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Review

The role of satellite remote sensing in structured ecosystem risk assessments

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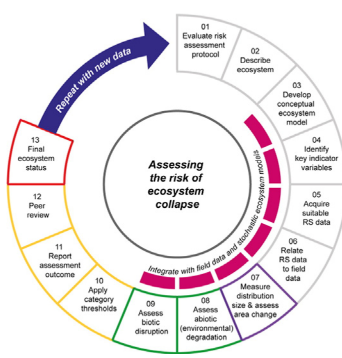
HIGHLIGHTS

- Ecosystem risk assessment protocols enable the use of a wide range of data to assess the changing status of ecosystems.
- Unstructured use of remote sensing data for assessing ecosystem dynamics can introduce substantial error and uncertainty.
- We identify case studies that have used satellite remote sensing to assess degradation of marine, aquatic and terrestrial ecosystem types.
- We provide guidance and a framework for integrating remote sensing data into ecosystem risk assessment.

GRAPHICAL ABSTRACT



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ABSTRACT

The current set of global conservation targets requires methods for monitoring the changing status of ecosystems. Protocols for ecosystem risk assessment are uniquely suited to this task, providing objective syntheses of a wide range of data to estimate the likelihood of ecosystem collapse. Satellite remote sensing can deliver ecologically relevant, long-term datasets suitable for analysing changes in ecosystem area, structure and function at temporal and spatial scales relevant to risk assessment protocols. However, there is considerable uncertainty about how to select and effectively utilise remotely sensed variables for risk assessment. Here, we review the use of satellite remote sensing for assessing spatial and functional changes of ecosystems, with the aim of providing guidance on the use of these data in ecosystem risk assessment. We suggest that decisions on the use of satellite remote sensing should be made *a priori* and deductively with the assistance of conceptual ecosystem models that identify the primary indicators representing the dynamics of a focal ecosystem.

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Contents

1. Introduction

Habitat loss, degradation and fragmentation continue to threaten ecosystems worldwide (Tittensor et al., 2014). The adoption of the Aichi 2020 Targets, agreed by 194 nations under the Convention on Biological Diversity (Convention on Biological Diversity, 2014), and the 2030 Sustainable Development Goals (UNDP, 2015) are crucial global policy responses to counteract these fundamental drivers of biodiversity loss. These agreements explicitly include goals on the conservation and restoration of ecosystems and their characteristic biota. For example, five of the twenty Aichi Targets relate directly to the status of ecosystems (Convention on Biological Diversity, 2014). Yet identifying tools that can be used to assess progress towards these ecosystem-based conservation targets remains a fundamental challenge (Collen and Nicholson, 2014; Tittensor et al., 2014). The emergence of ecosystem risk assessment protocols such as the IUCN Red List of Ecosystems (www.iucnrle.org), which provide decision rules for classifying ecosystems according to their risk of collapse, can help address this challenge.

Ecosystem risk assessment protocols aim to estimate the probability of ecosystem collapse over a specified time frame (Keith, 2015). Currently, >30 countries assess ecosystems, ecological communities, or habitats to estimate the risks they face, with the conservation status of at least 725 ecosystem types formally reviewed (Murray, unpub. data). For the purposes of risk assessment, ecosystems are normally defined as complexes of organisms and their physical environment within a particular area (see Nicholson et al., 2015 for a review of terms used in ecosystem risk assessment). They are recognized as having four essential elements: a biotic complex, an abiotic environment, the interactions within and between them, and a physical space in which these operate (Tansley, 1935). Risk assessments typically require information on the geographic distribution of an ecosystem, changes in spatial extent, and changes in ecosystem function over time (Nicholson et al., 2009; Nicholson et al., 2015). For example, the International Union for Conservation of Nature's (IUCN) Red List of Ecosystems, the only global protocol for ecosystem risk assessment, comprises a risk assessment model with five quantitative criteria that integrate multiple symptoms of ecosystem collapse (Fig. 1; Keith et al., 2013; Rodríguez et al., 2015). The Red List of Ecosystems criteria consider both the spatial aspects of ecosystem decline, including reductions in area (Criterion A) and susceptibility to spatially explicit threats (Criterion B), and the functional aspects of decline that focus on both abiotic and biotic symptoms of ecosystem degradation (Criteria C and D; Fig. 1). A fifth criterion allows the use of stochastic ecosystem models that may incorporate both the spatial and functional aspects of decline to estimate risks of collapse (Criterion E; Keith et al., 2013). Declines in geographic distribution and both biotic and abiotic functions are typically measured over a 50-year timeframe to capture long-term directional changes in ecosystem dynamics, although future projections to a 50-year time frame may also be used (Bland et al., 2017a).

Many data sources are relevant for ecosystem risk assessment, including those from short and long term monitoring programs, field surveys, and underwater, aerial and satellite sensors. Of these, satellite remote sensing offers the greatest opportunity to evaluate ecosystem change beyond the site level (Turner et al., 2003) and to scale the risk assessment process to provincial, national and continental jurisdictions. However, the need for interdisciplinary expert skills in the identification and use of satellite remote sensing data is a central factor that has limited the uptake of this source of environmental information by ecologists and slowed the development of national, continental and global lists of threatened ecosystems. Furthermore, the increasing availability of data from an ever-growing range of sensors has led to a bewildering choice of remotely sensed data that seem suitable for assessing ecosystem change over a range of time periods (Kennedy et al., 2014; Porter et al., 2012).

In this review we aim to investigate the proven capabilities and future potential of satellite remote sensing for assessing the status of ecosystems across a range of major ecosystem types, and identify important mechanisms and processes of ecosystem change and the sensors that best represent them. We identify recent case studies that demonstrate the advantages, challenges and key considerations of using remotely sensed data in studies of ecosystem dynamics. In doing so, we aim to provide a primer for environmental managers, risk assessors, and ecosystem scientists to judiciously utilise remote sensing for ecosystem risk assessments at a range of spatial scales. Lastly, we develop a simple framework for incorporating indicators that can be monitored with satellite remote sensing across a wide range of ecosystem types, with the aim of establishing a clear assessment workflow to progress a global list of threatened ecosystems.

2. Spatial distribution of ecosystems

Accurate maps of the geographic distributions of ecosystems and how they change over time are fundamental components of most ecosystem risk assessment protocols (Fig. 1; Nicholson et al., 2015). Ecosystems with small geographic range size are at greater risk of collapse from environmental catastrophes than those that are distributed over large areas (Keith et al., 2017; Murray et al., 2017a). Similarly, the rate of areal change is a widely used indicator of an ecosystem's trajectory towards collapse, because a decline in area reduces the ability of an ecosystem to maintain its characteristic biota and fundamental processes (Keith et al., 2013). The areal trajectories of many of Earth's major ecosystem types have been quantified with time-series remote sensing data. Examples of estimated annual rates of change in extent include −3.7% for tropical peatlands (Wilcove et al., 2013), −2% for coastal wetlands in East Asia (Murray et al., 2014; Murray et al., 2015) and >1% for forests globally (Hansen et al., 2013). However, producing time series of ecosystem maps at spatial and temporal scales that underpin such estimates of change is a specialist task. The need for detailed knowledge of available data, advanced analytical methods, and an understanding of constraints and uncertainties of remote sensing has limited the availability of highly accurate and consistent maps that can be used operationally for ecosystem risk assessments.

Traditional remote sensing methods, such as visual interpretation and classification of satellite, aerial and underwater imagery have