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**Seeing the forest as well as the trees: an expert opinion approach to
identifying holistic condition indicators for mangrove ecosystems**

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Abstract

Holistic ecosystem health indices are urgently needed for conserving and managing rapidly dwindling mangrove ecosystems. The appropriate indices should provide consistent outcomes that enable both the assessment of current conditions and assist future planning. The previous approaches mostly focus on the structural condition of trees, with mangrove ecosystems often treated as terrestrial forests. Structural features are too insensitive as representatives of negative internal creeping changes. Some unique mangrove ecosystem attributes can react to anthropogenic pressures much faster than tree or forest structures do, making them more useful as early warning indicators. The development of holistic indicators requires a multidimensional approach engaging specific functions and services underpinning the characteristics of mangrove ecosystems. We present an approach to identify potential variables ranging from assemblage structure to physiological and biochemical variables for reliably indicating mangrove condition. These indicators could then be tested against a range of ecosystem conditions (e.g. disturbance levels) to reveal their response to different degrees of pressures. These variables were first nominated based on the driver-response model relating changes in environmental conditions and ecosystem responses. The nominated variables were then prioritised through an expert questionnaire survey, in which the experts scored every nominated variable on the efficiency, the number of pertinent ecosystem services and the time required them to reflect the impact of the pressure. Sediment properties and elements of forest structure featured strongly in the survey, followed by variables pertaining to biomass, vegetation status and carbon cycling. With respect to community composition, components of the higher trophic levels (e.g. crabs, other macrofauna) were ranked higher by the experts. The mangrove-tree-related variables (e.g. Importance Value Index, IVI), associated biotic components of insects, annelids and moss were ranked lowest.

25 These results provide the basis for establishing a specific framework for mangrove ecosystem
26 assessment.

27

28 **Keywords:** Mangrove forests, ecosystem assessment, driver-response process, expert
29 opinion, health indicators, ecosystem services

30

1. Introduction

Over the last century, coastal development, and over-exploitation of resources have led to widespread mangrove ecosystem loss and degradation (Duke *et al.*, 2007; Polidoro *et al.*, 2010; Bosire *et al.*, 2014). Significant private and public funds have been expended on the conservation, restoration and rehabilitation of these ecosystems, with an increasing trend following the attention to their role in mitigating natural disasters such as tsunamis (Dahdouh-Guebas *et al.*, 2005) and other services (Lee *et al.*, 2014). The outcomes of these efforts need to be adequately assessed. However, monitoring and evaluation components are often absent or methods adopted are mostly inconsistent between projects (Sutula *et al.*, 2006; Sheaves *et al.*, 2014). This reveals the significant lack of current agreement on holistic, ecosystem health indices. There is therefore a pressing need for innovative approaches to improving the management of the remaining mangroves by developing a reliable and thorough assessment method for determining their ecosystem status and their likely future trajectory. Such a specific assessment method has to be built on robust indices that can be applied to a range of spatial and temporal scenarios to provide consistent outcomes, and also to support future planning. Indices have to be practical and applicable not only to various types of mangrove ecosystems but also should be suitable to a wide range of users from different disciplines (e.g. scientists and decision-makers). Accordingly, a comprehensive and holistic approach is required to develop such indices because mangrove ecosystems are indeed complex systems influenced by numerous components defining their functions and services (Lee *et al.*, 2014). Compiling detailed knowledge of such components and their relevant variables would provide a platform on which compatible assessment methods and a combination of indices for mangrove ecosystem could be built in an integrated fashion.

There is currently no single, consistent assessment method that comprehensively represents mangrove ecosystem characteristics. Table 1 summarises the main methods currently used to

assess mangrove ecosystems. Although some of the complicated modelling approaches include functional variables, the majority of the assessment methods consider mangrove ecosystem dynamics as primarily dominated by forest structural components. However, the assessment of ecological function and evaluation of the capacity of mangroves for ecosystem services go beyond forest structure (Lee *et al.*, 2014). Accordingly, broader multidimensional views of ecosystem functioning and condition are needed. The term “multidimensional” refers to a holistic consideration of mangrove forest functions and services in relation to the unique characteristics (e.g. connectivity with terrestrial and marine systems) of this ecosystem. This idea is backed by the specific characteristics underpinning mangrove ecosystem functioning and services.

Despite low tree species richness, mangrove ecosystems are complex because of the interactions amongst numerous geophysical (Berger *et al.*, 2008) and biological drivers (Lee, 1999; Kathiresan & Bingham, 2001), which are fundamentally different to terrestrial forests. Anoxic and saline conditions in mangrove sediments also result in unique biochemical transformation within the substrate. The role of tides and hydrologic connectivity, for instance, is paramount in the functioning of mangroves and has implications for organic matter exchange, carbon storage, and biodiversity (Twilley, 1985; Gopal & Chauhan, 2006; Adame & Lovelock, 2011). In addition to their physical impacts, water flow provides the vehicle for ecosystem connectivity and assists in transferring materials much faster than in terrestrial forests. Unlike terrestrial forests, mangroves are transitional ecosystems located at almost the end point of riverine catchments/basins, and are exposed to land and river runoff as well as the direct action of marine drivers such as waves and tides (Duke, 2001; Granek & Ruttenberg, 2008; Nagelkerken *et al.*, 2008). All these properties might be considered in the preferred assessment method for mangrove systems. This, in turn, requires consideration and integration of a greater number and range of variables, and development of a more holistic

understanding of the dynamics in mangrove ecosystems. This improved understanding would also allow stressor-induced changes to be identified much earlier compared to changes expressed by alterations in forest or canopy structures.

Table 1. Current mangrove health assessment approaches

Method	Supported by	Outcome	Reference
Synthetic aperture radar (SAR)	remote sensing data	Analysing mangrove forest canopy structure and its changes without any further consideration of other in-situ habitat variables, mainly due to a lack of field data.	Lucas <i>et al.</i> (2014)
Air-photo and satellite data interpretation and Very high-resolution (VHR) imagery	geographic information system		Kuenzer <i>et al.</i> (2011); Satyanarayana <i>et al.</i> (2011)
BioCondition assessment protocol	field data to determine a biodiversity index in terrestrial and mangrove vegetation communities	All the metrics being used are primarily bushland or forest characteristics.	Eyre <i>et al.</i> (2015)
Shoreline Video Assessment Method (S-VAM)	geo-referenced video and image data	Evaluating mangrove tree/forest structure	Mackenzie <i>et al.</i> (2016)
Complexity Index (CI)	in-situ measurements of mangrove species (e.g. stems, basal area)	Evaluating mangrove tree/forest structure	Lewis <i>et al.</i> (2016)
FORMAN	data on edaphic condition and its association with the structural characteristics (e.g. diameter-at-breast-height and tree height)	A gap dynamic model simulating the long-term dynamics of mangrove forest development	Chen & Twilley (1998)
KiWi model	theoretical and applied ecological features such as self-thinning trajectories and size-distributions, as well as neighbour competition	A vegetation model regarding mangrove forest dynamics	Berger & Hildenbrandt (2000); Berger <i>et al.</i> (2004); Grueters <i>et al.</i> (2014)
MANGRO	stand structure and environmental conditions	A spatial, stand-simulation model developed to predict the tree and gap replacement process	Doyle <i>et al.</i> (2003)
Mangrove Dynamics and Management (MADAM)	long periods of field monitoring, required considerable specialist engagement	A multidiscipline approach relied on combining the results of different modelling methods, which required sophisticated input data sets.	Berger <i>et al.</i> (1999); Behling <i>et al.</i> (2001); Saint-Paul & Schneider (2010)

1.1. Approaches to identifying Integrated Health Indicators for Ecosystem

Integrity

Apart from forest structure components, other potential variables may reflect the function and services of mangrove ecosystems, which can act as metrics for mangrove assessment. These variables can be identified by extending a driver-response model for the combined relationships among environmental conditions, their changes and ecosystem responses (Fig. 1 A). Environmental conditions or properties are defined by natural drivers including resources (e.g. CO₂ and nutrients) and regulators (e.g. salinity and temperature) (Huston & Huston, 1994; Berger *et al.*, 2008). Without any pressure, the drivers shape an ecosystem into its current natural state, i.e. its undisturbed healthy condition (Fig. 1 A). Where a stressor/pressure (e.g. an anthropogenic influence) develops, it will affect both abiotic and biotic factors (i.e. ecosystem properties) and therefore cause departures from normal ecosystem structure and function (Granek & Ruttenberg, 2008) (Fig. 1 A). This concept has been used to develop ecosystem assessment methods by calculating an Index of Biotic Integrity (IBI) for running waters. These methods use variables that are known for their sensitivity (e.g. fish community and assemblages) to anthropogenic pressures (e.g. Degerman *et al.*, 2007; Solana Gutierrez *et al.*, 2009; Mostafavi *et al.*, 2015). IBI has been used to categorize the health and/or degradation of wetlands (Wilcox *et al.*, 2002); however, this approach does not include an index of mangrove ecosystem integrity. Although a mangrove specific IBI could still be considered a multi-dimensional biodiversity-based health indicator, it would require long-term cost-intensive studies to develop an extensive database of species abundance and diversity across different trophic levels.

The same driver-response model can be used to identify a list of possible mangrove variables that could reflect the ecosystem condition. These variables must be first identified and then prioritised. The identification/nomination process is based on (a) how mangrove trees and

ecosystems react to pressures based on a literature review of the variables that are potential health indicators (see Fig. 1); and (b) the biotic community, which is the primary approach in ecosystem assessment, e.g. IBI. Further testing will be required to ascertain whether and how these variables correlate to various levels of disturbance, which determines their suitability for incorporation into health indicators. These nominated indicators [from (a) and (b) above] will then be prioritised through collecting expert opinions (Andreasen *et al.*, 2001). This process results in a set of candidate health indicators ready to be tested in the field.

This combination of indicators will holistically reflect mangrove ecosystem condition rather than that of a terrestrial forest, or simply forest structure. The holistic approach will more likely assess ecosystem functioning and capacity for services. However, to avoid collecting data for every variable of interest, a mechanism is required to identify promising variables while keeping sampling effort reasonable. Expert opinions (Andreasen *et al.*, 2001) about these variables in relation to fundamental mangrove functional traits and services can provide this mechanism. The outcome will be a suite of candidate variables that reflects the health condition, to inform future management of these endangered ecosystems.

A large number of indicators are in use to assess vegetated wetlands and forests (e.g. Wilcox *et al.*, 2002; Layman *et al.*, 2010; Eyre *et al.*, 2015; Mackenzie *et al.*, 2016). However, an acceptable suite of indicators reflecting mangrove conditions is still missing. The primary aim of this paper is to propose and demonstrate a selection process for indicators of mangrove health in relation to the capacity for services. Barbour *et al.* (1995) and Andreasen *et al.* (2001) suggest the variables selected for an integrated multidimensional assessment method need to be: a) easy and fast to collect data; b) cost-effective; and c) sensitive to changes. This study firstly focuses on the third requirement by identifying a list of mangrove attributes that are sensitive to human and natural pressures (see Fig. 1). Variables

representing different trophic levels of the mangrove biotic community are also included (see Fig. 5), because of the prominence of biotic assemblages as proxies for ecosystem conditions.

A practical next step would be to collect information from knowledgeable scientists (Andreasen *et al.*, 2001), whose collective opinions will help prioritise the nominated variables. In addition, the pertinent time scale of reaction to pressures and the number of ecosystem services, including climate regulation, coastal defence, water purification, biodiversity preservation, fishery nurseries and socio-economy, are also relevant (Fig. 1B). The time scale refers to the time lag required for the indicator to reflect the impact caused by stressors. Unlike the structural indicators, some indicators would respond to stressors quickly, or could reflect conditions around tipping points where ecosystem functioning changes dramatically. Those indicators can be used in an early alarm system to trigger precautions to avoid future habitat loss. However, those that reflect long-term disturbances are also important as signs of a higher degree of impact where the changes have already been settled and, accordingly, more effort for rehabilitation is required.

The processes that support mangrove services generate their ecosystem value. Taylor *et al.* (1990) distinguished between functions and values - values are the goods and services that originate from functions. For example, mangroves can be sinks for nutrients arriving from agricultural and urban landscapes (Ewel *et al.*, 1998; Rivera-Monroy *et al.*, 1999). Ecosystem functioning such as microbial activities and nutrient up-take provide the service of water purification (Wong *et al.*, 1997). In mangrove assessment, accordingly, it would be more useful if the assessment factors not only represent ecosystem functioning but also reflect the probable number and the capacity for key services.

To improve mangrove management and conservation, the knowledge of how these ecosystems react to stressors is crucial. This study reports on an approach to identifying key

indicators for mangrove ecosystem condition. The outcomes will provide the essential input for a holistic mangrove assessment method following a multidimensional approach that integrates indicators of different nature (e.g. physiological, forest structure) and response time scales.

Fig. 1 A: simplified model of the driver-response process in an ecosystem. A pressure influence deviates the ecosystem from the expected natural condition. B: A flow-diagram illustrating the approach taken in this paper to identify candidate variables potentially reflecting the ecosystem condition. The best candidate variables are selected on an evidence-based process prioritised by mangrove experts in a purposely designed questionnaire.

2. Method

To propose a list of candidate variables and to select those most useful for inclusion as ecosystem health indicators, a three-step approach was developed : (1) an extensive review of

the literature for the variables that are most reported as reflecting an impact on mangrove health and their relation/links to stressors; (2) relevant variables were then cross-checked and compiled into a list that formed the basis for a questionnaire; (3) all variables were ranked by a cumulative score combining their relevance to services and expert rankings (see Eq. 1).

2.1. Step 1: variable nomination

Fifty-two peer-reviewed journal articles (see Fig. 2) on mangrove assessment in the realms of physiology, geochemistry and forest structure were selected from a large collection and then analysed to identify variables as potential health indicators. This analysis followed the conceptual model depicted in Fig. 1A to identify links between pressures and ecosystem responses. This concept was extended to identify interactions between pressures and responses (Fig. 1A) by highlighting in the literature ‘pressures’, ‘impacts’, and ‘variables’ (see Fig. 2 and 3).

This literature review provided a list of variables to be scored by experts (see Fig. 2 and 3). Indistinct or overlapping variables were removed or amalgamated to avoid overwhelming respondents with an excessively long questionnaire. For example, “local adaptation”, “less peat production” and “less sediment accretion” (reported in Fig. 2 and Fig. 3) were outcomes caused by natural or anthropogenic stressors; however, the terms were not considered as readily measurable health indicators (e.g. because of ambiguity in interpretation and difficulty of measurement). A final list of 42 variables was then established (see Fig.4) based on interactions detailed in Fig. 2 and 3. They included structural, physiological, physico-chemical and other non-species related parameters.

In addition, 26 variables concerning the biotic community were included. The food sources in mangrove ecosystems in combination with specific physical and environmental parameters influence the species assemblages (Lee, 2008; Reef *et al.*, 2010). Accordingly, a list of

common ‘species types’ living in mangrove areas from different trophic levels was sent to the experts who were asked to rank the significance of the resident species of mangrove forests in assessing the ecosystem condition (see Fig. 5). The nature of this animal assemblage may be used for evaluating mangrove condition.

2.2. Questionnaire survey

For the second step, we ran a questionnaire survey and invited experts in mangrove ecology or management to select those variables that are the most popular and useful. The questionnaire comprised all final variables identified in step 1, supplemented by an information booklet of information providing more specific details about individual variables (see Supplementary Information). The booklet served to reduce misinterpretation by respondents with expertise in different disciplines, research interests and backgrounds. Each respondent was asked to score variables (from 1 for the lowest to 10 for the highest preference) that are potentially influential in mangrove functioning (Sc value; see Eq. 1). The scores show how confident the experts were about the items. A second aim of this questionnaire was to ascertain how many services would be affected by the nominated variables (Ser value; see Eq. 1). It would reveal the extent to which a variable supports ecosystem services. For each variable, respondents were asked to select any of six key mangrove services, namely, climate regulation, coastal defence, water purification, supporting biodiversity, supporting fisheries, and socio-economic services to the coastal human communities.

Another key factor for variable selection is the lag time or time interval between changes in pressures and detectable changes in the indicator variable. Accordingly, the experts were also asked to indicate the time delay that they considered necessary for each item to respond to

stressors and ecosystem changes, in three categories, i.e. short-term (few days to one month), medium-term (few months to one year) and long-term (more than one year).

Responses were provided by 18 experts from different regions across the globe. The questionnaire was delivered directly (in hard copy) or through email (digital format). The participants were also contacted by phone call, Skype and in-person during conferences and/or meetings.

The final step involved calculating a cumulative score for each variable based on the average score (Sc value) and the average number of services (Ser value) affected. The algorithm for the score would avoid any unnecessary elimination/transformation. The mean values were standardized by their corresponding standard error (Eq. 1). This cumulative score (CS) was determined as:

$$\text{Cumulative Score (CS)} = \left(\frac{\overline{Ser}/Max_{Ser}}{SE_{Ser}} \right) + \left(\frac{\overline{Sc}/Max_{Sc}}{SE_{Sc}} \right) \quad \text{Equation 1}$$

Where $\overline{Ser}$ and $\overline{Sc}$ are the mean values of the number of services affected and the scores, respectively; and SE_{Sc} and SE_{Ser} are the standard error values of their corresponding means. SE is influenced by the standard deviation value (SD) and also the number of respondents to each item. The number of responses is important because it shows how much each item is known to the mangrove experts. A low value of SD and a high number of responses result in a low value of SE, reflecting a more useful item. Max_{Sc} and Max_{Ser} are the maximum values for the scores (i.e. 10) and the number of services (i.e. 6), respectively. Using these values, the range of data values for both Sc and Ser will be unified, otherwise the Sc weighs more than the Ser value. The CS value provides a unique value representing each item. The results from the questionnaire help assess the importance of variables and their linkages to

ecosystem services, informing the selection of variables that may be appropriate for mangrove ecosystem assessment.

The top variables (those achieving the highest CVs) were further evaluated based on the expected time lag for the indicator to reflect the impact caused by stressors. For each variable, the first most frequently allocated value (short, intermediate, or long time lags) was used if it was solely selected by $\geq 50\%$ of all respondents. For example, $> 50\%$ of respondents may opine that changes in “Nutrient and ion concentration in sediment” are detectable after an intermediate time period after a pressure (see Table 2). If not, the values of the first and second most frequent time lags (e.g. short and intermediate) were combined; then these two had to be selected by $>66\%$ (expected chance of selection from two out of three options) of the respondents. For example, $> 66\%$ of the respondents believe that “Spatial distance among trees” responds to pressures with intermediate or long lag times (see Table 2). Otherwise all three time lags were selected (χ^2 proportion test; using SPSS Ver. 22; $\alpha=0.05$).

3. Results

Figures 2 and 3 illustrate the linkages between influential stressors, their impacts and finally the response of mangrove ecosystems/trees. The target was also to present the known ecosystem responses to a/group of pressure presence in a simple linear process. For example, stressors such as ‘cutting and exploitation’ of mangroves, cause a set of impacts including higher water temperature, less shade (Granek & Ruttenberg, 2008; Ellis & Bell, 2013), higher erosion and lower sedimentation rate (Furukawa & Wolanski, 1996). These impacts in turn result in a combination of responses (measured by variables) that discriminate intact from

disturbed ecosystems, which in this case include changes in biodiversity (Cocheret de la Morinière *et al.*, 2004; Crona & Rönnbäck, 2005; Nagelkerken *et al.*, 2010), soil respiration rate (Lovelock, 2008) and also forest structure (Allen *et al.*, 2001; Blanco *et al.*, 2012; Urrego *et al.*, 2014) that contribute to ecosystem stability. Similarly, pressures such as ‘coal dust’ and ‘herbicides’ cause ecosystem responses such as reduced quality of canopy condition and lower potential quantum yield of photosystem-II (Naidoo & Chirkoot, 2004; Duke *et al.*, 2005b). Following the same approach, the set of nominated variables is listed on the right of each flowchart (Fig. 2 and 3).

For ease of interpretation, the overall survey results based on CS rankings were separated into quartiles and presented for all environmental variables (Fig. 4) and all community-related variables (Fig. 5). Both figures also show expert ratings about the lag period each variable would require to show a response to changes in ecosystem condition. Alcohol dehydrogenase levels in roots, leaf orientation (Fig. 4), primary producers and first order consumers (Fig. 5) are considered by experts as indicators responding rapidly to changes in pressures. On the contrary, spatial distance among trees, mutation rate (Fig. 4), dominant mangrove species, Importance Value Index (IVI) (Fig. 5) were considered as slow response indicators.

Fig. 2 A diagram of influential human pressures and their impacts on mangrove ecosystems. Potential indicators respond to the impacts and may be considered in the selection of health indicators for mangrove ecosystems. Numbers in square brackets are reference identifications (details provided below). Black triangles indicate the direction of change upon disturbance. Continued on the following page.

Fig. 2 continued. (¹Jimenez et al., 1985; ²Wolfe et al., 1988; ³Galloway et al., 1995; ⁴Ellison & Farnsworth, 1996; ⁵Furukawa & Wolanski, 1996; ⁶Mandura, 1997; ⁷Medina, 1999; ⁸Takemura et al., 2000; ⁹Allen et al., 2001; ¹⁰Tuffers et al., 2001; ¹¹MacFarlane et al., 2003; ¹²Cocheret de la Morinière et al., 2004; ¹³Diaz et al., 2004; ¹⁴Naidoo & Chirkoot, 2004; ¹⁵Verheyden et al., 2004; ¹⁶Crona & Rönnbäck, 2005; ¹⁷Defew et al., 2005; ¹⁸Duke et al., 2005b; ¹⁹Dorenbosch et al., 2007; ²⁰Abreu & Munné-Bosch, 2008; ²¹Di Nitto et al., 2008; ²²Gilman et al., 2008; ²³Granek & Ruttenberg, 2008; ²⁴Krauss et al., 2008; ²⁵Lovelock, 2008; ²⁶Sarkar et al., 2008; ²⁷Rahman et al., 2009; ²⁸Feller et al., 2010; ²⁹Nagelkerken et al., 2010; ³⁰Reef et al., 2010; ³¹Lewis et al., 2011; ³²Alongi et al., 2012; ³³Blanco et al., 2012; ³⁴Ellis & Bell, 2013; ³⁵Fauzi et al., 2013; ³⁶Pawar, 2013; ³⁷Wang et al., 2013; ³⁸Lee et al., 2014; ³⁹Proffitt & Travis, 2014; ⁴⁰Satpathy & Biswas, 2014; ⁴¹Sheaves et al., 2014; ⁴²Urrego et al., 2014; ⁴³Lewis et al., 2016)

Fig. 3 A diagram of influential natural pressures and their impacts on mangrove ecosystems. The potential indicators respond to the impacts and may be considered in the selection of health indicators for mangrove ecosystems. Numbers in square brackets are reference identifications.

(¹Jimenez et al., 1985; ²Lin & Sternberg, 1992; ³Ellison & Farnsworth, 1997; ⁴Medina, 1999; ⁵Holguin et al., 2001; ⁶Duke et al., 2005; ⁷Holguin et al., 2006; ⁸Menzel et al., 2006; ⁹Schwartz et al., 2006; ¹⁰Berger et al., 2008b; ¹¹Gilman et al., 2008; ¹²Krauss et al., 2008; ¹³Feller et al., 2010; ¹⁴Flores-de-Santiago et al., 2012; ¹⁵Proffitt & Travis, 2014; ¹⁶Urrego et al., 2014)

Expert opinions suggest that the variables characterizing sediment properties and forest structure are considered as the best candidates to develop an index of mangrove ecosystem health. Apart from soil respiration rates, these variables were mostly classified as reacting to pressure impacts over mid to long time periods. The structural variables, however, were clearly identified as indicators with extended time lags. This leading suite of variables is followed by those relevant to biomass, vegetation status and the carbon cycle. The variables representing individual tree body composition and physiology ranked lowest in the nomination list. They are also indicated as responding relatively rapidly to impacts (Fig. 4).

For the biotic community, the respondents were strongly interested not only in consumers but also groups of species that are positioned in higher trophic levels. The highest rank relates to crabs, followed by fish and other macrofauna at intermediate trophic levels (the second order of consumers; see Fig. 5). These taxa were noted to react to the impact pressures in the mid-term. In addition, roving fish were also considered useful, followed by benthic species. Species body size of fin fish/crabs was also important as health indicators in mangrove ecosystems. On the contrary, the mangrove-tree-related variables (e.g. IVI and dominant tree species), insects, annelids and moss were least important to the experts, which could also reflect the lack of research effort in these taxa. The results also revealed that primary producers and first-order consumers were considered as responding most rapidly to pressures (Fig. 5).

Fig. 4 Potential variables (health indicators) for evaluating mangrove ecosystem condition and health level. The list of items was summarised from the results of the literature review represented in Fig. 2 and 3. The time interval reflected by the variables (short/mid/long-term time integration) is also represented based on respondent opinions.

Each CS value represent both indices of score (right) and service (left); as expressed in Eq. 1 and also Fig. 4

Fig. 5 Community assemblage of mangrove ecosystems. Living creatures (potential health indicators), the status and also the assemblage type of which may be used for evaluating mangrove condition and health level are presented. The time interval reflected by them (short/mid/long-term time integration) is also represented based on respondent opinion. This graph continues from Fig. 4, and has the same scale and therefore score values are comparable.

4. Discussion

It is anticipated that a broadly stable relationship exists between environmental conditions and mangrove ecosystem properties under natural conditions and that mangrove ecosystems, under temporally stable conditions, may progress directionally over time. However, anthropogenic activities and other disturbances can disrupt these patterns (Lugo, 1980; Urrego *et al.*, 2014). Mangrove ecosystems may respond to stressors in multiple ways that may be indicated by variables potentially suitable as health indicators. Following this idea, Figs 2 and 3 relate multiple anthropogenic and environmental pressures with the initial responses of mangrove ecosystems, both as trees and habitats. This information provides a preliminary confirmation of the variables (listed on the right side of each flowchart) that change due to impacts caused by the pressures. This nomination process is the preliminary identification of the potential variables that can indicate changes in ecosystem condition.

4.1. From structural features to multi-dimensional suite of variables

The urgent need for mangrove condition assessment requires a comprehensive approach to assist decision-making in management. Unlike many mangrove assessment methods that concentrate on forest structural features, our focus was to look at mangrove ecosystems as a complex system influenced by a variety of components. These components in essence are an array of ecosystem elements that together create the mangrove system. Although the results still reflect the importance of attributes of forest structure, they were outweighed by the edaphic and sediment properties (Fig. 4). Forest structure variables also have long lag periods in reflecting ecosystem condition. The metrics reacting to ecosystem condition in short and intermediate time scales are applicable not only to young and or restored ecosystems, but also established mangrove ecosystems for revealing the effect of temporary/sudden pressures (Fig. 4 and 5).

333 Table 2. Appropriate candidate variables appointed in three time-frames of assessments.

The top %75 variables prioritised	Recent/transient pressures	Early alarming system	Permanent Pressures
A: Potential variables (see Fig. 4)			
Nutrient and ion concentration in sediment			
Nutrient gradient in sediment from land to sea			
Complexity at aerial root level			
Biological nitrogen fixing rate			
Soil sulphide			
Phosphate solubilization rate			
Spatial distance among trees			
Stem density			
Soil respiration rates			
DBH/Tree height ratio			
Number and height of pneumatophores			
Wood density (toughness)			
Mutation			
Transpiration rate			
BA (Basal area)			
Diameter size class distribution			
Root/shoot ratio			
Complexity in canopy level			
Tree fall			
Vessel thickness/density			
Leaf thickness			
LAI (Leaf area index)			
Height size class distribution			
$\delta^{18}O$ values			
Root/leaves ratio			
Growth abnormality			
Cation exchange capacity (CEC)			
Leaf longevity			
Leaf sclerophylly level			
Leaf orientations/heliotropism			
Foliar composition (C:N)			
Photosynthetic pigments in water or sediments			
B: Variables representing the community assemblage (see Fig. 5)			
3rd order consumers; Crabs			
Water column-oriented species (Roving)			
3rd order consumers; Nektonic predatory fish			
1st order consumer; Herbivorous fish			
4th order consumers; Omnivorous fish			
3rd order consumers; Demersal fish			
2nd order consumers; Macrofauna			
Benthic-oriented species (Benthic)			
3rd order consumers; Shrimps			
Diversity in animal (fin fish/crab) body size			
Primary producers; Phytoplankton			
1st order consumer; Gastropods			
2nd order consumers; Detritivorous fish			
5th order consumers; Birds			
1st order consumers; Zooplankton			
Primary producers; Algae			
1st order consumers; Meiofauna			
Number of alien species			

Those variables reflecting long and mid-term time intervals of pressure impact achieved higher CS values (Fig. 4). This is likely because of the experience of the experts of working typically on established and natural mangrove ecosystems. This pattern did not happen in the case of variables pertinent to the biotic community, where a variety of time intervals of effect has been reported (Fig. 5). The expert respondents had particular interest in the majority of biodiversity-related indicators. This reflects the dominant approach among the researchers, i.e. the consideration of biodiversity as important criteria for assessing mangrove ecosystem condition (Fig. 5). The results also suggest a potential way to select the best biodiversity-related indices from mangrove residents, with prominence of the living creatures such as crabs, fish and also macrofauna (but note potential bias in research effort) that cover higher trophic levels (Table 2B). Describing their appearance and assemblage is paramount to developing an Index of Biotic Integrity (IBI) specific to mangrove ecosystems.

It must be mentioned that expert opinions strongly reflect individual interests, their methodological knowledge and experience/expertise. The selection of appropriate variables out of the lists provided in Fig. 4 and 5 depends on the specific aims and even the background of the users, e.g. less experienced researchers may have more open or innovative opinions. To simplify in the current study, items located more on the upper half of the graphs (Fig. 4 and 5) are more valuable as health indicators for mangrove ecosystem assessment. However, the confidence level (represented by the score values (Sc); Fig. 4 and 5) declared by the experts should also be considered. Although mutation rate, for instance, achieved a high ranking, the value of confidence is low, which may again be a result of the lack of research effort. It seems that the experts were not confident whether this variable is a good health indicator. The time interval reflected by the items is debatable when it comes to metric selection. Mid-term time scale of reaction to the pressure impacts denotes that the variable is an appropriate candidate to be used as an early warning indicator. Soil respiration rate, for instance, is

represented as a fast indicator of ecosystem condition in comparison to the spatial distance among trees (Fig. 4). The latter item is more likely to reflect long-term impacts and, consequently, is impractical for assessing the effect of recent or transient pressures. The mid-term time of reaction qualifies the variables to be used in projects using current databases of land-use and human activities. The long-term variables may persist to reflect the continual presence of a pressure. These variables may indicate an old pressure influence while its source may have actually gone. However, the short-term variables fluctuate much; they react to ecosystem changes too fast and return to a normal condition if acclimation occurs. They can be used to test temporary human activities such as recent waste/chemical discharge into a watershed. More importantly, the limitation of time, resource, and available facilities may also influence the selection of appropriate and cost-effective variables. Overall, those represented at the top three quartiles of the *CS* values (see Table 2A) are appropriate candidates to be tested for a spectrum of ecosystem degradation in mangroves.

4.2. Approaches for future

The fish and crab assemblages associated with mangrove ecosystems occupy the highest rank (Fig. 5 and Table 2) in the selection process. These assemblages may be further categorized based on their biological characteristics including feeding behaviour, reproduction strategies and life history traits for further application in assessment and management. This approach has been considered for riverine systems (Aarts & Nienhuis, 2003; Noble *et al.*, 2007). Besides, edaphic factors, including nutrient characteristics, also interested the respondents as mid-term indicators. Human activities such as channelization, dam construction, dredging, or construction of dikes influence the edaphic conditions of mangrove ecosystems (Jimenez *et al.*, 1985; Mandura, 1997; Defew *et al.*, 2005). The interaction among mangrove tree

conditions, edaphic properties and the prevalence of human activities could be explored to develop an appropriate assessment method specific for mangrove ecosystems.

This paper is part of a long-term study leading to a framework for establishing an index of mangrove ecosystem integrity. The aim is to use biotic and abiotic indicators and other ecosystem elements of interest to managers and regulatory agencies to assess wetland conditions and to apply this approach to monitor ecosystem quality. This interest has prompted the development of the concept of ecological integrity (EI) (see Andreasen *et al.*, 2001). The concept emphasises that ecosystem assessment in an integrated approach is critical. As no index of mangrove ecosystem integrity currently exists, the outcomes of this study provide a platform on which other mangrove assessment methods can be built, for instance, to prompt other complementary projects leading to the development of health indicators that are specific to mangrove ecosystems. These indicators will pave the way to establishing an Index of Mangrove Ecosystem Integrity (IMEI) and a framework for its application.

The complex interaction of pressures and ecosystem response eventually provides the ecological services supported by mangrove ecosystems. We suggest using the information concluded from this study of the interactions to look for direct links between mangrove attributes and the degree of degradation and also anthropogenic stressors impacting on the ecosystems. The rationale is that the ecological condition of wetlands varies along a stress gradient and this is generally the basis of assessment methods. It is anticipated that the subsequent status of the ecological condition can be evaluated with the use of a set of field metrics (Sutula *et al.*, 2006). There is, thus, the need to estimate the candidate metric trajectory against the range of disturbance quantified as the degree of degradation for each data point (Wilcox *et al.*, 2002). Overall, metrics that reveal a strong response to rising disturbance are selected for incorporation into the IMEI. Establishing these links provides the

408 facility to prioritise areas for conservation as well as developing protocols for ecosystem
409 enhancement, management policies and conservation planning.

410

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