Ecological Complexity 38 (2019) 98–111

Contents lists available at ScienceDirect

Ecological Complexity

journal homepage: www.elsevier.com/locate/ecocom

Classification of key ecological attributes and stresses of biodiversity for ecosystem-based conservation assessments and management

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ARTICLE INFO

Keywords:
Classification
Conservation
Ecosystem functionality
Key ecological attributes
Resilience
Stresses

ABSTRACT

A whole systems thinking approach to conservation has spawned new approaches in adaptive management planning that require a crucial understanding of what is essential for the functionality of ecosystems and the biodiversity they embrace. In this context, the key ecological attributes (KEA) have been introduced as aspects of a conservation target's biology or ecology that, if missing or altered, would lead to the loss of that target over time. Ecological stresses describe the impaired status of KEAs. Whilst for threats, the drivers of stresses, a systematic classification has been suggested and adopted by IUCN, all existing proposals for stresses and KEAs are preliminary. In order to fill the gap and provide conservation analysts and practitioners with a standard terminology supporting adaptive management planning we suggest a first hierarchical framework and comprehensive classification of key ecological attributes and corresponding stresses to biodiversity. Analyzing 22 vulnerability assessments in 13 countries, spread across 5 continents, as well as an extensive literature review, we identified 144 specific KEAs and stresses. These are differentiated and classified according to three hierarchical levels, 11 KEA and stress classes and 42 general KEAs and stresses. Our classification may help with describing and understanding both the natural functionality and also impaired functioning of biodiversity targets, as well as assist with the development of appropriate conservation strategies. The classification of key ecological attributes is presented as a list but it is important to recognize that the diverse array of KEAs and stresses are systemically interrelated across scales.

1. Introduction

Twenty years of intense theoretical and empirical research have highlighted the dependence of humans on natural systems for their wellbeing (Daily 1997; MA 2005; Watson et al., 2005; Díaz et al., 2006; Balvanera et al., 2006; Cardinale et al., 2012; Bernstein 2014; Haines-Young and Potschin, 2015; Sandifer et al., 2015). But despite the scientific evidence and political ambition of the international community, the decline in global biodiversity and the degradation and destruction of natural systems continues (Barnosky et al., 2011; Butchart et al., 2010; Tittensor et al., 2014). The scale and depth of complexity of environmental problems has driven science, specifically ecology and conservation, towards ever greater levels of sophistication, including the use of big data and the harnessing of social media to communicate and search for potential solutions (Aronova et al., 2010; Hampton et al., 2013; Kelling et al., 2009; Lynch, 2008; Mishler et al., 2014). The extent to which environmental problems are now shared across the globe has set demands for access to metadata systems and platforms, and for standardized, automated formats to allow wider community access and participation (Costello, 2009; Ellison, 2010; Hampton et al., 2013).

Widely applied approaches to adaptive conservation management such as the Open Standards for the Practice of Conservation (OS) presented by the Conservation Measures Partnership (CMP, 2013), use both standard terminology and classification systems to describe and evaluate conditions and trends of conservation sites, which allows for deeper analyses to be communicated amongst interested parties, and for a more useful exchange of knowledge. The CMP also introduced standard terminology for the elaboration of systemic situation analyses: The viability of biodiversity targets, otherwise known as the conservation targets, is analyzed by identifying *key ecological attributes* (KEA) that describe the conditions required for existence and functioning (Salafsky et al., 2008). When these are impaired, the

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https://doi.org/10.1016/j.ecocom.2019.04.001
Received 15 June 2018; Received in revised form 28 February 2019; Accepted 30 April 2019
1476-945X/

conservation targets suffer from *stresses*, which are induced by threats. *Threats* are caused by so-called *contributing factors* (Salafsky et al., 2008; CMP, 2013).

The concept of KEAs and stresses is immersed in non-equilibrium ecology with particular reference to integrated ecosystem theory, complex systems theory and ecosystem thermodynamics (Jørgensen, 2011). Integrated ecosystem theory describes ecosystems as entities that are able to utilize the influx of solar radiation both to maintain their complex system far from thermodynamic equilibrium and to channel any additional free energy into growth and development that moves the system further away from thermodynamic equilibrium (Begon et al., 2005; Fath et al., 2004). During their growth and development, ecosystems increase their biomass, network, and information (Jørgensen, 2007). Despite their development with increasing levels of self-organization and regulation, ecological systems are far from being unidirectional or in steady state, and natural perturbations are vital to sustaining them. The adaptive cycle has been proposed as a conceptual framework to describe how ecosystems behave during such perturbations (Gunderson and Holling, 2002; Holling, 1986). In the course of an adaptive cycle, a system proceeds through phases of growth (r), conservation (K), release (Ω), and reorganization (α). Whilst the phases of growth, conservation and reorganization are in line with the forms of growth and development proposed by Jørgensen (2007), the release phase needs further explanation. Holling (1986) refers to the release phase as a creative process, which implies the breakup of current patterns could allow for new opportunities. Such events may result in the emergence of a new system with potentially greater growth and development (even though such an outcome is not guaranteed).

Ecological resilience describes the capacity of a system to absorb perturbations and reorganize while under change, so that the system remains within the same regime, maintaining essentially its structure, functions and feedbacks (Gunderson and Holling, 2002; Holling, 1973; Walker et al., 2006). Furthermore, it describes the degree to which the system is capable of self-organization, learning and adaptation (Gunderson and Holling, 2002; Walker et al., 2002). Ecological systems rarely operate in isolation, hence, the resilience of a system at a particular focal scale will depend on the influences from states and dynamics at scales above and below (Berkes, 2002; Young, 2006).

At a global scale, human activities have increased the perturbations and reduced the resilience of the ecosystems by removing vital elements (species, functional groups or even entire trophic levels) or modifying the parameters of soils, water and air (Halpern et al., 2008; Steffen et al., 2004). The combined and often synergistic effects of those perturbations made ecosystems more vulnerable to changes that previously could have been absorbed (MacDougall et al., 2013; Oliver et al., 2015). Therefore, many ecosystems have shifted towards less favorable regimes, impairing their integrity and behavior, as well as their capacity to provide ecosystem services (Allen et al., 2014; Folke et al., 2004; Hughes et al., 2013). This has stimulated a debate about the health of ecosystems and the way their status could be assessed or not (Belaoussoff and Kevan, 2003; Callicott, 1995; Constanza and Mageau, 1999; Rapport, 2016, 1998).

While the debate continues, the focus of conservation and natural resource management has moved away from traditional approaches concentrated on specific species towards the maintenance of the functionality of natural system and the services they provide (Cardinale et al., 2012; Díaz et al., 2006; Harrison et al., 2014; Naeem et al., 2012; Poiani et al., 2000). Given the complexity of most natural systems, it might be rather difficult to estimate the functionality of a specific system. Perturbations can occur at diverse levels reaching from individual killing of an animal, which further affects the species population, the ecological community and so on, to the conversion of a complete ecosystem (e.g. conversion of a forest to agricultural fields). Therefore, it might be more practicable to assess the integrity of a given system by analyzing the absence or accumulation of perturbations.

There have been several efforts to develop classification schemes for threats and stresses (Salafsky et al., 2002; CMP, 2005; IUCN, 2005a,b), until Salafsky et al. (2008) proposed a general classification of direct threats to biological diversity that brought together earlier classification efforts by the CMP and the International Union for Conservation of Nature (IUCN). Salafsky and his co-authors also provided a first general and unspecified classification system for stresses. However, after applying their classification system to various case studies (Ibisch and Hobson, 2015; Schick et al., 2017), we found the potential of the 2 classes and 6 subclasses proposed by the classification system to be too coarse and limited to describe the complexity of changes in the KEAs induced by stresses. Another, more specific classification of stresses in biological and ecological systems exclusively refers to those induced by problems relating to climate change (Geyer et al., 2011). In order to fill the gap and provide conservation analysts and practitioners with a standard terminology and approach to identifying stresses, we propose a first comprehensive classification system that is grounded in modern ecosystem theory.

2. Methods

A conceptual model of KEAs and corresponding stresses of biodiversity targets was developed by reviewing the outcomes of 22 conservation-planning processes that were conducted in 13 countries in Africa, Asia, Europe and Latin America by applying the MARISCO method (Ibisch and Hobson, 2014, Appendix S1). MARISCO is an adaptive management approach that aims to provide a mistake-friendly method that encourages systematic learning from errors in order to build more effective, resilient and risk-robust management systems. The MARISCO method is based on the Open Standards for the Practice of Conservation of the Conservation Measures Partnership (CMP, 2013), but places greater emphasis on system dynamics and change, with a particular focus on the effects and problems relating to climate change. MARISCO encourages conservationists to address uncertainty and unknowns when planning for adaptive management, and facilitates the development of ecosystem-based solutions, as called for by the Convention on Biological Diversity (Salvaterra et al., 2016; Secretariat of the Convention on Biological Diversity, 2004). Like the Open Standards, the MARISCO method uses the concept of biodiversity targets to describe the ecological systems of conservation sites. Biodiversity targets can include a variety of ecological scales, ranging from a single species to whole ecosystems and landscapes. For each biodiversity target KEAs were identified by the participants of the 22 conservation-planning processes, which were defined as integral elements and properties of biological targets, based on the best biological and ecological knowledge available. Any variation of a KEA that would ultimately lead to the degradation or loss of the biological target was considered a stress (for a detailed description of the working process please consult the MARISCO manual). The participatory assessments covered a broad variety of ecosystems and their outcomes were used for the development of the first conceptual model of KEA and stresses. At the beginning, all identified KEAs and stresses were collected and structured according to their domains. The domains were grouped into categories and complemented to cover also ecosystem types that had not been addressed during the participatory assessments.

After the first model was completed, a literature review on KEAs and direct as well as indirect stresses in biodiversity targets was carried out to further complement the classification. This led to the development of a comprehensive list of references for all the specific KEAs and stresses we identified (Appendix S2).

The resulting conceptual model was then discussed with scientists and conservation experts of our working group. After the revision and complementation of the conceptual model, we tested the comprehensiveness of the classification system by comparing it to existing classification systems, such as the unified classification of the International

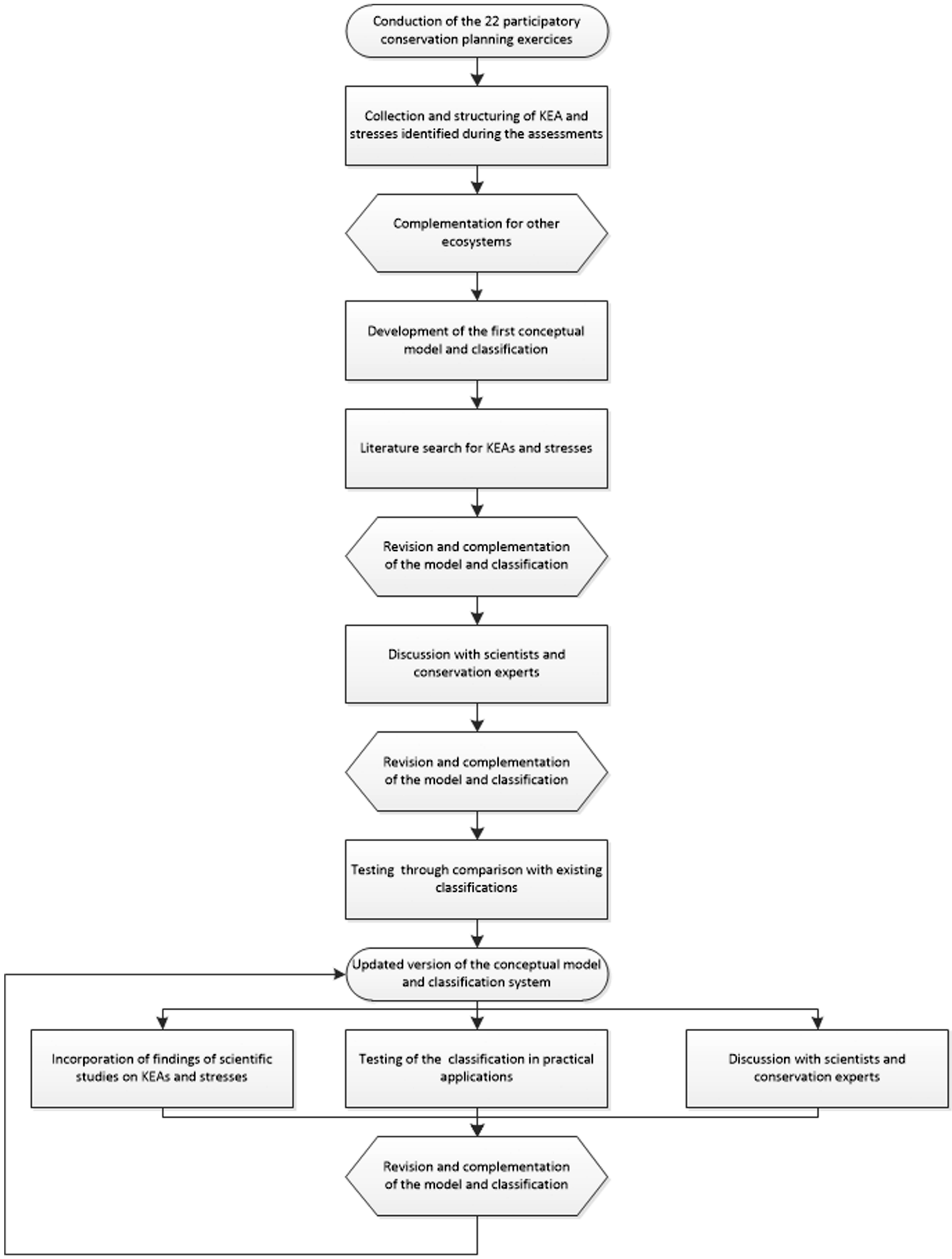

Fig. 1. A diagram depicting the working process of the development of the conceptual model and classification system of KEAs and stresses. A cyclical process is envisioned for future revisions and complementation leading to an ever-improving conceptual model and classification system.

Union for Conservation of Nature and the Conservation Measures Partnership (IUCN−CMP), the United States Environmental Protection Agency (EPA), National Park System (NPS), or the Nature Conservancy (TNC), in order to test its overall coherence (Noss, 1990 (EPA); Young and Sanzone, 2002 (EPA); McElhinny et al., 2005; TNC, 2006; Salafsky et al., 2008 (IUCN−CMP); Unnasch et al., 2008 (NPS) Timpane-Padgham et al., 2017). The testing was executed by analyzing if the KEAs of each classification systems could be assigned to the categories of our new classification, which proved to be feasible without exception. The whole working process of the development of the classification system (including future steps) is depicted in Fig. 1.

Following previous work by Salafsky et al. (2008) and Geyer et al. (2011), in our classification system we adopted the procedure both studies took of using 3 hierarchical levels for the development of categories to assign the identified KEAs and stresses. The hierarchical levels were ordered from coarse to fine resolution, for example for stresses: stress class (thematic grouping with the coarsest resolution), general stress (thematic group of specific stresses), and specific stress (most detailed definition of a stress).

3. Results

Key Ecological Attributes are classified into 11 classes, 42 general and 144 specific attributes (Table 1). The classification of stresses mirrors the corresponding KEAs.

A schematic diagram in the form of concentric circles was produced to best represent both functional and hierarchical levels of the KEAs (Fig. 2). Although the categories are presented as distinct circles, they are deeply interrelated. The hierarchical order of the classes reflects the scale at which they function. For instance, in the outermost shell of the circle, the attributes operate at global scale, such as the global **energy input** (1.), the **atmosphere** (2.), **hydrosphere** (3.) and **lithosphere** (4.). **Matter cycles** (5.) are located in the next shell in and represent the interface between the abiotic components of the outer layers and the biotic components closer to the core of the circle. As proposed by Jørgensen et al. (2007), the biotic components are divided into three distinct groups, **biomass** (6.), **information** (7.) and **network** (8.). Always conscious of the complex interconnectedness within ecosystems, but also aware of the need to provide a simple interpretation of the situation, the KEAs were presented in distinct classes. At a smaller scale, **species-specific** (9.) KEAs were identified. These attributes include components that relate to individuals, or populations, as well as components that refer to habitat components that are relevant for specific species. Ultimately, the so-called *emergent key ecological attributes* are situated in the core of the circle. These include all attributes that are related to the **energy, matter and water efficiency** in the ecosystem (10.), and/or the **resilience** and **resistance** (11.). Emergent KEAs are derived from the complex interactions of other KEAs.

The classifications for both the KEAs and environmental stresses are designed to be comprehensive, consistent, and exclusive. For example, the stress class: '*changed energy input'* (1.), includes the general stress: '*changed solar radiation'* (1.1), which can be further divided into the specific stresses: '*Reduced energy input through solar radiation due to increase in shading or filtering elements and surface albedo (*e.g. *solid pollutants, sediments, cloud or vegetation cover)'* (1.1.1) and '*Increased energy input of solar radiation due to reduction of filtering or shading elements and surface albedo (*e.g. *filtration of sediments, logging of riverine forests, decrease of snow cover)'* (1.1.2).

4. Discussion

The classification system for KEAs and stresses presented in this paper is designed to assist conservation practitioners in the assessment and evaluation of environmental conditions prior to planning and implementation of strategies. The linear and hierarchical structuring and formulation of the classification system does not pretend to represent the deep complexity inherent in natural ecosystems, but has been chosen to increase the ease of use. In this way, it is designed to provide a baseline reference and it is up to the practitioners to interpret and apply the system to fit the nature of the ecosystems under consideration. The negative influences of stresses can reach beyond the directly targeted KEA and can have effects on other (sub)systems. Therefore, we would like to encourage all users of the classification systems to think of the possible interactions that the KEAs and stresses might have within the analyzed ecological system, including those across scale breaks.

There is a generally accepted view amongst scientists that scale is fundamental in the structuring and function of biological systems and that hierarchical organization in nature is attributed to scale dependency (Allen and Starr, 1982). It makes logical sense to devise the classification system for KEAs and stresses with hierarchical organization in mind, which is why they are presented schematically as a circle with shells (Fig. 2). Each organizational level represents a system made of smaller and interacting subsystems and is itself a component of a the larger system, they are all holons (Köstler 1969; Allen and Starr, 1982; Ahl and Allen, 1996). The implication to conservation planning of natural hierarchical organization and systems complexity is that both vertical and horizontal connections and interactions should be considered during the analysis (Jørgensen and Fath, 2004; Jørgensen and Nielsen, 2015).

Hierarchical organization in nature, including cascade effects and feedback loops between meta-systems has been researched in various studies (Burcher et al., 2007; Harley et al., 2006; Steffen et al., 2004). For instance, the *loss of specific plant species* (7.2.1) can lead to a *loss of net photosynthesis* (6.1.1), if the plant species are not replaced with equally productive substitutes, which can further cause the *loss of biomass of the system* (6.2; 6.3). Such changes can trigger shifts in several other characteristics of the systems, including the *organic matter of soils* (4.2.2), which will ultimately alter the *soil structure and composition* (4.1.3). With changes in soil conditions, the *capacity of the system to store water and nutrients* will be affected (4.2.1; 4.1.5). Consequently, *matter cycling process* (5.1–5.5), as well as the *hydrological regime* (3.3) will deteriorate, which will finally lead to an impaired behavior of the system or even its collapse. It is important to note that the effects of environmental change, such as global climate change, will be expressed in different ways at different levels of organization (Noss, 1990). Furthermore, the impact of a specific stress within the system is also depended on the interactions with other stresses and the environmental conditions, in which it is expressed. Stresses are context-dependent. For example, the impact of heat on plants will interact with drought, both producing synergistically acting stresses especially at sites with sandy soils (Rezaei et al., 2018).

The influences of KEAs and stresses have the potential to affect other elements both on smaller and larger scales. Such linkages across scale breaks impact the overall dynamics of the system, often generating nonlinearities and time-lapse responses, which make it even more difficult to predict the behavior of the analyzed system. Therefore, we would recommend the development of a systemic conceptual model depicting (potential or hypothetical) interactions between stresses when applying the classification to a situation analysis. Such a visualization can help to identify existing cause-effect relationships between KEAs and stresses. However, it is unlikely that all these relationships will be identified in the first analysis, as complex dynamic systems are subject to a large number of uncertainties. The goal of such an exercise is not to capture all probable results of the dynamic systems, but to represent the complexity on a superficial level. Cyclical, adaptive management approaches, such as the Open Standards or the MARISCO method, can help to respond to nonlinearities by acknowledging uncertainties and examining the responses of the systems as a whole rather than a sum of its parts. In this way, practitioners can be enabled to deal robustly with uncertainties without having to try to validate empirically the level or extent of uncertainties.

Although our classification is in line with other published systems, there are clear differences. For instance, the unified IUCN−CMP stress classification and the one presented here differ in the way the stresses were derived. The unified IUCN−CMP classification defines a stress as "*an impaired attribute of a conservation target's ecology that results directly or indirectly from human activities*" (Salafsky et al., 2008). The proximate human activities or processes that are the cause of this impairment are the direct threats, which are synonymous with sources of stress and proximate pressures. Natural phenomena are also regarded as direct threats in some situations, yet the classification proposed by Salafsky et al. (2008) is focused on human activities. Consequently, their stress categories were defined by their sources of origin, namely the threats. In contrast, the categories of the stress classification presented in our study were derived from the KEAs they affect, placing more emphasis on system functioning and on the result rather than the source.

There are other conceptual differences between the model offered here and the schemes in current use that reflect a more considered understanding of ecosystem structure and function. For example, the degradation of ecosystems and deforestation are not considered to be stresses in their own right but are part of group of stresses related to the

Table 1
Key ecological attribute and stress classes, general key ecological attributes and stresses, and specific key ecological attributes and stresses. A list of references for each item is provided in Appendix S2.

Key ecological attribute	Stress	Literature references
1. Energy input	1. Changed energy input	
1.1 Solar radiation	1.1 Changed solar radiation	
1.1.1 Energy input through solar radiation	1.1.1 Reduced energy input through solar radiation due to increase in shading or filtering elements and surface albedo (e.g. solid pollutants, sediments, cloud or vegetation cover)	(Fabricius, 2005; Graham et al., 2003; Huang et al., 2016; Pyrina et al., 2015; Qian et al., 2007; Raga et al., 2001; Yentsch et al., 2002; Zou et al., 2007)
1.1.2 Reduction of energy input of solar radiation through filtering or shading elements and surface albedo (e.g. sediments, cloud or vegetation cover)	1.1.2 Increased energy input of solar radiation due to reduction of filtering or shading elements and surface albedo (e.g. filtration of sediments, logging of riverine forests, decrease of snow cover)	(Koren et al., 2004; Zhang and Walsh, 2006)
1.2 Heat flow (turbulent and latent heat flows)	1.2 Changed heat flow	
1.2.1 Energy input through oceanic circulation	1.2.1 Changed energy input due to change of oceanic circulation	(Robson et al., 2016; Rudels, 2016)
1.2.2 Energy input of atmospheric circulation and wind patterns	1.2.2 Changed energy input due to change of atmospheric circulation and wind patterns	(Ganachaud and Wunsch, 2000; Rudels, 2016)
1.2.3 Geothermal input (e.g. hot springs, geysers, fumaroles, hydrothermal vents)	1.2.3 Changed geothermal input (e.g. hot springs, geysers, fumaroles, hydrothermal vents)	(Adcroft et al., 2001; Caracausi et al., 2005; Coykendall et al., 2011; Haymon et al., 1993)
1.2.4 Energy input through evaporation	1.2.4 Changed energy input due to change of evaporation	(Boisvert et al., 2015; Faizal and Rafiuddin Ahmed, 2011)
1.2.5 Anthropogenic energy input (e.g. urban heat islands, power plant discharges)	1.2.5 Changed anthropogenic energy input (e.g. urban heat islands, power plant discharges)	(Block et al., 2004; Kirillin et al., 2013)
1.3 Other energy inputs	1.3 Changed other energy inputs	
1.3.1 Mechanical input of wind on water surfaces	1.3.1 Changed energy input due to change of atmospheric circulation and wind patterns (mechanical energy input)	(Byrne et al., 2016; Rudels, 2016)
1.3.2 Energy input through lightning	1.3.2 Changed energy input due to changed lightning frequency	(Krawchuk et al., 2009; Romps et al., 2014)
2. Atmosphere	2. Changes in the atmosphere	
2.1 Air quality	2.1 Changed air quality	
2.1.1 Quantity and quality of solid pollutants and particles (e.g. dust, ash, heavy metals)	2.1.1 Changed air quality due to changed quantity and quality of solid pollutants and particles (e.g. dust, ash, heavy metals)	(Raga et al. 2001; Dagsson-Waldhauserova et al. 2016; Huang et al. 2016; Li et al. 2016)
2.1.2 Quantity and quality of gaseous pollutants (e.g. carbon dioxide (CO_2), methane (CH_4), ozone (O_3), sulphur oxides, nitrogen oxides, volatile organic compounds)	2.1.2 Changed air quality due to changed quantity and quality of gaseous pollutants (e.g. carbon dioxide (CO_2), methane (CH_4), ozone (O_3), sulphur oxides, nitrogen oxides, volatile organic compounds)	(Guo et al., 2017; Pedroso et al., 2016; Qian et al., 2007; Raga et al., 2001)
2.2 Global climate conditions	2.2 Changed global climate conditions	
2.2.1 Global annual average temperatures and temperature variability	2.2.1 Changed global annual average temperatures and temperature variability	(Root et al., 2005; Walther et al., 2007; Welbergen et al., 2008)
2.2.2 Global annual average humidity, humidity variability and cloud cover	2.2.2 Changed global annual average humidity, humidity variability and cloud cover	(Croke et al. 1999; Pounds et al. 1999; Sperling et al. 2004; Zhu et al. 2007; Tejeda-Martinez et al. 2008; Uhlmann et al. 2009)
2.2.3 Global wind and pressure patterns	2.2.3 Changed global wind and pressure patterns	(Goldenberg, 2001; McInnes et al., 2005; Reichler, 2016)
2.2.4 Global precipitation patterns (e.g. amount, distribution, form)	2.2.4 Changed global precipitation patterns (e.g. amount, distribution, form)	(Burlando and Rosso, 2002a; Fowler and Kilsby, 2003; Shongwe et al., 2011)
2.2.5 Interannual and long-term global climatic variability	2.2.5 Changed interannual and long-term global climatic variability	(Schär et al., 2004; Timmerman et al., 1999; van Oldenborgh, 2007)
2.3 Weather and local climate conditions	2.3 Changed weather and local climate conditions	
2.3.1 Local annual average temperatures and temperature variability	2.3.1 Changed local annual average temperatures and temperature variability	(Pingale et al., 2014; Ruiz et al., 2012; Scherrer et al., 2016)
2.3.2 Frequency, intensity or length of events of extreme temperature	2.3.2 Changed frequency, intensity or length of events of extreme temperature	(Easterling et al., 2000; Parmesan et al., 2000; Schär et al., 2004)
2.3.3 Local annual average humidity, humidity variability and cloud cover	2.3.3 Changed local annual average humidity, humidity variability and cloud cover	(Parding et al., 2016; Ruiz et al., 2012; Vourlitis et al., 2015)
2.3.4 Local wind and pressure patterns	2.3.4 Changed local wind and pressure patterns	(Balaguru et al., 2016; Garza et al., 2012; Rollenbeck et al., 2015; Wu et al., 2014)
2.3.5 Frequency, intensity or length of events of extreme winds	2.3.5 Changed frequency, intensity or length of events of extreme winds	(Goldenberg, 2001; Mei and Xie, 2016)
2.3.6 Local precipitation patterns (e.g. amount, distribution, form)	2.3.6 Changed local precipitation patterns (e.g. amount, distribution, form)	(Pingale et al., 2014; Ruiz et al., 2012; Scherrer et al., 2016)
2.3.7 Frequency, intensity or length of events of extreme precipitation	2.3.7 Changed frequency, intensity or length of events of extreme precipitation	(Easterling et al., 2000; Parmesan et al., 2000)
2.3.8 Interannual and long-term local climatic variability	2.3.8 Changed interannual and long-term local climatic variability	(Alemayehu and Bewket, 2016; Gichangi et al., 2015)
3. Hydrosphere	3. Changes in the hydrosphere	
3.1 Physical water characteristics	3.1 Changed physical water characteristics	
3.1.1 Water temperature	3.1.1 Changed water temperature	(Barnett, 2001; Beaugrand, 2002; Levitus et al., 2005; Magnuson et al., 1997; Mooij et al., 2008; Sharma et al., 2007)

(*continued on next page*)

Table 1 (*continued*)

Key ecological attribute	Stress	Literature references
3.1.2 Water turbidity	3.1.2 Changed water turbidity	(Alongi and McKinnon, 2005; Fabricius, 2005)
3.1.3 Total dissolved solids (TDS)	3.1.3 Changed total dissolved solids (TDS)	(Doxaran et al., 2015; Fantin-Cruz et al., 2016; Ndam Ngoupayou et al., 2016)
3.1.4 Electrical conductivity	3.1.4 Changed electrical conductivity	(Chang et al., 2018; Fantin-Cruz et al., 2016; Santos et al., 2016)
3.1.5 Transparency	3.1.5 Changed transparency	(Gois et al., 2015; Santos et al., 2016)
3.1.6 Other physical water characteristics (e.g. color, odor, taste, density, redox potential)	3.1.6 Other changed physical water characteristics	(Caesar et al., 2018; Ito et al., 2016; Sado-Inamura and Fukushi, 2018; Su et al., 2017; Tóth, 2016)
3.2 Water chemistry	3.2 Changed water chemistry	
3.2.1 pH	3.2.1 Changed pH	(Yan et al. 1996; Alongi & McKinnon 2005; Fabricius 2005; Gibson et al. 2005; Harley et al. 2006; Portner & Knust 2007; Turley & Findlay 2016)
3.2.2 Quantity and quality of dissolved gases (e.g. oxygen (O_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4))	3.2.2 Changed quantity and quality of dissolved gases (e.g. oxygen (O_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4))	(Albright et al., 2016; Alshboul et al., 2016; Carrera et al., 2016; Piontkovski and Queste, 2016; Sado-Inamura and Fukushi, 2018; Santos et al., 2016)
3.2.3 Water salinity (Quantity and quality of main ions, e.g. bicarbonate (HCO_3^-), carbonate (CO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}))	3.2.3 Changed water salinity (Changed quantity and quality of main ions, e.g. bicarbonate (HCO_3^-), carbonate (CO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}))	(Bern et al., 2015; Chang et al., 2018; Jeziorski and Smol, 2017; Piontkovski and Queste, 2016; Qishlaqi et al., 2016; Qu et al., 2015)
3.2.4 Quantity and quality of biogenic elements (e.g. nitrogen (N), phosphor (P), silicon (Si), iron (Fe))	3.2.4 Changed quantity and quality of biogenic elements (e.g. nitrogen (N), phosphor (P), silicon (Si), iron (Fe))	(Chang et al., 2018; Fantin-Cruz et al., 2016; Kumar et al., 2017; Maavara et al., 2015; Piontkovski and Queste, 2016)
3.2.5 Quantity and quality of organic compounds (e.g. organic carbon, amino acids, proteins, oils)	3.2.5 Changed quantity and quality of organic compounds (e.g. organic carbon, amino acids, proteins, oils)	(Doxaran et al., 2015; Ndam Ngoupayou et al., 2016; Piontkovski and Queste, 2016; Santos et al., 2016)
3.2.6 Quantity and quality of microelements, toxic inorganic substances, heavy metals and pollutants (e.g. cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), zinc (Zn))	3.2.6 Changed quantity and quality of microelements, toxic inorganic substances, heavy metals and pollutants (e.g. cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), zinc (Zn))	(Akele et al., 2016; Elkady et al., 2015; Ito et al., 2016)
3.3 Hydrologic regimes	3.3 Changed hydrologic regimes	
3.3.1 Water levels	3.3.1 Permanent change of water levels	(Gehrels, 2016; Lofgren et al., 2002; Magnuson et al., 1997; Nicholls et al., 2016; Schwartz et al., 2004)
3.3.2 Water-level variability in wetlands (including extreme lows)	3.3.2 Changed water-level variability in wetlands (including extreme lows)	(Jöhnk et al., 2004; Kebede et al., 2006; Pasquini et al., 2008)
3.3.3 Groundwater flows	3.3.3 Changed groundwater flows	(Eckhardt and Ulbrich, 2003; Herrera-Pantoja and Hiscock, 2008; Nasta et al., 2016)
3.3.4 Flood occurrence, frequency, intensity, and area flooded (including hydroperiod)	3.3.4 Changed flood occurrence, frequency, intensity, and area flooded (including hydroperiod)	(Allamano et al., 2009; Cunderlik and Simonovic, 2005; Dankers and Feyen, 2008; Fowler and Kilsby, 2003; Jones, 2008; Knowles and Cayan, 2002; Wilby et al., 2008)
3.3.5 Runoff and flow of water (e.g. amount, speed of runoff)	3.3.5 Changed runoff and flow of water (e.g. amount, speed of runoff)	(Barnett et al., 2005; Burlando and Rosso, 2002b; Gibson et al., 2005)
3.3.6 Evaporation	3.3.6 Changed evaporation	(Li and Mölders, 2008; Mei and Xie, 2016)
3.3.7 Currents and upwelling	3.3.7 Changed currents and upwelling	(Bakun and Weeks, 2004; Kanzow et al., 2016; McGregor et al., 2007; Schmittner, 2005)
3.3.8 Wave and spray patterns	3.3.8 Changed wave and spray patterns	(Gulev, 2004; Vikebø et al., 2003)
3.4 Snow/ice regimes	3.4 Changed snow/ice regimes	
3.4.1 Snow pack	3.4.1 Changed snow pack	(Barnett et al., 2005; Beniston et al., 2003; Stewart, 2009; Wipf et al., 2009)
3.4.2 Snow loads	3.4.2 Changed snow loads	(Laternser and Schneebeli, 2003; Wipf et al., 2009)
3.4.3 Snow cover period	3.4.3 Changed snow cover period	(Barnett, 2001; Beniston et al., 2003; Laternser and Schneebeli, 2003; Wipf et al., 2009)
3.4.4 Thickness of permanent ice sheets, melting of glaciers and permanent snow cover	3.4.4 Changed thickness of permanent ice sheets, melting of glaciers and permanent snow cover	(Bamber, 2016; Haeberli and Hohmann, 2008; Qu et al., 2014; Schroeder, 2016; Singh and Bengtsson, 2004; Wadhams, 2016)
3.4.5 Duration and thickness of seasonal ice sheets and freezing of water bodies	3.4.5 Changed duration and thickness of seasonal ice sheets and freezing of water bodies	(Bamber, 2016; Beltaos and Prowse, 2009)
3.4.6 Melting of permafrost soils	3.4.6 Increased or decreased melting of permafrost soils	(Haeberli and Hohmann, 2008; McGuire et al., 2009)
4. Lithosphere	4. Changes in the lithosphere	
4.1 Physical soil parameters	4.1 Changed physical soil characteristics	

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Table 1 (*continued*)

Key ecological attribute	Stress	Literature references
4.1.1 Soil temperature	4.1.1 Changed soil temperature	(Hirota et al., 2006; Mellander et al., 2007; Ooi et al., 2009; Zhang et al., 2004)
4.1.2 Soil moisture	4.1.2 Changed soil moisture	(Holsten et al., 2009; Huszar et al., 1999; Jasper et al., 2006)
4.1.3 Soil structure	4.1.3 Changed soil structure	(Capra, 2006; Jungerius, 2008)
4.1.4 Slope (e.g. aspect, steepness)	4.1.4 Changed slope (e.g. aspect, steepness)	(Nyssen and Vermeersch, 2010; Wickham et al., 2013)
4.1.5 Soil texture, particle size distribution patterns, aggregation, density, drainage, and water-holding capacity	4.1.5 Changed soil texture, particle size distribution patterns, aggregation, density, drainage, and water-holding capacity	(Garcia-Fayos and Bochet, 2009; Kooistra and Tovey, 1994)
4.1.6 Floor structure of aquatic systems (e.g. rivers, lakes, oceans)	4.1.6 Changed floor structure of aquatic systems (e.g. rivers, lakes, oceans)	(de Jong et al., 2014; Jia et al., 2007; Knaapen and Hulscher, 2002; Yuill et al., 2016)
4.1.7 Coastline morphology (e.g. due to sea level rise, fluctuation and costal impact)	4.1.7 Changed coastline morphology (e.g. due to sea level rise, fluctuation and costal impact)	(Galbraith et al., 2002; Gehrels, 2016; Nicholls et al., 2016)
4.1.8 Channel morphology (e.g. sinuosity, thread)	4.1.8 Changed channel morphology (e.g. sinuosity, thread)	(Gilvear et al., 1995; Jaffe et al., 2007; Jia et al., 2007; Magliulo et al., 2013; Yuill et al., 2016)
4.1.9 Erosion, transport and deposition of sediments	4.1.9 Changed erosion, transport and deposition of sediments	(Jaffe et al., 2007; Macklin and Lewin, 1989)
4.2 Chemical soil characteristics	4.2 Changed chemical soil characteristics	
4.2.1 Chemical soil characteristics (e.g. pH, salinity, cation exchange capacity)	4.2.1 Changed chemical soil characteristics (e.g. pH, salinity, cation exchange capacity)	(Keller et al., 2004; Schofield and Kirkby, 2003; Verburg, 2005)
4.2.2 Organic matter and macronutrient concentrations (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulphur (S), magnesium (Mg))	4.2.2 Changed organic matter and macronutrient concentrations (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulphur (S), magnesium (Mg))	(Dominy et al., 2002; Matos-Moreira et al., 2011; Rowe et al., 2012)
4.2.3 Micronutrients/trace inorganic chemicals concentrations (boron (B), chlorine (Cl), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo), nickel (Ni))	4.2.3 Changed micronutrients/trace inorganic chemicals concentrations (boron (B), chlorine (Cl), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo), nickel (Ni))	(Baldantoni et al., 2010; Mather et al., 2012)
4.2.4 Availability of other elements and substances (e.g. heavy metals, xenobiotic substances such as pesticides, PCB, dioxins)	4.2.4 Changed availability of other elements and substances (e.g. heavy metals, xenobiotic substances such as pesticides, PCB, dioxins)	(Burek et al., 2008; Lynch and St.Clair, 2004; Natali et al., 2008)
4.3 Geomorphological processes	4.3 Changed geomorphological processes	
4.3.1 Physical weathering processes (e.g. due to changes in temperature extremes, winds)	4.3.1 Changed physical weathering processes (e.g. due to changes in temperature extremes, winds)	(Akselsson et al., 2016; Mavris et al., 2015)
4.3.2 Chemical weathering processes	4.3.2 Changed chemical weathering processes	(Mavris et al., 2015; McCabe et al., 2013)
4.3.3 Tectonic and volcanic processes	4.3.3 Changed tectonic and volcanic processes	(Huybers and Langmuir, 2009; McGuire et al., 1997)
4.3.4 Surface movements (e.g. avalanches, erosion, landslides)	4.3.4 Changed surface movements (e.g. avalanches, erosion, landslides)	(Jakob and Lambert, 2009; Nearing et al., 2004; Wei et al., 2009)
5. Matter cycle-related processes	5. Changed matter cycle-related processes	
5.1 Oxygen cycle	5.1 Changed oxygen cycle	
5.1.1 Oxygen reservoirs and fluxes (e.g. oxygen concentrations, solubility)	5.1.1 Changed oxygen reservoirs and fluxes (e.g. changes in oxygen concentrations, solubility)	(Beaty-Sykes, 2014; Bianucci and Denman, 2012)
5.2. Carbon cycle	5.2 Changed carbon cycle	
5.2.1 Carbon reservoirs and fluxes (including the processes of ocean soaking, photosynthesis and carbonate formation)	5.2.1 Changed carbon reservoirs and fluxes (e.g. changes in emissions (e.g. due to changes in respiration, combustion and decomposition rates) and sequestration (e.g. assimilation during photosynthesis)	(Bianucci and Denman, 2012; Chapin III et al., 2009; Falloon et al., 2007; Lu and Cheng, 2009; McGuire et al., 2009)
5.3 Nitrogen cycle	5.3 Changed nitrogen cycle	
5.3.1 Nitrogen reservoirs and fluxes (including fixation, assimilation, ammonification, nitrification and denitrification rates)	5.3.1 Changed nitrogen reservoirs and fluxes (e.g. use of fertilizers, biomass burning, combustion of fossil fuels)	(Andersen et al., 2006; Bouraoui et al., 2004; Keller et al., 2004; Verburg, 2005)
5.4 Phosphorus cycle	5.4 Changed phosphorus cycle	
5.4.1 Phosphorus reservoirs and fluxes (Availability, concentration and runoff of phosphorus)	5.4.1 Changed phosphorus reservoirs and fluxes (e.g. eutrophication due to emissions of industry, farmlands, animal feed and household consumption, soil erosion)	(Bouraoui et al., 2004; Jennings et al., 2009; Malmaeus et al., 2006)
5.5 Other nutrient cycles (calcium, sulphur, iron, etc.)	5.5 Changed other nutrient cycles (calcium, sulphur, iron, etc.)	
5.5.1 Nutrient reservoirs and cycles	5.5.1 Changed nutrient reservoirs and fluxes (e.g. changes due to anthropogenic release)	(Asami et al., 2005; Griffith et al., 2008; Jeong et al., 2012)
6. Biomass	6. Changes in biomass	
6.1 Primary production	6.1 Changed primary production	
6.1.1 Primary production (including photosynthetic and chemosynthetic producers)	6.1.1 Changed primary production (e.g. due to increasing temperatures, but also changed availability of primary net production due to human appropriation)	(López-Mársico et al., 2015; Moreau et al., 2015; Vitousek et al., 1997; Zhao and Running, 2010)
6.2 Above ground biomass	6.2 Changed above ground biomass	
6.2.1 Quantity and quality of above ground plant biomass (e.g. leaves, twigs, branches, stems, fruits)	6.2.1 Changed quantity and quality of above ground plant biomass	(Bai et al., 2015; Kaczynski and Cooper, 2015; Laurance, 1997; Mazzei et al., 2010; Mudongo et al., 2016)

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Key ecological attribute	Stress	Literature references
6.2.2 Quantity and quality of above ground animal biomass	6.2.2 Changed quantity and quality of above ground animal biomass	(Bodmer et al., 1994; Fa et al., 2002; Hallmann et al., 2017)
6.2.3 Quantity and quality of above ground microorganism biomass (e.g. bacteria, fungi)	6.2.3 Changed quantity and quality of above ground microorganism biomass	(Bell-Dereske et al., 2017; Pattison et al., 2016)
6.3 Below ground biomass	6.3 Changed below ground biomass	
6.3.1 Quantity and quality of below ground plant biomass (e.g. roots, rhizomes)	6.3.1 Changed quantity and quality of below ground plant biomass (e.g. roots, rhizomes)	(Bai et al., 2015; Graham and Mendelssohn, 2016; López-Mársico et al., 2015)
6.3.2 Quantity and quality of below ground animal biomass	6.3.2 Changed quantity and quality of below ground animal biomass	(de Vries et al., 2013; Lehmann et al., 2011)
6.3.3 Quantity and quality of below ground microorganism biomass (e.g. bacteria, fungi)	6.3.3 Changed quantity and quality of below ground microorganism biomass (e.g. bacteria, fungi)	(Clemmensen et al., 2006; Koyama et al., 2014; Wallenstein et al., 2006)
6.4 Aquatic biomass	6.4 Changed aquatic biomass	
6.4.1 Quantity and quality of aquatic plant biomass	6.4.1 Changed quantity and quality of aquatic plant biomass	(Boyd et al., 2000; Flanagan et al., 2003)
6.4.2 Quantity and quality of aquatic animal biomass	6.4.2 Changed quantity and quality of aquatic animal biomass	(Brodeur et al., 2002; Christensen et al., 2014)
6.4.3 Quantity and quality of aquatic microorganism biomass (e.g. bacteria, fungi)	6.4.3 Changed quantity and quality of aquatic microorganism biomass (e.g. bacteria, fungi)	(Cudowski et al., 2015; Hyde et al., 2016; Wang et al., 2016)
6.5 Extent of ecosystems	6.5 Changed extent of ecosystems	
6.5.1 Extent of ecosystems	6.5.1 Changed extent of ecosystems (e.g. due to changed climatic conditions, human activities)	(D'Odorico et al., 2013; Hansen et al., 2013)
7. Information	7. Changes in information	
7.1 Intraspecific/Genetic diversity	7.1 Changed intraspecific/genetic diversity	
7.1.1 Quantity of genes	7.1.1 Changed quantity of genes due to the loss of existing or appearance of new genes	(Jamieson, 2011; Oke et al., 2013; van Heerwaarden et al., 2012; Vranckx et al., 2012)
7.2 Interspecific diversity/species richness	7.2 Changed interspecific diversity/species richness	
7.2.1 Quantity of species	7.2.1 Changed quantity of species due to the loss of existing or appearance of new species	(Dukes and Mooney, 1999; Gritti et al., 2006; MacDougall et al., 2013; Maskell et al., 2010; McCauley et al., 2015; Richardson and Rejmánek, 2011; Schiel et al., 2004; Schofield and Loftus, 2015; Walther et al., 2009)
7.3 Morphofunctional diversity (variety of lifeforms and diversity of functional groups)	7.3 Changed morphofunctional diversity (variety of lifeforms and diversity of functional groups)	
7.3.1 Quantity of morphofunctional groups	7.3.1 Changed quantity of morphofunctional groups due to the loss or dissolving of known or appearance of new morphofunctional groups	(Câmara et al., 2015; Caplan and Yeakley, 2013; Deikumah et al., 2013; Wright et al., 2012)
7.4 Diversity of ecological traits	7.4 Changed diversity of ecological traits	
7.4.1 Quantity of ecological traits	7.4.1 Changed quantity of ecological traits due to the loss or dissolving of known or the appearance of new ecological traits	(Bihn et al., 2010; Ellers et al., 2012; Touchton and Wikelski, 2015)
7.5 Habitat diversity	7.5 Changed habitat diversity	
7.5.1 Quantity of habitats	7.5.1Changed quantity of habitats due to the loss or dissolving of known or the emergence of formerly unknown habitats (includes novel habitats)	(Kowarik, 2011; Kozlov and Zvereva, 2007; Krause et al., 2011; Mantyka-Pringle et al., 2012)
7.6 Ecosystem diversity	7.6 Changed ecosystem diversity	
7.6.1 Quantity of ecosystems	7.6.1 Changed quantity of ecosystems due to the loss or dissolving of known or the emergence of formerly unknown ecosystems (includes novel ecosystems)	(Beaugrand, 2002; Berry et al., 2002; Chapin III and Starfield, 1997; Hobbs et al., 2009, 2006; Williams and Jackson, 2007)
8. Network	8. Changes in network	
8.1 Distribution and connectivity of ecosystems	8.1 Changed distribution and connectivity of ecosystems	
8.1.1 Spatial distribution of ecosystem types	8.1.1 Changed spatial distribution of ecosystem types	(Beaugrand, 2002; Berry et al., 2002)
8.1.2 Meta-ecosystem connectivity (between different, spatially separated ecosystems)	8.1.2 Changed meta-ecosystem connectivity (between different, spatially separated ecosystems)	(Yu et al., 2015)
8.1.3 Inter-ecosystem connectivity (between adjacent ecosystems, e.g. terrestrial/aquatic)	8.1.3 Changed inter-ecosystem connectivity (between adjacent ecosystems, e.g. terrestrial/aquatic)	(Connon et al., 2014; Karim et al., 2016)
8.1.4 Intra-ecosystem connectivity (within an individual ecosystem)	8.1.4 Changed intra-ecosystem connectivity (within an individual ecosystem)	(Crooks and Sanjayan, 2006; Tischendorf and Fahrig, 2000)
8.2 Extent, distribution and connectivity of communities	8.2 Changed extent, distribution and connectivity of communities	
8.2.1 Spatial extent of communities	8.2.1 Changed spatial extent of communities	(Henden et al., 2013; Sirami et al., 2008)
8.2.2 Spatial distribution of communities	8.2.2 Changed spatial distribution of communities	(Barbar et al., 2015; Liu et al., 2013)
8.2.3 Connectivity of different communities	8.2.3 Changed connectivity of different communities	(Braaker et al., 2014; Sale, 2004)
8.2.4 Connectivity of an individual community	8.2.4 Changed connectivity of an individual community	(Favaro et al., 2014)

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Key ecological attribute	Stress	Literature references
8.3 Structure and composition of communities	8.3 Changed the structure and composition of communities	
8.3.1 Community composition	8.3.1 Changed community composition (including abundance changes due to changed species interactions between or within trophic levels)	(Ahola et al., 2004; Beaugrand, 2002; Brooker et al., 2007; Ims and Fuglei, 2005; Jiang and Morin, 2004; Ma et al., 2015; MacLeod et al., 2007; Morecroft et al., 2008; Moritz et al., 2008; Pauli et al., 2007; Root et al., 2003; Schiel et al., 2004; Svensson et al., 2005)
8.3.2 Presence of key ecological guilds	8.3.2 Changes in key ecological guilds	(Alevizon and Porter, 2015; Ding et al., 2015)
8.3.3 Presence of keystone species	8.3.3 Changes in keystone species	(Cancio et al., 2016; Stringer and Gaywood, 2016; White and O'Donnell, 2010)
8.3.4 Food web structure	8.3.4 Changed food web structure	(Kong et al., 2016; McMeans et al., 2016; Shurin et al., 2012)
8.3.5 Basic biotic structural elements (e.g., structure-constituting species such as trees or corals)	8.3.5 Changed basic biotic structural elements (e.g., structure-constituting species such as trees or corals)	(Phillips et al., 2008, 2002)
8.4 Synecological interactions and interdependencies	8.4 Changed synecological interactions and interdependencies	
8.4.1 Predator-prey interactions	8.4.1 Changed predator-prey interactions (e.g. loss of interaction due to local extinction, abundance loss or phenological mismatch of a partner species, development of new interactions due to appearance of new prey species or predators, changed fitness, competitiveness or behavior of a partner species)	(Both et al., 2009; DeLucia et al., 2008; Durant et al., 2007; Jepsen et al., 2008; Maran and Pelini, 2016; Post et al., 1999; Roy et al., 2004; Stenseth and Mysterud, 2002)
8.4.2 Competition	8.4.2 Changed interactions between competitors (e.g. loss of interaction due to local extinction, abundance loss or phenological mismatch of a competitor, appearance of new competitors, changed fitness, competitiveness or behavior of a competitor)	(Alexander et al., 2015; Jiang and Morin, 2004)
8.4.3 Parasitism	8.4.3 Changed host-parasite interactions (e.g. loss of interaction due to local extinction, abundance loss or phenological mismatch of an interacting species, development of new interactions due to appearance of new host species or parasites, changed fitness, competitiveness or behavior of an interacting species)	(Burek et al., 2008; Garrett et al., 2016; Harvell et al., 2002; Roy et al., 2004; van Nouhuys and Lei, 2004)
8.4.4 Mutualism (including pollination, seed dispersal, etc.)	8.4.4 Changed mutualism (e.g. loss of interaction due to local extinction, abundance loss or phenological mismatch of an interacting species, development of new interactions due to appearance of new species, changed fitness, competitiveness or behavior of an interacting species)	(Caughlin et al., 2014; Hofstetter et al., 2007; Memmott et al., 2007; Palmer et al., 2008; Richardson et al., 2007)
8.4.5 Commensalism	8.4.5 Changed commensalism (e.g. loss of interaction due to local extinction, abundance loss or phenological mismatch of an interacting species, development of new interactions due to appearance of new species, changed fitness, competitiveness or behavior of an interacting species)	(Fischer et al., 2017; Hofstetter et al., 2007; Ramsey et al., 2016; Zimmermann et al., 2011)
8.4.6 Amensalism	8.4.6 Changed amensalism (e.g. loss of interaction due to local extinction, abundance loss or phenological mismatch of an interacting species, development of new interactions due to appearance of new species, changed fitness, competitiveness or behavior of an interacting species)	(Dittmann, 1990; Osakabe et al., 2006)
8.4.7 Beneficial anthropogenic influences (e.g. conservation actions, agricultural practices, management measures, disturbances such as military activities)	8.4.7 Changed beneficial anthropogenic influences (e.g. end of conservation projects or management measures, abandonment of agricultural lands or changed agricultural practices, intensification or abandonment of disturbances),	(Lawrence et al., 2015; MacDonald et al., 2000; Queiroz et al., 2014; van Noordwijk et al., 2017)
9. Species specific key attributes	9. Direct stresses to individuals and populations, including habitat related stresses	
9.1 Physiology and behavior of individuals	9.1 Changed physiology and behavior of individuals	
9.1.1 Species morphology	9.1.1 Changed morphology	(Babin-Fenske et al., 2008; Meiri et al., 2009)
9.1.2 Species metabolism and physiology	9.1.2 Changed metabolism and physiology	(Burek et al., 2008; Gillooly, 2001; Reyer et al., 2013)

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Key ecological attribute	Stress	Literature references
9.1.3 Species immune function	9.1.3 Changed immune function	(Burek et al., 2008; Raffel et al., 2006)
9.1.4 Species growth rate	9.1.4 Changed growth rate	(Broadmeadow, 2005; Morecroft et al., 2008; Piovesan et al., 2008)
9.1.5 Species photosynthetic rate	9.1.5 Changed photosynthetic rate	(Niu et al., 2008; Zavalloni et al., 2009)
9.1.6 Species rate, timing, and frequency of life-cycle events	9.1.6 Changed rate, timing, and frequency of life-cycle events	(Ahola et al., 2004; Barbraud and Weimerskirch, 2006; Bradley et al., 1999; Dingemanse and Kalkman, 2008; Doi and Takahashi, 2008; Gaston et al., 2005; Gordo and Sanz, 2010; Jenni and Kery, 2003; Stenseth and Mysterud, 2002)
9.1.7 Species behavior (e.g. foraging, migration)	9.1.7 Changed behavior (e.g. foraging, migration)	(Kearney et al., 2009; Post et al., 1999)
9.2 Viable population size, structure and natural population dynamics (including dispersal, recruitment, colonization, etc.)	9.2 Changed population size, structure, dynamics and growth rate	
9.2.1 Population growth rate (birth, death, migration), including dynamics of meta populations	9.2.1 Changed population growth rate (birth, death, migration), including dynamics of meta populations	(Both et al., 2006; Halford, 2010; McLaughlin et al., 2002; Moss et al., 2001; Saba et al., 2007; Seifert et al., 2015; Thibault and Brown, 2008; Welbergen et al., 2008)
9.2.2 Size and age distribution	9.2.2 Changed size and age distribution (e.g. loss of tall old trees, individuals in reproductive age)	(Gobush et al., 2008; Lindenmayer et al., 2014)
9.2.3 Sex determination and sex ratio	9.2.3 Changed sex determination and sex ratio	(Godley et al., 2002; Hawkes et al., 2007; Janzen, 1994; Mitchell et al., 2010)
9.2.4 Gene flow	9.2.4 Changed gene flow	(Egelund et al., 2012; Franks and Weis, 2009)
9.2.5 Dispersal, recruitment, and colonization	9.2.5 Changed dispersal, recruitment, and colonization	(Brooker et al., 2007; Chaloupka et al., 2008; Gaston et al., 2005; Ibáñez et al., 2007; Pavlova et al., 2012)
9.3 Habitat quantity and quality (including abiotic and biotic habitat components)	9.3 Changed habitat quantity and quality	
9.3.1 Quantity of suitable habitat	9.3.1 Reduction of local or global quantity of suitable habitat (includes physical surface conversions, elevational and latitudinal shifting, occurrence of new barriers and poor connectivity between recent and potential future habitats)	(Baker et al., 2006; Berry et al., 2003, 2002; Burek et al., 2008; Colwell et al., 2008; Croxall, 2002; Galbraith et al., 2002; Gillooly, 2001; Goldenberg, 2001; Hill et al., 1999; Moritz et al., 2008; Preston et al., 2008; Stirling et al., 2016; Thomas et al., 2004; Townsend Peterson, 2003; Virkkala et al., 2008)
9.3.2 Abiotic habitat components and factors (e.g. soundscapes, natural light regimes, but also cf. 1.1 to 3.1)	9.3.2 Changed abiotic habitat components and factors (e.g. changed soundscapes, changes in natural light regimes, but also cf. 1.1 to 3.1)	(Beaugrand, 2002; Berry et al., 2002; Chaloupka et al., 2008; Dumyahn and Pijanowski, 2011; Kaniewska et al., 2015; Wrighton, 2000)
9.3.3 Biotic habitat components and interactions (e.g. resource and food availability, but also cf. 4.1 to 4.3)	9.3.3 Changed biotic habitat components and interactions (e.g. changed resource and food availability, but also cf. 4.1 to 4.3)	(Durant et al., 2007; Roy et al., 2004; Schweiger et al., 2008)
10. Energy, matter and water efficiency of ecosystems	10. Changed energy, matter and water efficiency of ecosystems	
10.1 Energy efficiency	10.1 Changed energy flow and efficiency	
10.1.1 Total dissipation due to photosynthetic activity, respiration and transpiration, ecosystem biomass and diversity	10.1.1 Changed total dissipation due to changes in photosynthetic activity, respiration and transpiration, ecosystem biomass and diversity	(Bright et al., 2014; Lopes et al., 2015; Maes et al., 2011; E.D. Schneider and Kay, 1994; Eric D. Schneider and Kay, 1994)
10.1.2 Quantity of exergy captured by the ecosystem	10.1.2 Changed quantity of exergy captured by the ecosystem	(Debeljak, 2002)
10.1.3 Quantity of exergy stored in the ecosystem (e.g. due to changed surface albedo of vegetation cover)	10.1.3 Changed quantity of exergy stored in the ecosystem (e.g. due to changed surface albedo of vegetation cover)	(Debeljak, 2002; Hu et al., 2016; Jørgensen, 2002; Jørgensen and Mejer, 1977; Myhre and Myhre, 2003)
10.1.4 Exergy through flow through the system	10.1.4 Changed exergy through flow through the system	(Fath et al., 2004; Odum, 1983)
10.1.5 Retention time (stored biomass/through flow) of energy within the system	10.1.5 Changed retention time (stored biomass/through flow) of energy within the system	(Cheslak and Lamarra, 1981; Fath et al., 2004)
10.1.6 Relative entropy production of the biological components, according to the respiration to biomass ratio	10.1.6 Changed relative entropy production of the biological components, due to changes in the respiration to biomass ratio	(Fath et al., 2004; Prigogine, 1980)
10.1.7 Release of energy during fire events (frequency, intensity, timing, duration or extent)	10.1.7 Changed release of energy due to changes in the fire regime (frequency, intensity, timing, duration or extent)	(McKenzie et al., 2004; Robinson, 2009; Westerling, 2006)
10.2 Matter efficiency	10.2 Changed matter efficiency	
10.2.1 Increased efficiency of matter cycles due to changes of existing cycles, or replacement of less effective cycles by more effective ones	10.2.1 Reduced efficiency of matter cycles due to changes of existing cycles, or replacement of more effective cycles by less effective ones	(Thuille et al. 2000; Maia et al. 2010)
10.2.2 Increased strength of greenhouse effect modification due to improvement of carbon cycling qualities of ecosystems	10.2.2 Reduced strength of greenhouse effect modification due to changes of carbon cycling qualities of ecosystems	(Zhao and Running, 2010)

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Key ecological attribute	Stress	Literature references
10.2.3 Oxygen concentration modifications through vegetation cover of surfaces	10.2.3 Changed oxygen concentration modifications due to changes in vegetation cover of surfaces	(Peng et al., 2015; Wu et al., 2012)
10.2.4 Decomposition and mineralization rates (e.g. due to changes in temperature, soil moisture, heavy metal accumulation)	10.2.4 Changed decomposition and mineralization rates (e.g. due to changes in temperature, soil moisture, heavy metal accumulation)	(Aerts, 2006; Lensing and Wise, 2007; Perez-Harguindeguy et al., 2007; Risch et al., 2007)
10.2.5 Biogeomorphological processes through local biota	10.2.5 Changed biogeomorphological processes due to changes in local biota	(Mavris et al., 2015; Thorley et al., 2015)
10.3 Water efficiency	10.3 Changed water efficiency	
10.3.1 Water cycling feedback due to changed vegetation cover of surfaces	10.3.1 Changed water cycling feedback due to changed vegetation cover of surfaces	(Calanca et al., 2006; Huntington, 2004; Keys et al., 2016; Zemp, 2016)
10.3.2 Soil moisture recycling due to changed vegetation root systems	10.3.2 Changed soil moisture recycling due to changed vegetation root systems	(Nepstad et al., 1994)
10.3.3 Production of compounds acting as cloud condensation nuclei by organisms	10.3.3 Changed production of compounds acting as cloud condensation nuclei due to changes in vegetation densities	(Croft et al., 2016; Orellana et al., 2011; Steiner et al., 2015)
10.3.4 Acquisition of subsidiary water due to foliar water uptake	10.3.4 Changed acquisition of subsidiary water due to changed foliar water uptake	(Limm et al., 2009; Yan et al., 2015)
11. Resilience and resistance	11. Changed resilience and resistance	
11.1 Recovery	11.1 Changed recovery	
11.1.1 Recovery (including primary and secondary succession)	11.1.1 Changed recovery (e.g. due to loss of biological legacies, etc.)	(Adam et al., 2011; Chazdon, 2008; Côté and Darling, 2010; Kelm et al., 2008; López et al., 2013)
11.2 Adaptive capacity	11.2 Changed adaptive capacity	
11.2.1 Adaptive capacity (including diversity of genes, species and ecosystems)	11.2.1 Changed adaptive capacity (e.g. due to loss of diversity)	(Messier et al., 2015; Puettmann, 2014)
11.3. Resistance	11.3 Changed resistance	
11.3.1 Resistance (including abiotic and biotic resistance)	11.3.1 Changed resistance (e.g. due to anthropogenic disturbances)	(Côté and Darling, 2010; Downing et al., 2012; López et al., 2013; Malone et al., 2015)

biomass of an ecosystem, more specifically the category 6.5 *Changed extent of ecosystems*. Ecosystems operate as ``bioreactors" that capture and use the energy input of solar radiation and other sources and convert it into chemical energy. The result of these conversion processes are complex molecules, building up with biomass, carrying information and inducing function. These bioreactors also have the capacity to store remaining energy in long-living organisms like trees or in organic compounds in the soils, to maintain food webs and to transfer it through and between systems. By using energy in coalescent structures, ecosystems promote self-ordering and become more complex and more functional. Consequently, the extent of an ecosystem will co-determine the extent of biomass and information, and therefore of the work capacity, functionality, and resilience of the bioreactor.

Another distinct character of the proposed classification system is that it does not include a separate category for *(natural) disturbance regimes*. Since most (natural) disturbances are just strong variations of natural patterns, we decided to include them within the corresponding sphere where these variations occur. For example, *variations of the flood regime* are located within the hydrosphere (3.3.4). While most of the common disturbance regimes are easily assigned to their corresponding spheres, (natural) fire regimes represent an exception. In order for a natural fire to occur, the interaction of several components of natural systems have to come into play, such as certain *climatic conditions* (e.g. 2.3.1; 2.3.3; 2.3.4), a *source of energy to ignite the fire* (e.g. 1.3.2 or 4.3.3), as well as the presence of *sufficient organic material as fuel* (6.2.1 or 6.3.1). The reaction to a fire of a biological network is the result of the individual reactions of the subsystem components and the interaction between them. Therefore, we considered the behavior of a given system during such an event to be an emergent property. Consequently, KEAs and stresses related to fire are located within the category of *energy efficiency* (10.1.7). As mentioned earlier, the two categories located in the center of the conceptual model (Fig. 1) represent more derived emergent properties of the ecological systems. Emergent properties are properties of a system that are not possessed by component subsystems alone, but emerge as a consequence of the interactions within the system (Müller and Nielsen, 2008). Category 10 comprises all elements related to the energy, matter and water efficiency of ecosystems, while category 11 refers to elements defining their resilience and resistance.

The original ecological concept of resilience first defined by Holling (1973) has been transformed considerably (Brand and Jax, 2007). Here we refer to ecological resilience as the amount of perturbation that a system can absorb before changing to another stable regime, which is controlled by a different set of variables and characterized by a different structure (Gunderson and Holling, 2002; Holling, 1996). Contrary to the traditional equilibrium view of ecological systems, this concept of resilience assumes the existence of alternative stable regimes (Wallington et al., 2005). For instance, a savannah may exhibit either as a locally stable 'grassy regime' or a locally stable 'woody regime', depending on the status of certain KEAs, such as *precipitation* (2.3.6), *grazing pressure* (8.4.1) and *fire events* (10.1.7) (Walker et al., 2002). Regime changes occur when thresholds of the system's resilience are crossed and the processes responsible for its structure and function change and create new self-organized structures (Allen et al., 2014).

The concept of panarchy provides a framework to describe how complex systems of people and nature are dynamically organized and structured within and across scales of space and time (Gunderson and Holling, 2002). Within panarchic systems components are interlinked in never-ending adaptive cycles of growth, conservation, release and reorganization. Perturbations are therefore neither good nor bad, but important agents of change. The complete absence of any perturbations would deprive the system from processes that provide diversity and renewal (Holling and Meffe, 1996; Paine et al., 1998). Natural stresses are often vital to successional processes and drivers of change within the system. Likewise, several landscapes and biomes around the globe have been shaped by human-induced perturbations for millennia. Consequently, systems that are subjected to a variety of recurring

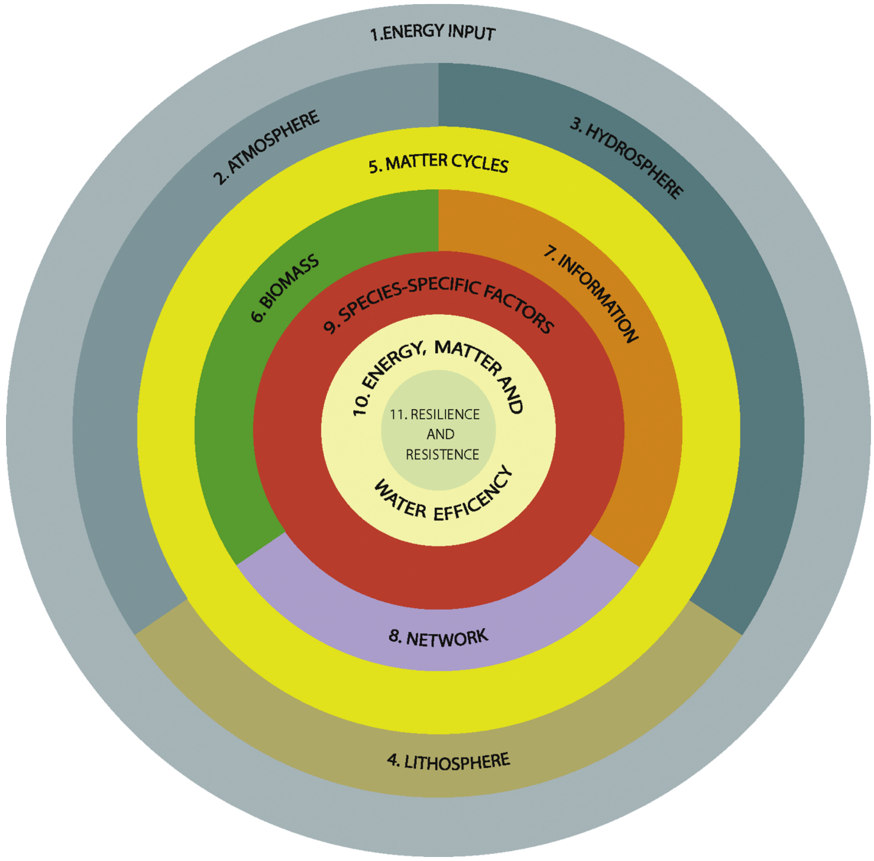

Fig. 2. A schematic model of key ecological attributes.

stresses usually contain biota that have evolved life history traits favoring adaptability or flexibility (Li et al., 2012; Robinson, 2012). The presence of stresses represent symptoms of change within the system and it should be carefully evaluated, if the ongoing change is within the natural variability of the system, or if it represents a degradation. It is worth mentioning that a regime change is rather untypical during the release phase within an adaptive cycle. In most cases, the system is likely to simply reorganize around the same structures and processes. However, human activities have significantly altered most ecological systems, impaired their integrity and in doing so changed their behavior (e.g., Vörösmarty et al., 2010; Freudenberger et al., 2012; Ibisch et al., 2016). This has reduced the capacity of the affected ecological systems to absorb perturbations and has led to catastrophic shifts within a variety of ecosystems around the globe (Scheffer et al., 2001). Even though such state shifts are often triggered by stochastic events, for instance extreme weather events or disease outbreaks, they are usually the result of gradual changes that have reduced the resilience of the systems over a longer period of time (Kong et al., 2016; Scheffer et al., 2001). Since stochastic events are difficult to predict or control, it might be more pragmatic and effective to focus on the KEAs of the biological systems when considering management strategies designed to build and maintain their resilience.

Given the increased attention placed on functionality in the management of ecological systems, we firmly believe that the analysis of KEAs and stresses should be part of any holistic and systemic situation analysis as fundament for strategy development. There exists a variety of threat-analysis systems that differentiate between the sources of stresses and stresses themselves, such as The Nature Conservancy's Conservation Action Planning Framework (TNC, 2007), the EPA framework (EPA, 1998) or the MARISCO method (Ibisch and Hobson, 2014). The classification system for KEAs and stresses presented in this paper is designed to be sufficiently exhaustive and exclusive to enable practitioners to assign their identified elements with ease. It is anticipated that ongoing development of the system will happen as practitioners and scientists encounter novel changes and challenges in the living landscape.

Acknowledgements

We would like to thank all counterparts in the projects, the instructors involved in the adaptive management exercises, as well as all the workshop participants. Special thanks go Daniela Aschenbrenner, Jeanette Blumröder, Jamie Call, Felix Cybulla, Laura Geiger, Juliane Geyer, Anja Krause, Stefan Kreft, Christoph Nowicki, Lena Strixner, Christina Sandig and Sara Silva de Oliveira, who were involved in various assessments analyzed in this study and contributed to the development and testing of the MARISCO methodology. The study is based on workshops conducted in the framework of different projects that are listed in Table 1. We acknowledge the support received by the staff representing the various projects and donors. We especially thank Isabel Renner, formerly GIZ, for encouraging and supporting the development of the MARISCO methodology.

PLI co-conceived and supervised the study in the framework of his long- term research program facilitated by the research professorships "Biodiversity and Natural Resource Management under Global Change" (2009–2015) as well as "Ecosystem-based Sustainable Development" (since 2015) granted by Eberswalde University for Sustainable Development.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecocom.2019.04.001.

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Appendix S1: Overview of the 22 assessed conservation sites, where key ecological attributes and stresses were identified by experts and stakeholders.

Code	Name	Country	Year	Biome	Protected Areas included [IUCN category]	WDPA ID	Project
BR-CPB	Corridor Cabralia - Pao Brasil	Brazil	2015	Tropical moist broadleaf forest, Mangroves, Tropical coral, Atlantic Ocean	Veracel Private Reserve [not reported]	not listed	"Biodiversity and Climate Change in the Atlantic Forest" project implemented by GIZ
CO-GUA	Guajaro Reservoir and surroundings	Colombia	2014	Tropical dry broadleaf forests			“Programa Medio Ambiente en Colombia PROMAC” program implemented by GIZ/Gopa
CO-TOL	Saldaña River Watershed	Colombia	2014	Tropical dry broadleaf forests			“Programa Medio Ambiente en Colombia PROMAC” program implemented by GIZ/Gopa
CR-CAH	Cahuita National Park	Costa Rica	2011	Tropical moist broadleaf forest, Mangroves, Tropical coral, Pacific Ocean	Cahuita National Park [II]	2235	"BIOMARCC Marine and coastal biodiversity of Costa Rica – capacity building and adaptation to climate change" project implemented by GIZ
CR-MAN	Manuel Antonio National Park	Costa Rica	2011	Tropical moist broadleaf forest, Mangroves, Tropical coral, Pacific Ocean	Manuel Antonio National Park [II]	2250	"BIOMARCC Marine and coastal biodiversity of Costa Rica – capacity building and adaptation to climate change" project implemented by GIZ
DE-AUE	Lower Lusatia	Germany	2013	Temperate broadleaf and mixed forests	Niederlausitzer Heidelandschaft nature reserve; Niederlausitzer Landrücken nature reserve [both not reported]	555537514; not listed	"Projekt zur Wiederansiedlung des Auerhuhns" project of the INKA BB – Innovation Network of Climate Change Adaptation Brandenburg Berlin consortium

DE-LRP	Barnim county	Germany	2011-2013	Temperate broadleaf and mixed forests	Barnim nature reserve [V]	319792	"Adaptation of administrative nature conservation in Brandenburg" project of the INKA BB – Innovation Network of Climate Change Adaptation Brandenburg Berlin consortium
DE-RAN	Randow watershed	Germany	2012	Temperate broadleaf and mixed forests			INKA BB – Innovation Network of Climate Change Adaptation Brandenburg Berlin
EC-SIE	Municipal Ecological Conservation Area Siete Iglesias and Bosque Tinajillas-Río Gualaceño Forest Reserve	Ecuador	2013	Tropical moist broadleaf forest	Municipial Ecological Conservation Area Siete Iglesias and Bosque Tinajillas-Río Gualaceño Forest Reserve [both not reported]	555592963; not listed	GESOREN program implemented by GIZ and “Apoyo al Sistema Nacional de Áreas Protegidas (SNAP)” project implemented by KfW/GOPA
GE-DED	Dedosplitskaro District	Georgia	2014	Temperate broadleaf and mixed forests	Vashlovani Nature Reserve [Ia] and National Park [II]	1660; 555549413	“Sustainable biodiversity management in the South Caucasus” project implemented by GIZ
GE-TUS	Tusheti Protected Areas	Georgia	2014	Temperate broadleaf and mixed forests	Tusheti Strict Nature Reserve [Ia] , Tusheti National Park [II] and Tusheti Protected Landscape [V]	313053; 555549414; 555549416	“Sustainable biodiversity management in the South Caucasus” project implemented by GIZ
GT-LAC	Sierra del Lacandon National Park	Guatemala	2011	Tropical moist broadleaf forest	Sierra del Lacandon National Park [II]	30605	“Lacandón – Forests for Life” Project implemented by Oro Verde and Defensores de la Naturaleza
KR-BDA	Baekdudaegan	South Korea	2013	Temperate broadleaf and mixed forests			"Deutsch-Koreanischer Dialog: Stärkung der Zivilgesellschaft und Naturschutzkommunikation als Grundlage für eine nachhaltige Entwicklung" project of Deutsche Bundesstiftung Umwelt (DBU)

KZ-ALY	Great Altay Transboundary Biosphere Reserve	Kazakhstan	2012 - 2015	Mountain steppe, mountain forest, tundra, glaciers	Katon-Karagay State National Park [II], respectively Biosphere Reserve [not applicable]	not listed	"Development of a management plan for the planned transboundary reserve “Altai” "project of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Germany (BMUB) implemented by Centre for Econics and Ecosystem Management
MY-RSP	Sabah state	Malaysia	2015	Tropical moist broadleaf forest			"Was bewirken Zertifizierungssysteme für Biokraftstoffe vor Ort (WIESO)?" project implemented by WWF
NA-GMU	George Mukoya Conservancy and Community Forest	Namibia	2015	Zambezian Baikiaea woodlands	George Mukoya Conservancy and Community Forest [not reported]	555542945; 555555541	"Biodiversity Management and Climate Change (BMCC)" project implemented by GIZ
NA-MNY	Muduva Nyangana Conservancy and Community Forest	Namibia	2015	Zambezian Baikiaea woodlands	Muduva Nyangana Conservancy and Community Forest [not reported]	555542946; 555555542	"Biodiversity Management and Climate Change (BMCC)" project implemented by GIZ
NA-OKO	Okongo Complex	Namibia	2014	Zambezian Baikiaea woodlands	Okongo Conservancy and Community Forest [not reported]; Omufituwekuta Community Forest [not reported]	555542968; 555542985; 555555540	"Biodiversity Management and Climate Change (BMCC)" project implemented by GIZ
PE-ACR	Regional Conservation Area Imiria	Peru	2013	Tropical moist broadleaf forest	Regional Conservation Area Imiria [not reported]	555555623	"Co-Management Amazon Region Peru (CoGAP)" project implemented by GIZ
PE-PIN	Puerto Inca Province	Peru	2013	Tropical moist broadleaf forest	El Sira Community Reserve [VI]	not listed	"Co-Management Amazon Region Peru (CoGAP)" project implemented by GIZ
PE-RCS	El Sira Community Reserve	Peru	2011	Tropical moist broadleaf forest	El Sira Community Reserve [VI]	not listed	“Biodiversity and Climate Change Project in the El Sira Community

							Reserve” project implemented by GIZ
RU-ALY	Great Altay Transboundary Biosphere Reserve	Russia	2012 - 2015	Mountain steppe, mountain forest, tundra, glaciers	Katunsky Biosphere Reserve [not applicable]; State Nature Zapovednik Katunskiy [Ia] and Belukha Nature Park [not reported]	198345; 68519; not listed	German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Germany (BMUB)
RU-FCS	Archangelsk Region	Russia	2014	Boreal forests/Taiga			“Assessing conservation impacts of FSC in Northwest Russia” project implemented by WWF

Appendix S2 – Literature references of the identified key ecological attributes and stresses

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