workflow provides a customizable assessment tool, while considering inherent differences in geographic and environmental characteristics. Importantly, a full assessment of the functionality and service provision of a degraded (or recovering) ecosystem requires a broad suite of indicators, including physical, chemical, biological, and socio-economic factors. A holistic view that considers degradation within the broader socio- ecological system is critical as drivers of ecosystem degradation and solutions for their reduction and management are inherently socio- ecological. As with all monitoring tools and frameworks, the data pro- vide a snapshot of a given system at that moment in time. Once assessment has been completed, the process should be repeated regularly and components reassessed to provide context, directionality, and to evaluate the efficacy of management plans for both a system's status and potential degradation impacts. For example, the framework and workflow could be used to assess the efficacy of management strategies by employing the framework before and after any action, be it hydro- logic restoration, reduced resource extraction, removal of a pollution source, etc..

Any disciplinary focus when conducting ecological monitoring can lead to the underrepresentation of critical aspects and processes of the ecosystem under concern, resulting in a skewed or oversimplified assessment. The indicators presented here are in part based on the knowledge and experience of an international team of multidisciplinary mangrove researchers with experience in multiple countries from around the world with mangroves representing all major biogeomorphic and climatic settings. While additional indicators and components may be needed, this framework has been developed with multiple biogeographical, geomorphological, and temporal/spatial considerations from a variety of locations worldwide. We feel this global perspective strengthens this framework for both mangroves and other systems. We encourage users to modify this framework to meet the needs and re- sources of their location(s) and ecosystems of interest. Additionally, we recognize that the framework presented here should be complemented with site-specific social and/or wellbeing indicators where appropriate (Corrigan et al., 2018; Dahdouh-Guebas et al., 2021).

The presented conceptual framework gives information on the site- specific causes, scope, and impact of ecosystem degradation. Such location specific metrics of degradation are critical to ensure that remedial management actions are suitable, as such actions will vary greatly depending on the cause of degradation, the user, and site. Strategies may include no action, increased monitoring, restoration, re-instatement of physical conditions, control of biotic components, or various management interventions such as increasing protected area status, or socio-economic interventions. Relatively few of these strategies may be considered universally applicable, and they require site specific socio-ecological and socio-political knowledge to be successful. The Degradation Indicator Framework and workflow provide a path towards assessing the presence and causes of degradation which can be used to inform management and evaluate the efficacy of management actions. Usage is meant to elucidate gaps and shortcomings, while providing opportunities for future research, conservation action, or amelioration to occur.

7. Conclusions

As ecosystems continue to be lost and degraded, and the causes of ecosystem degradation are increasingly obscured by anthropogenic in- fluences on natural processes, broader characterization of ecosystem status and degradation will facilitate a comprehensive understanding of system change and identification of drivers of such change. The conceptual framework presented here emphasizes the necessity of considering each site's unique characteristics and recommends a work- flow for comparing the site's current status and drivers of degradation to reference conditions. We encourage users to adapt this framework for their own systems of interest to provide data-driven, objective assessments that can inform and re-equilibrate management and policy actions in the face of ecosystem degradation and loss. The challenge of accurately identifying, defining, and addressing ecosystem degradation is substantial, by critically using appropriate indicators of stressors and overarching drivers in a comprehensive framework, users can assess both recognizable and cryptic degradation, allowing for a better choice of management actions to address degradation and aid subsequent ecosystem recovery and conservation.

CRediT authorship contribution statement:

Guilherme M.O. Abuchahla: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing- Original Draft, Writing-Review & Editing, Visualization; Janine B. Adams: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing-Original Draft, Writing-Review & Editing; Stefano Cannicci: Conceptualization, Methodology, Validation, Investigation, Formal Analysis, Investigation, Data Curation, Writing-Original Draft, Writing-Review & Editing; Steven W.J. Canty: Conceptualization, Methodology, Validation, Investigation, Writing- Original Draft, Writing-Review & Editing, Visualization; Kyle C. Cavanaugh: Conceptualization, Methodology, Validation, Investigation, Writing-Review & Editing; Rod M. Connolly: Conceptualization, Methodology, Validation, Investigation, Writing-Original Draft, Writing-Review & Editing; Nicole Cormier: Conceptualization, Methodology, Validation, Investigation, Writing-Review & Editing, Visualization; Farid Dahdouh-Guebas: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing- Original Draft, Writing-Review & Editing, Supervision; Karen Diele: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing-Original Draft, Writing-Review & Editing; Ilka C. Feller: Conceptualization, Methodology, Validation, Investigation, Writing-Review & Editing; Sara Fratini: Conceptualization, Methodology, Validation, Investigation, Writing-Review & Editing; Daniel A. Friess: Conceptualization, Methodology, Validation, Investigation, Writing-Original Draft, Writing-Review & Editing, Supervision, Administration; Tim C. Jennerjahn: Conceptualization, Methodology, Validation, Investigation, Writing-Original Draft, Writing-Review & Editing; Shing Yip Lee: Conceptualization, Methodology, Validation, Investigation, Writing-Original Draft, Writing-Review & Editing; Danielle E. Ogurcak: Conceptualization, Methodology, Validation, Investigation, Writing-Original Draft, Writing-Review & Editing; Kerrylee Rogers: Conceptualization, Methodology, Validation, Investigation, Writing-Original Draft, Writing-Review & Editing, Supervision; Xiao- guang Ouyang: Conceptualization, Methodology, Validation, Investigation, Writing-Review & Editing; Jennifer K. Rowntree: Conceptualization, Methodology, Validation, Investigation, Writing-Original Draft, Writing-Review & Editing; Sahadev Sharma: Conceptualization, Methodology, Validation, Investigation, Writing-Original Draft, Writing-Review & Editing; Taylor M. Sloey: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing- Original Draft, Writing-Review & Editing, Visualization, Supervision; Alison K.S. Wee: Conceptualization, Methodology, Validation, Investigation, Writing-Review & Editing; Erik S. Yando: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing-Original Draft, Writing-Review & Editing, Visualization, Supervision, Administration.

Acknowledgements:

This study was conceptualized during the workshop of the 5th Mangrove Macrobenthos and Management (MMM5) conference, July 2019. The DSI/NRF Research Chair in Shallow Water Ecosystems (UID 84375) supported JBA. RMC is Director of the Global Wetlands Project, supported by a charitable organization which neither seeks nor permits publicity for its efforts. KD acknowledges the Natural Environment Research Council Grant NE/S006990/1. FDG was supported by the EC- funded Erasmus Mundus Master Program in Tropical Biodiversity and Ecosystems (TROPIMUNDO). DEO was supported by the National Science Foundation under Grant No. HRD-1547798. SS was supported by USFS International Program Funding (IF039-2018). NC was supported by an Australian Government funded International Research Training Program scholarship. This is Smithsonian Marine Station Contribution number: 1163.

References:

Adame, M.F., Reef, R., Santini, N.S., Najera, E., Turschwell, M.P., Hayes, M.A., Masque, P., Lovelock, C.E., 2020. Mangroves in arid regions: ecology, threats, and opportunities. Estuar. Coast. Shelf Sci., 106796 https://doi.org/10.1016/j. ecss.2020.106796.

Adger, W.N., 2005. Social-ecological resilience to coastal disasters. Science 309 (5737), 1036–1039. https://doi.org/10.1126/science.1112122.

Anderies, J.M., Hegmon, M., 2011. Robustness and resilience across scales: migration and resource degradation in the prehistoric U.S. Southwest. Ecol. Soc. 16 (2), art22. https://doi.org/10.5751/ES-03825-160222.

Aziz, A., Dargusch, P., Phinn, S., & Ward, A. (2015). Using REDD+ to balance timber production with conservation objectives in a mangrove forest in Malaysia. Ecol. Econ., 120, 108–116. https://doi.org/10.1016/j.ecolecon.2015.10.014.

Bakhtiyari, M., Lee, S.Y., Warnken, J., 2019. Seeing the forest as well as the trees: an expert opinion approach to identifying holistic condition indicators for mangrove ecosystems. Estuar. Coast. Shelf Sci. 222, 183–194. https://doi.org/10.1016/j. ecss.2019.03.003.

Bartolini, F., Cimò, F., Fusi, M., Dahdouh-Guebas, F., Lopes, G.P., Cannicci, S., 2011. The effect of sewage discharge on the ecosystem engineering activities of two East African fiddler crab species: consequences for mangrove ecosystem functioning. Mar. Environ. Res. 71 (1), 53–61. https://doi.org/10.1016/j.marenvres.2010.10.002.

Bender, E.A., Case, T.J., Gilpin, M.E., 1984. Perturbation experiments in community ecology: theory and practice. Ecology 65 (1), 1–13. https://doi.org/10.2307/ 1939452.

Bindoff, N.L., Stott, P.A., AchutaRao, K.M., Allen, M.R., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., Mokhov, I.I., Overland, J., Perlwitz, J., Sebbari, R., Zhang, X., Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. Detection and attribution of climate change: From global to regional. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bosire, J.O., Dahdouh-Guebas, F., Walton, M., Crona, B.I., Lewis, R.R., Field, C., Kairo, J. G., Koedam, N., 2008. Functionality of restored mangroves: a review. Aquat. Bot. 89 (2), 251–259. https://doi.org/10.1016/j.aquabot.2008.03.010.

Bryan-Brown, D.N., Connolly, R.M., Richards, D.R., Adame, F., Friess, D.A., Brown, C.J., 2020. Global trends in mangrove forest fragmentation. Sci. Rep. 10 (1), 1–8. https:// doi.org/10.1038/s41598-020-63880-1.

Burkhard, B., Maes, J., 2017. Mapping ecosystem services. https://public.ebookcentral. proquest.com/choice/publicfullrecord.aspx?p=5165307.

Cannicci, S., Bartolini, F., Dahdouh-Guebas, F., Fratini, S., Litulo, C., Macia, A., Mrabu, E. J., Penha-Lopes, G., Paula, J., 2009. Effects of urban wastewater on crab and mollusc assemblages in equatorial and subtropical mangroves of East Africa. Estuar. Coast. Shelf Sci. 84 (3), 305–317. https://doi.org/10.1016/j.ecss.2009.04.021.

Cannicci, S., Lee, S.Y., Bravo, H., Cantera-Kintz, J.R., Dahdouh-Guebas, F., Fratini, S., Fusi, M., Jimenez, P.J., Nordhaus, I., Porri, F., Diele, K., 2021. A functional analysis reveals extremely low redundancy in global mangrove invertebrate fauna. Proc. Natl. Acad. Sci. U. S. A. 118 (32), e2016913118 https://doi.org/10.1073/ pnas.2016913118.

Cavanaugh, K.C., Kellner, J.R., Forde, A.J., Gruner, D.S., Parker, J.D., Rodriguez, W., Feller, I.C., 2014. Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. Proc. Natl. Acad. Sci. 111 (2), 723–727. https://doi.org/10.1073/pnas.1315800111.

Clewell, A.F., Aronson, J., 2013. Ecological Restoration: Principles, Values, and Structure of an Emerging Profession. Island Press.

Corrigan, C., Robinson, J., Burgess, C., D., N., Kingston, N., Hockings, M., 2018. Global review of social indicators used in protected area management evaluation: global review of protected area indicators. Conserv. Lett. 11 (2), e12397 https://doi.org/ 10.1111/conl.12397.

Costanza, R., De Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j. ecoser.2017.09.008.

Côté, I.M., Darling, E.S., Brown, C.J., 2016. Interactions among ecosystem stressors and their importance in conservation. Proc. R. Soc. B Biol. Sci. 283 (1824), 20152592 https://doi.org/10.1098/rspb.2015.2592.

Dahdouh-Guebas, F., Hettiarachchi, S., Lo Seen, D., Batelaan, O., Sooriyarachchi, S., Jayatissa, L.P., Koedam, N., 2005. Transitions in ancient inland freshwater resource management in Sri Lanka Affect Biota and Human Populations in and around coastal lagoons. Curr. Biol. 15 (6), 579–586. https://doi.org/10.1016/j.cub.2005.01.053.

Dahdouh-Guebas, Farid, Huǵe, J., Abuchahla, G.M.O., Cannicci, S., Jayatissa, L.P., Kairo, J.G., Arachchilage, S.K., Koedam, N., Mafaziya Nijamdeen, T.W.G.F., Mukherjee, N., Poti, M., Prabakaran, N., Ratsimbazafy, H.A., Satyanarayana, B., Thavanayagam, M., Velde, K.V., Wodehouse, D., 2021. Reconciling nature, people and policy in the mangrove social-ecological system through the adaptive cycle heuristic. Estuar. Coast. Shelf Sci., 106942 https://doi.org/10.1016/j. ecss.2020.106942.

Davy-Bowker, J., Clarke, R., 2015. Testing RICT prediction of expected values using an independent RIVPACS model and new RIVPACS test data. In: Report to Environment Agency, Published by Freshwater Biological Association.

de Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41 (3), 393–408. https://doi.org/10.1016/S0921-8009(02)00089-7.

Deng, H., He, J., Feng, D., Zhao, Y., Sun, W., Yu, H., Ge, C., 2021. Microplastics pollution in mangrove ecosystems: a critical review of current knowledge and future directions. Sci. Total Environ. 753, 142041 https://doi.org/10.1016/j. scitotenv.2020.142041.

Duke, N.C., Ball, M.C., Ellison, J.C., 1998. Factors influencing biodiversity and distributional gradients in mangroves. Glob. Ecol. Biogeogr. Lett. 7 (1), 27–47. https://doi.org/10.2307/2997695.

Ellison, A.M., 2000. Mangrove restoration: do we know enough? Restor. Ecol. 8 (3), 219–229. https://doi.org/10.1046/j.1526-100x.2000.80033.x.

Ellison, A.M., Farnsworth, E.J., 1996. Anthropogenic disturbance of Caribbean mangrove ecosystems: past impacts, present trends, and future predictions. Biotropica 28 (4), 549–565. https://doi.org/10.2307/2389096.

Ewel, K., Twilley, R., Ong, J., 1998. Different kinds of mangrove forests provide different goods and services. Glob. Ecol. Biogeogr. Lett. 7 (1), 83–94. https://doi.org/ 10.1111/j.1466-8238.1998.00275.x.

Eyring, V., Gillett, N.P., Achuta Rao, K.M., Barimalala, R., Barreiro Parrillo, M., Bellouin, N., Cassou, C., Durack, P.J., Kosaka, Y., McGregor, S., Min, S., Morgenstern, O., Sun, Y., 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., P ́ean, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Human Influence on the Climate System. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

Friess, D.A., Yando, E.S., Abuchahla, G.M.O., Adams, J.B., Cannicci, S., Canty, S.W.J., Cavanaugh, K.C., Connolly, R.M., Cormier, N., Dahdouh-Guebas, F., Diele, K., Feller, I.C., Fratini, S., Jennerjahn, T.C., Lee, S.Y., Ogurcak, D.E., Ouyang, X., Rogers, K., Rowntree, J.K., Wee, A.K.S., 2020. Mangroves give cause for conservation optimism, for now. Curr. Biol. 30 (4), R153–R154. https://doi.org/ 10.1016/j.cub.2019.12.054.

Ghazoul, J., Burivalova, Z., Garcia-Ulloa, J., King, L.A., 2015. Conceptualizing forest degradation. Trends Ecol. Evol. 30 (10), 622–632. https://doi.org/10.1016/j. tree.2015.08.001.

Gilman, E.L., Ellison, J., Duke, N.C., Field, C., 2008. Threats to mangroves from climate change and adaptation options: a review. Aquat. Bot. 89 (2), 237–250. https://doi. org/10.1016/j.aquabot.2007.12.009.

Goessens, A., Satyanarayana, B., Stocken, T.V. der, Zuniga, M.Q., Mohd-Lokman, H., Sulong, I., Dahdouh-Guebas, F., 2014. Is Matang Mangrove Forest in Malaysia sustainably rejuvenating after more than a century of conservation and harvesting management? PLoS One 9 (8), e105069. https://doi.org/10.1371/journal. pone.0105069.

Goldberg, L., Lagomasino, D., Thomas, N., Fatoyinbo, T., 2020. Global declines in human-driven mangrove loss. Glob. Chang. Biol. 26 (10), 5844–5855. https://doi. org/10.1111/gcb.15275.

Hamilton, L.S., Snedaker, S.C., 1984. Handbook for Mangrove Area Management. East- West Environment and Policy Institute, Honolulu. http://scholarspace.manoa.hawaii.edu/handle/10125/26547.

Harris, R.M.B., Beaumont, L.J., Vance, T.R., Tozer, C.R., Remenyi, T.A., Perkins- Kirkpatrick, S.E., Mitchell, P.J., Nicotra, A.B., McGregor, S., Andrew, N.R.,

Letnic, M., Kearney, M.R., Wernberg, T., Hutley, L.B., Chambers, L.E., Fletcher, M.- S., Keatley, M.R., Woodward, C.A., Williamson, G., Bowman, D.M.J.S., 2018. Biological responses to the press and pulse of climate trends and extreme events. Nat. Clim. Chang. 8 (7), 579–587. https://doi.org/10.1038/s41558-018-0187-9.

Hegerl, G., Zwiers, F., 2011. Use of models in detection and attribution of climate change. Wiley Interdiscip. Rev. Clim. Chang. 2 (4), 570–591.

Hobbs, R.J., 2016. Degraded or just different? Perceptions and value judgements in restoration decisions. Restor. Ecol. 24 (2), 153–158. https://doi.org/10.1111/ rec.12336.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 1–23.

IPBES, 2019. Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. In: Brondizio, E.S., Settele, J., Díaz, S., Ngo, H.T. (Eds.), IPBES secretariat, Bonn, Germany.

Jennerjahn, T.C., Gilman, E., Krauss, K.W., Lacerda, L.D., Nordhaus, I., Wolanski, E., 2017. Mangrove ecosystems under climate change. In: Rivera-Monroy, V.H., Lee, S. Y., Kristensen, E., Twilley, R.R. (Eds.), Mangrove Ecosystems: A Global Biogeographic Perspective—Structure, Function and Services. Springer International Publishing, pp. 211–244. https://doi.org/10.1007/978-3-319-62206-4_7.

Kaufmann, M. R, Graham, R. T., Jr D. A. B., Moir, W. H., Perry, L., Reynolds, R. T., Bassett, R. L., Mehlhop, P., Edminster, C. B., Block, W. M., & Corn, P. S. (1994). An Ecological Basis for Ecosystem Management (General Technical Report RM-246; p. 28). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Kaufmann, M.R., Huckaby, L.S., Regan, C.M., Popp, J., 1998. Forest Reference Conditions for Ecosystem Management in the Sacramento Mountains, New Mexico (RMRS-GTR-19; p. RMRS-GTR-19). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-19.

Kennedy, C.M., Oakleaf, J.R., Theobald, D.M., Baruch-Mordo, S., Kiesecker, J., 2019. Managing the middle: a shift in conservation priorities based on the global human modification gradient. Glob. Chang. Biol. 25 (3), 811–826. https://doi.org/10.1111/ gcb.14549.

Lee, S.Y., 2008. Mangrove macrobenthos: assemblages, services, and linkages. J. Sea Res. 59 (1–2), 16–29. https://doi.org/10.1016/j.seares.2007.05.002.

Lee, S.Y., Dunn, R.J.K., Young, R.A., Connolly, R.M., Dale, P.E.R., Dehayr, R., Lemckert, C.J., Mckinnon, S., Powell, B., Teasdale, P.R., Welsh, D.T., 2006. Impact of urbanization on coastal wetland structure and function. Austral Ecol. 31 (2), 149–163. https://doi.org/10.1111/j.1442-9993.2006.01581.x.

Lee, S.Y., Primavera, J.H., Dahdouh-Guebas, F., McKee, K., Bosire, J.O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C., Mendelssohn, I., Mukherjee, N., Record, S., 2014. Ecological role and services of tropical mangrove ecosystems: a reassessment. Glob. Ecol. Biogeogr. 23 (7), 726–743. https://doi.org/10.1111/ geb.12155.

Lee, S.Y., Hamilton, S., Barbier, E.B., Jurgenne, P., Lewis, R.R., 2019. Better restoration policies are needed to conserve mangrove ecosystems. Nat. Ecol. Evol. London 3 (6), 870–872 https://doi.org.proxy.lib.odu.edu/10.1038/s41559-019-0861-y.

Lewis, R.R., Milbrandt, E.C., Brown, B., Krauss, K.W., Rovai, A.S., Beever, J.W., Flynn, L. L., 2016. Stress in mangrove forests: early detection and preemptive rehabilitation are essential for future successful worldwide mangrove forest management. Mar. Pollut. Bull. 109 (2), 764–771. https://doi.org/10.1016/j.marpolbul.2016.03.006.

Lovelock, C.E., Ball, M.C., Martin, K.C., Feller, I.C., 2009. Nutrient enrichment increases mortality of mangroves. PLoS One 4 (5), e5600. https://doi.org/10.1371/journal. pone.0005600.

Lugo, A.E., Snedaker, S.C., 1974. The ecology of mangroves. Annu. Rev. Ecol. Syst. 5 (1), 39–64. https://doi.org/10.1146/annurev.es.05.110174.000351.

Luo, Y.Y., Not, C., Cannicci, S., 2021. Mangroves as unique but understudied traps for anthropogenic marine debris: a review of present information and the way forward. Environ. Pollut. 271, 116291 https://doi.org/10.1016/j.envpol.2020.116291.

McQuatters-Gollop, A., Mitchell, I., Vina-Herbon, C., Bedford, J., Addison, P.F.E., Lynam, C.P., Geetha, P.N., Vermeulan, E.A., Smit, K., Bayley, D.T.I., Morris-

Webb, E., Niner, H.J., Otto, S.A., 2019. From science to evidence – how biodiversity indicators can be used for effective marine conservation policy and management. Front. Mar. Sci. 6, 109. https://doi.org/10.3389/fmars.2019.00109.

Moberg, F., Rönnbäck, P., 2003. Ecosystem services of the tropical seascape: interactions, substitutions and restoration. Ocean Coast. Manag. 46 (1), 27–46. https://doi.org/ 10.1016/S0964-5691(02)00119-9.

Nolan, C., Overpeck, J.T., Allen, J.R.M., Anderson, P.M., Betancourt, J.L., Binney, H.A., Brewer, S., Bush, M.B., Chase, B.M., Cheddadi, R., Djamali, M., Dodson, J., Edwards, M.E., Gosling, W.D., Haberle, S., Hotchkiss, S.C., Huntley, B., Ivory, S.J., Kershaw, A.P., Jackson, S.T., 2018. Past and future global transformation of terrestrial ecosystems under climate change. Science (New York, N.Y.) 361 (6405), 920–923. https://doi.org/10.1126/science.aan5360.

Osland, M.J., Enwright, N., Day, R.H., Doyle, T.W., 2013. Winter climate change and coastal wetland foundation species: salt marshes vs. mangrove forests in the southeastern United States. Glob. Chang. Biol. 19 (5), 1482–1494. https://doi.org/ 10.1111/gcb.12126.

Osland, M.J., Feher, L.C., Griffith, K.T., Cavanaugh, K.C., Enwright, N.M., Day, R.H., Stagg, C.L., Krauss, K.W., Howard, R.J., Grace, J.B., Rogers, K., 2017. Climatic controls on the global distribution, abundance, and species richness of mangrove forests. Ecol. Monogr. 87 (2), 341–359. https://doi.org/10.1002/ecm.1248.

Penha-Lopes, G., Torres, P., Cannicci, S., Narciso, L., Paula, J., 2011. Monitoring anthropogenic sewage pollution on mangrove creeks in southern Mozambique: a test of Palaemon concinnus Dana, 1852 (Palaemonidae) as a biological indicator. Environ. Pollut. 159 (2), 636–645. https://doi.org/10.1016/j.envpol.2010.09.029.

Peterson, G., Allen, C.R., Holling, C.S., 1998. Ecological resilience, biodiversity, and scale. Ecosystems 1 (1), 6–18. https://doi.org/10.1007/s100219900002.

Quisthoudt, K., Schmitz, N., Randin, C.F., Dahdouh-Guebas, F., Robert, E.M.R., Koedam, N., 2012. Temperature variation among mangrove latitudinal range limits worldwide. Trees Struct. Funct. 26 (6), 1919–1931. https://doi.org/10.1007/ s00468-012-0760-1.

Raw, J.L., Godbold, J.A., van Niekerk, L., Adams, J.B., 2019. Drivers of mangrove distribution at the high-energy, wave-dominated, southern African range limit. Estuar. Coast. Shelf Sci. 226, 106296 https://doi.org/10.1016/j.ecss.2019.106296.

Rogers, K., Krauss, K.W., 2019. Moving from generalisations to specificity about mangrove-saltmarsh dynamics. Wetlands 39 (6), 1155–1178. https://doi.org/ 10.1007/s13157-018-1067-9.

Rovai, A.S., Twilley, R.R., Castañeda-Moya, E., Riul, P., Cifuentes-Jara, M., Manrow- Villalobos, M., Horta, P.A., Simonassi, J.C., Fonseca, A.L., Pagliosa, P.R., 2018. Global controls on carbon storage in mangrove soils. Nat. Clim. Chang. 8 (6), 534–538. https://doi.org/10.1038/s41558-018-0162-5.

Scales, I.R., Friess, D.A., Glass, L., Ravaoarinorotsihoarana, L., 2018. Rural livelihoods and mangrove degradation in south-west Madagascar: lime production as an emerging threat. Oryx 52 (4), 641–645. https://doi.org/10.1017/ S0030605316001630.

Schaeffer-Novelli, Y., Cintrón-Molero, G., Soares, M.L.G., De-Rosa, T., 2000. Brazilian mangroves. Aquat. Ecosyst. Health Manag. 3 (4), 561–570. https://doi.org/ 10.1080/14634980008650693.

Schwerdtner Máñez, K., Krause, G., Ring, I., Glaser, M., 2014. The Gordian knot of mangrove conservation: disentangling the role of scale, services and benefits. Glob. Environ. Chang. 28, 120–128. https://doi.org/10.1016/j.gloenvcha.2014.06.008.

Sippo, J.Z., Lovelock, C.E., Santos, I.R., Sanders, C.J., Maher, D.T., 2018. Mangrove mortality in a changing climate: an overview. Estuar. Coast. Shelf Sci. 215, 241–249. https://doi.org/10.1016/j.ecss.2018.10.011.

Smale, D.A., Wernberg, T., Oliver, E.C.J., Thomsen, M., Harvey, B.P., Straub, S.C., Burrows, M.T., Alexander, L.V., Benthuysen, J.A., Donat, M.G., Feng, M., Hobday, A. J., Holbrook, N.J., Perkins-Kirkpatrick, S.E., Scannell, H.A., Sen Gupta, A., Payne, B. L., Moore, P.J., 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nat. Clim. Chang. 9 (4), 306–312. https://doi.org/ 10.1038/s41558-019-0412-1.

Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdaña, Z.A., Finlayson, M., Halpern, B.S., Jorge, M.A., Lombana, A., Lourie, S.A., Martin, K.D., McManus, E., Molnar, J., Recchia, C.A., Robertson, J., 2007. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. BioScience 57 (7), 573–583. https:// doi.org/10.1641/B570707.

Stoddard, J.L., Larsen, D.P., Hawkins, C.P., Johnson, R.K., Norris, R.H., 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. Ecol. Appl. 16 (4), 1267–1276. https://doi.org/10.1890/10510761(2006) 016[1267:SEFTEC]2.0.CO;2.

Thom, B.G., 1984. Coastal landforms and geomorphic processes. In: The Mangrove Ecosystem: Research Methods, vol. 8. UNESCO, pp. 3–17.

Thompson, I.D., Guariguata, M.R., Okabe, K., Bahamondez, C., Nasi, R., Heymell, V., Sabogal, C., 2013. An operational framework for defining and monitoring forest degradation. Ecol. Soc. 18 (2), 20. https://doi.org/10.5751/ES-05443-180220.

Tomlinson, P.B., 2016. The Botany of Mangroves. Cambridge University Press. Turschwell, M.P., Tulloch, V.J., Sievers, M., Pearson, R.M., Andradi-Brown, D.A., Ahmadia, G.N., Connolly, R.M., Bryan-Brown, D., Lopez-Marcano, S., Adame, M.F., Brown, C.J., 2020. Multi-scale estimation of the effects of pressures and drivers on mangrove forest loss globally. Biol. Conserv. 247, 108637 https://doi.org/10.1016/ j.biocon.2020.108637.

Twilley, R.R., Rivera-Monroy, V.H., Chen, R., Botero, L., 1999. Adapting an ecological mangrove model to simulate trajectories in restoration ecology. Mar. Pollut. Bull. 37 (8), 404–419. https://doi.org/10.1016/S0025-326X(99)00137-X.

Woodroffe, C., 1992. Mangrove sediments and geomorphology. In: Tropical Mangrove Ecosystems. American Geophysical Union (AGU), pp. 7–41. https://doi.org/ 10.1029/CE041p0007.

Woodroffe, C.D., Rogers, K., McKee, K.L., Lovelock, C.E., Mendelssohn, I.A., Saintilan, N., 2016. Mangrove sedimentation and response to relative sea-level rise. Annu. Rev. Mar. Sci. 8 (1), 243–266. https://doi.org/10.1146/annurev-marine-122414-034025.

Worthington, T.A., Zu Ermgassen, P.S., Friess, D.A., Krauss, K.W., Lovelock, C.E., Thorley, J., Tingey, R., Woodroffe, C.D., Bunting, P., Cormier, N., Lagomasino, D., 2020. A global biophysical typology of mangroves and its relevance for ecosystem structure and deforestation. Sci. Rep. 10 (1), 1–11. https://doi.org/10.1038/s41598- 020-71194-5.

WWF (World Wildlife Federation), 2020. In: Almond, R.E.A., Grooten, M., Petersen, T. (Eds.), Living Planet Report 2020 - Bending the Curve of Biodiversity Loss. WWF, Gland, Switzerland.

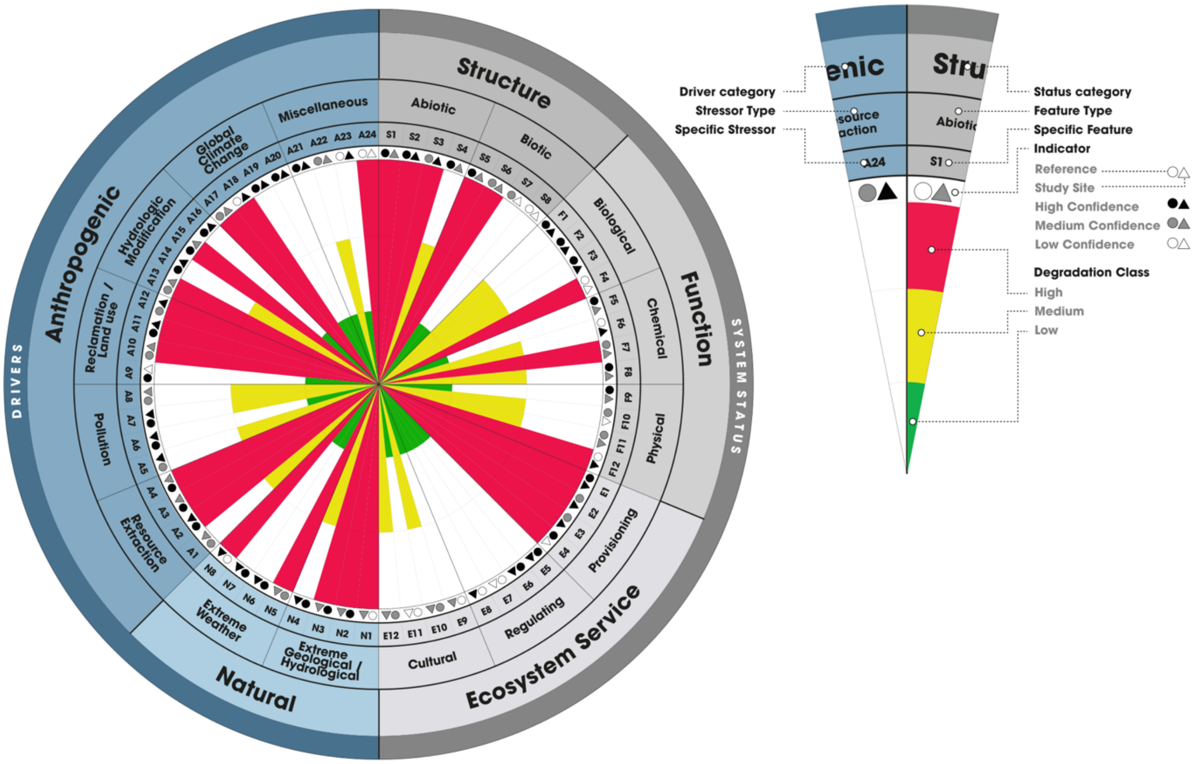


Fig. 1. The Degradation Indicator Framework quantifies drivers of degradation and system status to provide a holistic understanding of a given ecosystem (this example uses hypothetical data to illustrate multiple possibilities). Driver categories (anthropogenic [A] and natural [N]) are further broken down into potential stressor types (e.g., resource extraction, pollution, extreme weather, etc.) and specific stressors with measurable and comparable indicators (segment A1-Ak & N1- Nk). System status is broken down into status category (structure [S], function [F], ecosystem service [E]) and feature type (abiotic, biotic; biological, chemical, physical; provisioning, regulating, cultural) and specific features with measurable and comparable indicators (segment S1-Sk, F1-Fk, E1-Ek). Note that supporting services fall under functions. All specific stressors (Ax, Nx) and indicators (Sx, Fx, Ex) are user derived and will differ depending on the system and available re- sources. The confidence of the data at the reference (circle) and study (triangle) sites are reflected in the shapes within each segment (white = low, gray = medium, black = high). Size and color of radiating bars from center of diagram represent degradation state of system compared to reference condition (green = low, yellow = medium, red = high). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

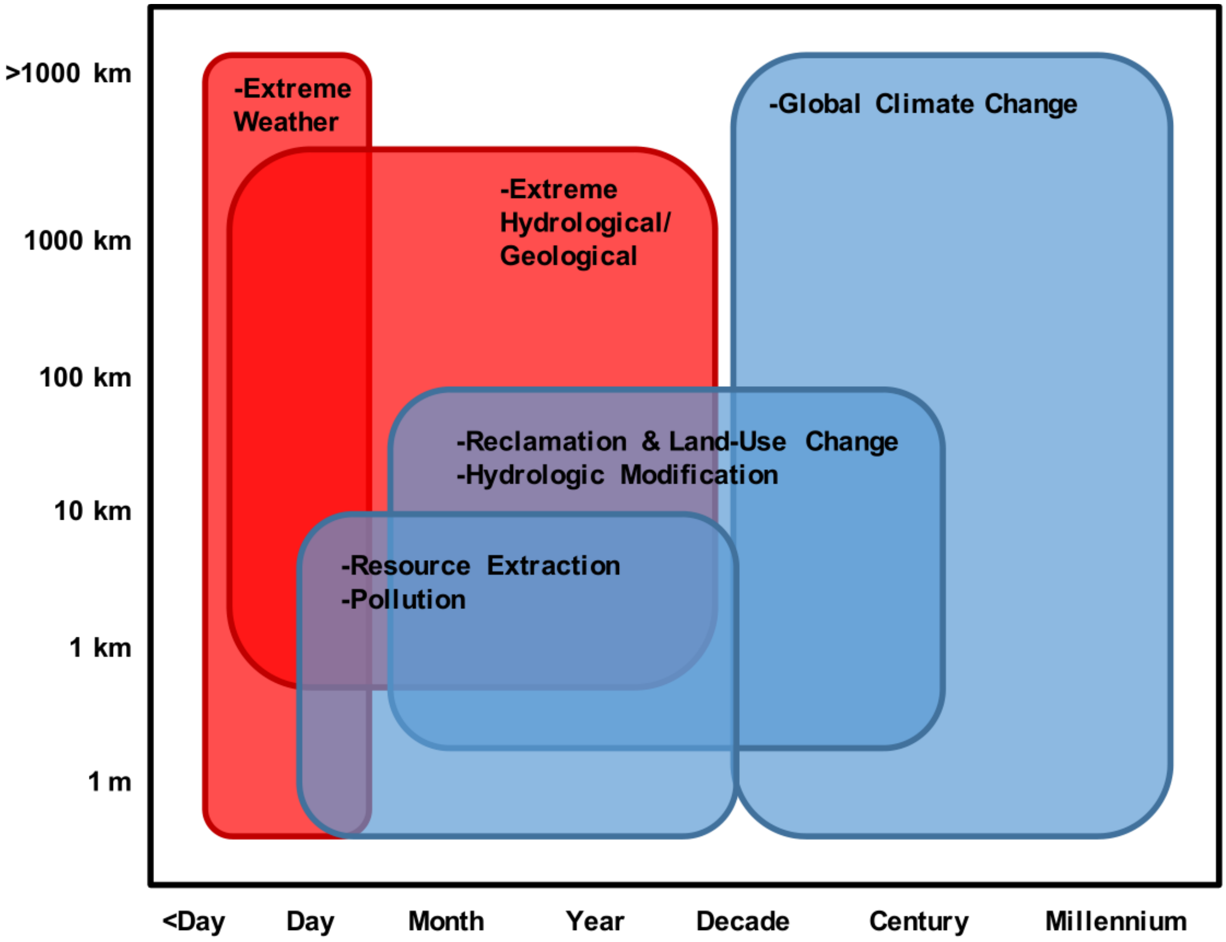


Fig. 2. Mangrove degradation driver categories and the spatial (1 km to >1000 km) and temporal (< Day to Millennium) scales in which they operate. Adapted from Rogers and Krauss (2019).

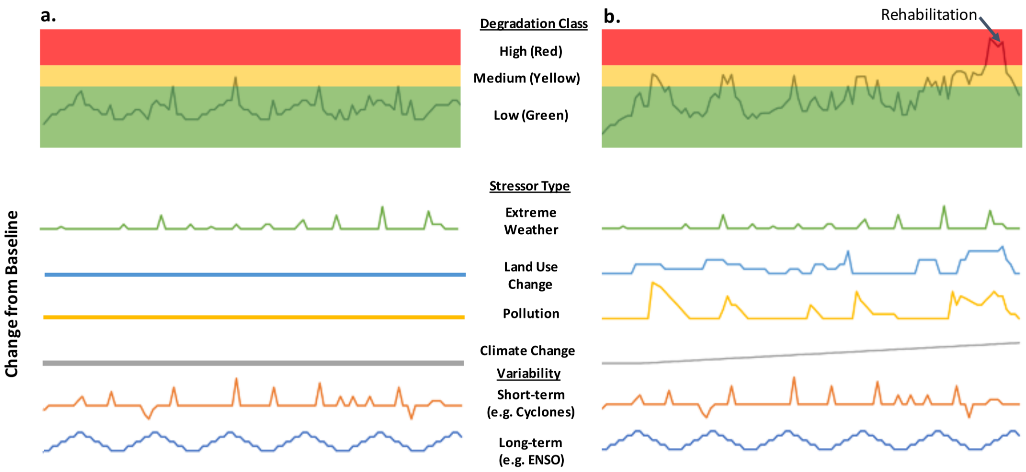
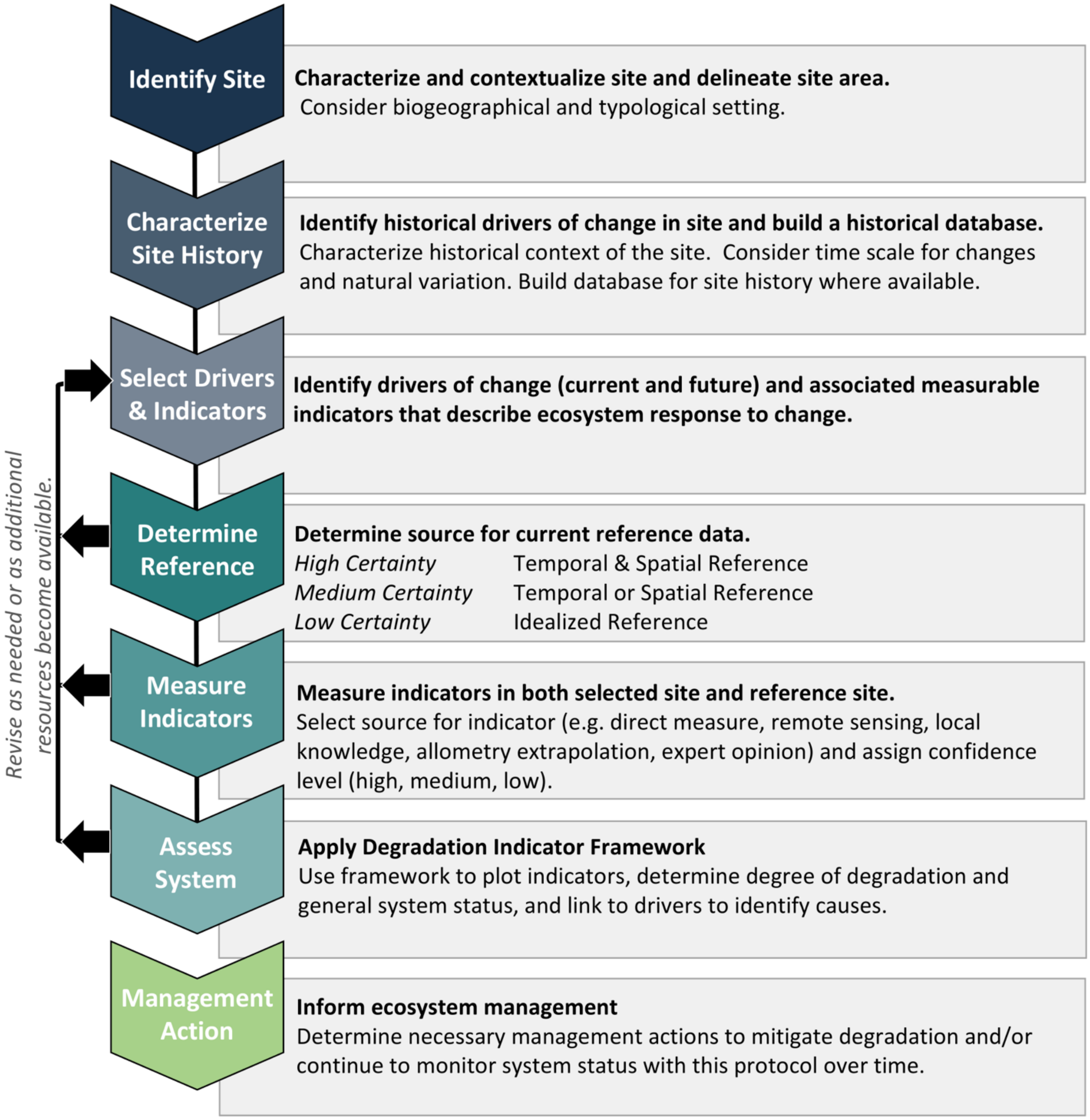


Fig. 3. Conceptualization of the impact of short- and long-term variability on baseline conditions with a) natural drivers of degradation (e.g., extreme weather) and b) combined impact of natural and anthropogenic drivers of degradation. When all impacts (natural variability + natural degradation + anthropogenic degradation) are combined the system shifts from being able to recover from rare disturbances (Green-Bottom Level to Yellow-Mid Level) (Shown in Panel A) to a regularly impacted state (greater frequency in Yellow-Mid Level) (Shown in Panel B). Without a reduction of the impacts of some of the drivers of degradation the system will be pushed into a state where it is unable to recover (Red-Top Level) without managed rehabilitation of the system and/or key drivers (Shown in Panel B). Modified from Harris et al. (2018). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).



Characterize and contextualize site and delineate site area.
Consider biogeographical and typological setting.

Identify historical drivers of change in site and build a historical database.
Characterize historical context of the site. Consider time scale for changes and natural variation. Build database for site history where available.

Identify drivers of change (current and future) and associated measurable indicators that describe ecosystem response to change.

Determine source for current reference data.

High Certainty	Temporal & Spatial Reference
Medium Certainty	Temporal or Spatial Reference
Low Certainty	Idealized Reference

Measure indicators in both selected site and reference site.
Select source for indicator (e.g. direct measure, remote sensing, local knowledge, allometry extrapolation, expert opinion) and assign confidence level (high, medium, low).

Apply Degradation Indicator Framework
Use framework to plot indicators, determine degree of degradation and general system status, and link to drivers to identify causes.

Inform ecosystem management
Determine necessary management actions to mitigate degradation and/or continue to monitor system status with this protocol over time.

Fig. 4. Workflow for use of the Degradation Indicator Framework and implementation with built-in iterative process to allow for re-evaluation.

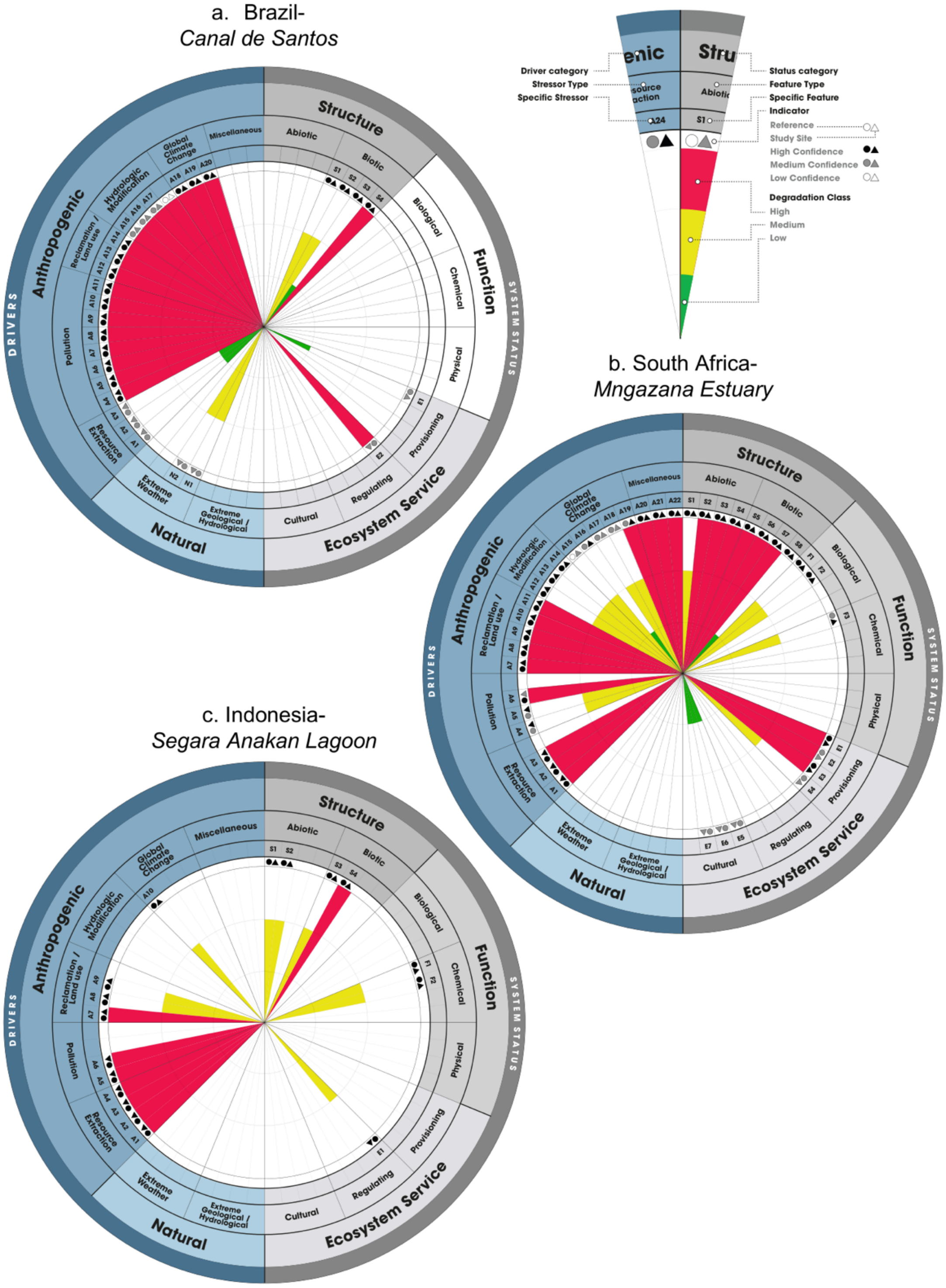


Fig. 5. Example Degradation Indicator Frameworks as applied to case study sites in: a. Brazil- Canal de Santos, b. South Africa- Mngazana Estuary, and c. Indonesia- Segara Anakan Lagoon. Three additional case studies from Kenya- Mikindani, Sri Lanka- Galle-Unawatuna, Malaysia-Matang Mangrove Forest are included in SI 1. All specific data (e. g., indicator and values) are presented in tabular form for all case studies in SI 2. Reference Fig. 1 and supporting text for detailed descriptions of the framework components.