Environmental Research 144 (2016) 8–14

Contents lists available at ScienceDirect

Environmental Research

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

Consolidating new paradigms in large-scale monitoring and assessment of forest ecosystems

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ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form
6 October 2015
Accepted 15 October 2015
Available online 26 October 2015

Keywords:
Global changes
Resilience thinking
Complex adaptive system
Forest inventory
Forest mapping
Forest management

ABSTRACT

Forests provide a wide range of ecosystem services from which people benefit, and upon which all life depends. However, any rational decision related to the maintenance and enhancement of the multiple functions provided by the forests needs to be based on objective, reliable information. As such, forest monitoring and assessment are rapidly evolving as new information needs arise or new techniques and tools become available. Global change issues and utilities from ecosystem management are distinctively to be considered, so that forest inventory and mapping are broadening their scope towards multipurpose resources surveys. Recent changes in forest management perspective have promoted the consideration of forests as complex adaptive systems, thereby highlighting the need to account that such approaches actually work: forest monitoring and assessment are then expected to address and fully incorporate this perspective at global scale, seeking to support planning and management decisions that are evidence-based. This contribution provides selected considerations on the above mentioned issues, in the form of a commented discussion with examples from the literature produced in the last decade.

1. Introduction

Forests provide a wide range of ecosystem services from which people benefit, and upon which all life depends. The ecosystem service concept has an increasing popularity in contemporary science (e.g. Seppelt et al., 2012) and political commitment (see, e.g., the Millennium Ecosystem Assessment, http://www.millenniumassessment.org/en/Condition.html, and TEEB, 2010). However, any rational decision related to the maintenance and enhancement of the multiple functions provided by the forests needs to be based on objective, reliable information (Corona et al., 2011).

Forest monitoring and assessment are rapidly evolving as new information needs arise or new techniques and tools become available. Two main driving forces are currently stimulating innovation in this field:

1. Technological advances are increasing the capability and cost-effectiveness of remote sensing techniques to collect forest data over spatially extensive areas (see e.g. the recent rapid development of satellite and aerial laser scanning to capture three-dimensional above-ground information of ecosystems and landscapes).
2. Recent developments in forest management perspective have led to reconsider the bases of forest ecosystem functioning by embracing new concepts like e.g. resilience thinking (e.g. Walker and Salt, 2006) and complex adaptive system analysis and behavior (e.g. Filotas et al., 2014).

In addition, global change issues and utilities from ecosystem management are distinctively to be considered, so that forest inventory and mapping are broadening their scope towards multipurpose resources surveys. Two major directions can be currently highlighted as: (i) inclusion of additional variables not directly related to timber assessment, wood volume growth and carbon-related issues, like e.g. biodiversity attributes; (ii) extension of the target population to include non-traditional objects, like urban forests and forest trees in non-forest rural landscapes.

This contribution provides selected considerations about recently consolidating paradigms under the above mentioned perspectives in large-scale forest monitoring and assessment, in the form of a commented discussion with examples from the literature produced in the last decade. The following sections are organized upon the following concepts:

1. The methodological focus shifts from deterministic planning, typical of conventional forestry, to learning-based trial and error approaches.
2. The rising relevance of resilience thinking.
3. The need of more rigorous scientific inference.

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http://dx.doi.org/10.1016/j.envres.2015.10.017

4. The integration of forest inventory and forest mapping approaches.
5. The trend towards 3-D representations of forest ecosystems.
6. The increasing opportunity for multipurpose surveys.

Conceptual hints concerning updated vision of forest monitoring and assessment are devised to support landscape and ecosystem management decisions that are evidence-based.

2. From forecasting to monitoring

Traditional forest management has long been dominated by the reductionist and deterministic paradigm founded on two basic principles: (i) the perpetuity of the forest based on an equilibrium between standing volume, standing volume increment and allowable cut; (ii) the constrained optimization of productions (either marketable or not marketable).

This conventional paradigm assumes the environmental space of forest ecosystems to be stationary and forest stand dynamics to proceed according to predictable trajectories. Classical forest ecosystem management aims at controlling natural processes and tends towards a regulated distribution of tree age or diameter classes. Under such a perspective, silvicultural techniques aim at obtaining forest regeneration according to a predefined stand structure model: even-aged or uneven-aged. Yield tables for even-aged stands, or norms for uneven-aged forests, are the main expression of the classical idea that, in principle, following such “optimal” schemes, forest growth will probably match managers' expectation. Under this view, forest ecosystem processes (e.g. growth, regeneration, succession) are supposed to be fully predictable and, thus, can be manipulated so that forest responses to silvicultural treatments meet management expectations. This paradigm inherently assumes that: (i) forest ecosystems react to management in a predictable manner; (ii) it is then expedient to anticipate the predicted consequences of decisions (i.e. the classical anticipatory management idea, *sensu* Kay and Regier, 2000: once all necessary information is gathered to make a scientific forecast, the “right” decision can be made).

Undoubtedly, in former times this approach has contributed to regulate forest exploitation and reducing forest degradation. However, classical silviculture and management, with the aim of predicting regeneration rate and producing a constant yield of merchantable wood, have in practice tended to transform complex ecosystems into simplified ones (Ciancio and Nocentini, 2011). A vast bulk of evidence from operational forest management demonstrates that predicted outcomes are rarely achieved, at least for naturally regenerated forests (Puettman et al., 2009; Messier et al., 2013). When dealing with complex adaptive systems (for detailed reference to the meaning of this concept applied to forests and forest management, see Messier et al. (2013)), only hypotheses can be drawn about the effects of management practices. Forest functioning and structure are neither completely predictable nor completely random (Anand et al., 2010): as complex systems, forests are characterized by multiple feedback and close dependency on initial conditions, so that prediction has only a weak power being very high the degree of uncertainty (Puettman et al., 2009; Messier et al., 2013).

These considerations recently supported the definition of a systemic approach, according to which forest management strategies are based on an adaptive approach and continuous monitoring of the reactions of the forest ecosystem to silvicultural interventions (Ciancio and Nocentini, 1997; Chapin III et al., 2009; Filotas et al., 2014). Adaptive management explicitly recognizes ecosystem's unpredictability and resilience, i.e. capacity to deal with environmental change and disturbances and continue to develop, as a value. The main question for forest ecosystem management thus becomes: how can the self-organizing capacity of a forest be supported by silviculture? Accordingly, the methodological focus shifts from deterministic planning (i.e. predictability of the effects interventions, the root of the anticipatory management idea) to *a posteriori* assessment, which calls for a heuristic approach (learning-based trial and error method), based on monitoring the effects of treatments by means of relevant indicators.

3. Sustainability-oriented vs. resilience-oriented approaches

Moving from a strictly ruled forest planning to adaptive management means that monitoring indicators are not generally intended as reference thresholds but as parameters to measure changes over time (Ciancio and Nocentini, 2011). Sets of criteria and indicators have usually been conceived to evaluate aspects of forest management under the well-known sustainability paradigm (for details, see e.g. Hahn and Knoke, 2010). By definition, sustainability assumes that socio-ecological systems (*sensu* Folke, 2006) can reach desirable states that humans can maintain (within a certain range of variability) indefinitely. The pursuit of sustainability inherently assumes that we (i) know what can be sustained and (ii) have the capacity to hold onto some type of stationarity and/or equilibrium (Milly et al., 2008). But the goal of “sustainability” is largely unattainable in a world characterized by extreme complexity, uncertainty and lack of stationarity (e.g. Lafortezza et al., 2013a), and, in practice, sustainability-based goals have proved difficult to be achieved even before climate change impacts have become noticeable (Benson and Craig, 2014).

The concept of resilience holds promise to formulate ecosystem monitoring and assessment goals by metrics other than sustainability (Benson and Craig, 2014). Resilience can be characterized in four ways (Benson and Craig, 2014): (i) the amount of change the system can undergo and still retain the same controls on function and structure; (ii) the degree to which the system is capable of self-organization; (iii) the ability to build and increase the capacity for learning and adaptation (Carpenter et al., 2001); (iv) the adaptive capacity and adaptive management of forest ecosystems (e.g. Kolström et al., 2011; Wagner et al., 2014).

4. Monitoring and assessment as scientific inference

Landscape and ecosystem monitoring and assessment should be a result of scientific inference. To this end, rigorous statistical procedures have been developed to infer the estimates of the population parameters based on monitoring a sample of units of the population (e.g. Gregoire and Valentine, 2008; Mandallaz, 2008). Correct inference requires identification of the relationships between the population parameter and its estimate within a probabilistic framework: failure to account for the estimation of parameters in probabilistic terms prevents the characterization of the monitoring and assessment results as valid scientific inference (McRoberts, 2011). Good statistical design, coupled with rigorous statistical analyses of high quality data, is an inherently critical component of any successful monitoring and assessment program (Lindenmayer and Likens, 2010). This aspect is neither trivial nor negligible: for instance, current biodiversity assessments frequently rely on floristic data collected using preferential non-probabilistic sampling schemes which do not permit objective estimation of the sampling variability (Corona et al., 2010).

Large-scale forest inventories provide unbiased or nearly unbiased estimators for the total of biophysical attributes, together with the expressions of their variances (Köhl et al., 2006). Many