Forest Ecology and Management 355 (2015) 109–123

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Review and synthesis

The role of remote sensing in process-scaling studies of managed forest ecosystems ☆

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ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form 19 May 2015
Accepted 23 May 2015
Available online 24 June 2015

Keywords:
Remote sensing
Forest ecology
Scaling

ABSTRACT

Sustaining forest resources requires a better understanding of forest ecosystem processes, and how management decisions and climate change may affect these processes in the future. While plot and inventory data provide our most detailed information on forest carbon, energy, and water cycling, applying this understanding to broader spatial and temporal domains requires scaling approaches. Remote sensing provides a powerful resource for "upscaling" process understanding to regional and continental domains. The increased range of available remote sensing modalities, including interferometric radar, lidar, and hyperspectral imagery, allows the retrieval of a broad range of forest attributes. This paper reviews the application of remote sensing for upscaling forest attributes from the plot scale to regional domains, with particular emphasis on how remote sensing products can support parameterization and validation of ecosystem process models. We focus on four key ecological attributes of forests: composition, structure, productivity and evapotranspiration, and disturbance dynamics. For each attribute, we discuss relevant remote sensing technologies, provide examples of their application, and critically evaluate both strengths and challenges associated with their use.

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☆ This article is part of a special issue entitled "Carbon, water and nutrient cycling in managed forests".

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http://dx.doi.org/10.1016/j.foreco.2015.05.032
0378-1127/Published by Elsevier B.V.

1. Introduction

Forests provide critical ecosystem services to society, including provision of food and fiber, maintaining water availability and quality, and regulating climate (Krieger, 2001; Millennium Ecosystem Assessment, 2005). Sustaining these services under increasing societal demand depends on effective forest management, which in turn relies on solid scientific understanding of the natural processes of carbon, water, and nutrient cycling. Historically, much of our scientific knowledge on key ecological processes and management impacts has come from field-based studies and experimental manipulations. To extrapolate this understanding to larger domains in both time and space, however, requires scaling techniques often based on forest inventories and ecological modeling. Upscaling plot-level measurements of carbon, water and nutrient cycling in forests to broader spatial and temporal scales can be accomplished by different approaches including measure-and-multiply, or "book-keeping", techniques (e.g., Houghton et al., 1983), formal national-level resource inventories (e.g., Heath et al., 2011), and mechanistic modeling of biogeochemical processes (e.g., Thornton et al., 2009). Across these various scaling approaches are common data requirements for initializing, calibrating, driving and validating these methods.

Remote sensing observations and derived products fill a critical role in meeting these data requirements, particularly where spatially- and temporally-explicit information is needed for inputs and evaluation (Turner et al., 2004). In theory, remote sensing is straightforward. Energy from either the sun or the sensor itself can be interpreted as it interacts with the Earth's surface to infer forest attributes or, as observations are combined over time, change. These inferences can be made over different spatial scales and frequencies, with consistent records going back decades in some cases. From this simple concept however come a large variety of sensors that vary by platform, passive or active systems, spectral wavelengths, spatial resolution and coverage, and repeat frequency and available historical record (Jensen, 2009). The choice of system, or combination of systems, depends on the scale of the application or process of interest and the particular forest attribute of interest (e.g., composition, structure, productivity, water balance, or disturbance).

Here we review current remote sensing capabilities that can be used to characterize carbon, water, and nutrient cycling in managed forests. Our particular focus is describing remote sensing data and products describing key ecosystem attributes that can be used to parameterize process-based models, or scale inventory and field measurements to regional or even global extents. Despite the wide differences across the various scaling approaches, there are common spatio-temporal data requirements that can be addressed by remote sensing. Accordingly, we discuss the application of remote sensing to four key ecological aspects of forests: composition, structure, productivity and evapotranspiration, and disturbance dynamics.

Our emphasis is not exclusively on data sources that directly inform forest management (which often requires spatial resolution at the scale of individual stands), but more broadly on data sources useful for studying the ecological impact of forest management as a land use practice. We also note that the definition of "managed forest" itself is ambiguous, encompassing management goals as diverse as maximizing extraction (rapid rotation harvest, fertilization, thinning) and minimizing disturbance (fire suppression, protection from development). For example, large swaths of forest in the US and Canada are designated as "managed", although their composition and structure do not differ substantially from "natural" forests with similar land use history. Most of the discussion in this paper focuses on extractive management, including clear-cutting, partial harvest, and planting, by which human activities rapidly alter forest attributes. Given the increased societal attention to forest resource pressures and environmental uncertainty, we also discuss emerging challenges and opportunities in the use of remote sensing to inform forest science, management, and policy.

2. Remote sensing and scaling approaches

To support sustainable management of forest resources, we need to understand the broader implications of our local-scale knowledge of ecological processes. Most any scaling approach will first require at least one – or more typically many – geospatial map product(s) describing forest attributes across the landscape of interest. Whether using a simple spreadsheet or "book-keeping" approach (e.g., Houghton, 2003) or more sophisticated process-based simulation modeling (e.g., Melillo et al., 1993), the basic premise of a scaling approach is to associate a particular parameter with the land cover or forest type where it was measured, and then extrapolate its local value according to the areal extent and spatial pattern of that type across the mapped landscape. For example, in their book-keeping approach to estimate the forest-sector greenhouse gas budget of Mexico, de Jong et al. (2010) developed a nation-wide initial biomass estimate by extrapolating measured, per area carbon stock density values to the spatial extent of the main forest cover types based on medium spatial resolution (30 m) satellite data classification. In U.S. forests, higher spatial resolution maps of composition and structural attributes have been achieved using statistical scaling techniques that integrate inventory plot data with optical- and laser-based remote sensing (e.g., Blackard et al., 2008; Ohmann et al., 2014; Zald et al., 2014). At the global-scale, process-based simulations by biogeochemical and land surface models require initialization with maps of plant functional types (PFTs) that are typically based on coarse resolution ($\sim$1 km) remote sensing data products (e.g., Jung et al., 2006; Huntzinger et al., 2013; Wullschleger et al., 2014). Where data products are available at finer scales ($\sim$1 m–30 m), some process-based modeling applications can be directly initialized with spatially-explicit data on forest biomass (e.g., Kimball et al., 2000), structural characterizations (e.g., Hurtt et al., 2004) or foliar chemistry (Ollinger and Smith, 2005) (Fig. 1).

Repeat remote sensing imagery that captures forest dynamics through multiple observations over time is also used to explicitly drive inventory and modeling approaches for quantifying changes in carbon, water and nutrient cycling at landscape to regional scales. While model initialization data incorporate the spatial variability of a particular parameter, remote sensing driver data are used to represent the temporal dynamics of that parameter. In the greenhouse gas accounting example cited above, de Jong et al. (2010) calculated the change in Mexico forest-sector carbon stocks by updating their initial area-based biomass estimate with two time-periods of spatially-explicit land cover change maps classified from Landsat imagery. The national carbon accounting system in Canada is also largely driven by modeling the components of change based in part on remote sensing of forest disturbances, such as wildfires and insect outbreaks (Kurz et al., 2009). Similarly, these components of change can be incorporated into simulation modeling frameworks to capture the impacts of disturbance and land use change on ecosystem processes (e.g., Galford et al., 2010; Hayes et al., 2011; Turner et al., 2011). Remote sensing indices are also used in empirical and explicitly diagnostic scaling approaches, such as the global estimation of vegetation productivity based on the light-use efficiency (LUE) approach (Running et al., 2004) and the upscaling of site-level observations of carbon, water