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Review

How is ecosystem health defined and measured? A critical review of freshwater and estuarine studies

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ABSTRACT

Assessing ecosystem health is an ongoing priority for governments, scientists and managers worldwide. There are several decades of scientific literature discussing ecosystem health and approaches to assess it, with applications to aquatic and terrestrial environments incorporating economic, environmental and social processes. We conducted a systematic review of studies that assess ecosystem health to update our current understanding of how ecosystem health is being defined, and provide new ideas and directions on how it can be measured. We focused the review on studies that used the term 'ecosystem health' or the equivalent terms 'ecosystem integrity', 'ecosystem quality' and 'ecosystem protection', in lotic freshwater and estuarine environments, and examined how many of these included explicit definitions of what ecosystem health means for their study system. We collected information about the temporal and geographical distribution of studies, and the types of indicators (biological, physical or chemical) used in the assessments. We found few studies clearly defined ecosystem health and justified the choice of indicators. Given the broad use of the term it seems impractical to have an overarching definition of ecosystem health, but rather an approach that is able to define and measure health on a case by case basis. A combination of biological, physical and chemical indicators was commonly used to assess ecosystem health in both estuarine and freshwater studies, with a strong bias towards fish and macroinvertebrate community metrics (e.g. diversity, abundance and composition). We found only two studies that simultaneously considered both freshwater and estuarine sections of the ecosystem, highlighting the significant knowledge gap in our understanding of the transfer of flow, nutrients and biota between the different systems—all key factors that influence ecosystem health. This review is the first to combine knowledge from both freshwater and estuarine ecosystem assessments and critically review how aquatic ecosystem health is defined and measured since the late-1990s, providing the basis for setting achievable management goals relating to ecosystem health into the future.

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1. Introduction

'Ecosystem health' is a common term used in environmental science and management as a way to describe the state of a system relative to a desired management target or reference condition (Rapport, 1989 Schaeffer et al., 1988). Other definitions of ecosystem health have emphasized the integration of ecological, economic and human processes (Rapport et al., 1998) and measures of sustainability and system resilience (Costanza et al., 1992). Ecosystem health can be linked to management and political objectives (Fairweather, 1999) and used in the context of environmental management legislation and policies (Karr, 1990; Negus et al., 2009), as well as defining different societal, recreational or commercial benefits (Karr, 1999). Although ecosystem health is not a new term, but one that has been discussed and defined in the literature since the late 1980s, achieving a state or condition that reflects a healthy ecosystem is an ongoing priority for government, scientists and managers worldwide (Burger et al., 2006).

Assessing ecosystem health can be approached in several different ways (Rapport et al., 1998). It can involve the identification of certain characteristics that indicate a healthy ecosystem, such as a river system that is free from algal blooms, has a high biological diversity or a particular biotic score (Di Battista et al., 2016; Pont et al., 2006). Alternatively, the health of an ecosystem can be characterized by ecosystem services that humans depend on, such as the provision of clean drinking water (Keeler et al., 2012), nutrient recycling and maintenance of biodiversity (US National Research Council, 2005). Ecosystem health assessments may also involve predictions about food web functioning and different trophic levels required to sustain a healthy ecosystem (Thompson et al., 2012), or an ecosystem's ability to maintain structure and function when confronted with external stress (Mageau et al., 1995).

In aquatic ecosystems, there is now more pressure than ever for appropriate monitoring and management strategies that will maintain ecosystem health. With over 50% of the world's population living within three kilometers of freshwater (Kummu et al., 2012) and many of the largest cities around the globe situated on estuaries (Boesch, 2000; Johnston et al., 2015b), these ecosystems are continually under pressure from an array of anthropogenic stressors (Halpern et al., 2008; Vorosmarty et al., 2010). Contamination, habitat degradation and non-indigenous species are among the main threats that affect aquatic ecosystem health through changes in community composition and biological diversity, ecological functioning and provisioning of ecosystem services (Tolkkinen et al., 2016).

Assessing aquatic ecosystem health has been an ongoing theme in the scientific literature for several decades, possibly originating with river health indicators such as the Index of Biotic Integrity (Karr, 1981, 1991) or even earlier with the development of the Saprobic Index to assess water quality (Friedrich et al., 1992; Kolkwitz and Marsson, 1909) and biological surveys of whole river (Forbes and Richardson, 1913) and lake ecosystems (Thienemann, 1925). There are now many approaches for assessing the health of freshwater and estuarine systems that use biological community measures either separately or in combination with chemical or physical parameters. Multi-metric indices are useful in that they can distill a lot of information and parameters onto a uniform scale that can be easily used to make management decisions. However, they are not always transferrable between regions or countries, often depend on comparisons with appropriate reference conditions and rarely provide information on what aspects of the ecosystem are responsible for changes in health (Borja et al., 2012; Pont et al., 2006). Measures of ecosystem function, such as respiration, primary productivity, metabolism and decomposition, are becoming more common in ecosystem health assessments (e.g. Bunn and Davies, 2000; Woodward et al., 2012). Combining measures of ecosystem function with multi-metric indices and other indicators of ecosystem structure may provide a better representation of whole ecosystem health (Woodward et al., 2012). Further progress in the way ecosystem assessments are approached may continue to arise as molecular techniques, such as next-generation sequencing, become more cost-effective and new types of biodiversity indicators are developed (Forbes and Richardson, 1913; Zinger et al., 2014).

Considering the broad use of the term 'ecosystem health' and the many different definitions and assessment approaches, it seems unrealistic to have an overarching definition of ecosystem health (Costanza et al., 1992), but one defined relative to the system being studied (Dobbie and Negus, 2013). Palmer et al. (2005) highlight that endpoints to stream restoration are unlikely to be universally applied, and suggest that a 'guiding image' must be articulated to describe the most dynamic, ecologically dynamic state possible at a site, taking into account the likely influence of irreversible anthropogenic changes, such as alterations to catchment hydrology and geomorphology, the installation of permanent infrastructure (e.g. on floodplains or along coasts), and the spread of invasive species that cannot be easily removed. In a similar vein, a range of information could be used to help determine what should reflect a 'healthy ecosystem', including historical information (e.g. photographs, maps, survey records), appropriate reference sites, analytical/process based models, stream classifications, or in some instances common sense (Palmer et al., 2005).

Here, we present the results of a systematic review undertaken to update our current understanding of how ecosystem health is defined and measured in lotic freshwater and estuarine environments. Our first aim was to identify studies seeking to measure ecosystem health, and then to examine how many of these included an explicit definition of what ecosystem health means for their study system. Our second aim was to examine the spatial and temporal distribution of studies that had the primary goal of measuring ecosystem health or equivalent (i.e. ecosystem integrity, quality or protection) in lotic ecosystems (i.e. freshwater, streams, rivers, waterway or estuaries), to examine if they are geographically biased and whether these types of studies are becoming increasingly common through time. Geographic biases can hinder conservation efforts, for example, if the location of research is misaligned with research needs or priorities (Lawler et al., 2006). Our third aim was to examine how ecosystem health is being assessed, in terms of the types of indicators that are being used (i.e. chemical, biological, physical), and for biological indicators, the level of organization at which they are monitored (i.e. individual, population, community), and the taxonomic groups that are commonly studied. We use the results of our study to critically evaluate ecosystem health assessments in lotic freshwater and estuarine environments, identify key knowledge gaps, and ultimately aid in the development of robust and appropriate approaches to assess ecosystem health in the future.

2. Methods

The systematic review followed the method of Pickering and Byrne (2014). We reviewed studies that assessed ecosystem health in lotic freshwater and estuarine environments (rivers, streams and estuaries) which excluded marine, wetland, lake and lagoon systems to keep the scope of the study manageable. Search terms were "ecosystem health" and similar phrases that are often used interchangeably; "ecosystem integrity", "ecosystem quality" and "ecosystem protection" plus freshwater or river* or stream* or waterway or estuar*. These terms were used in a multi-database search using Web of Science Core Collection, CABI: CAB Abstracts and Global Health, Current Contents Connect and SciELO Citation