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Assessing the provisioning potential of ecosystem services in a Scandinavian boreal forest: Suitability and tradeoff analyses on grid-based wall-to-wall forest inventory data

Jari Vauhkonen *, Roope Ruotsalainen

University of Eastern Finland, School of Forest Sciences, Yliopistokatu 7, P.O. Box 111, FI-80101 Joensuu, Finland
University of Helsinki, Department of Forest Sciences, Latokartanonkaari 7, P.O. Box 27, FI-00014 Helsinki, Finland

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A B S T R A C T

Determining optimal forest management to provide multiple goods and services, also referred to as Ecosystem Services (ESs), requires operational-scale information on the suitability of the forest for the provisioning of various ESs. Remote sensing allows wall-to-wall assessments and provides pixel data for a flexible composition of the management units. The purpose of this study was to incorporate models of ES provisioning potential in a spatial prioritization framework and to assess the pixel-level allocation of the land use. We tessellated the forested area in a landscape of altogether 7500 ha to 27,595 pixels of 48×48 m^2 and modeled the potential of each pixel to provide biodiversity, timber, carbon storage, and recreational amenities as indicators of supporting, provisioning, regulating, and cultural ESs, respectively. We analyzed spatial overlaps between the individual ESs, the potential to provide multiple ESs, and tradeoffs due to production constraints in a fraction of the landscape. The pixels considered most important for the individual ESs overlapped as much as 78% between carbon storage and timber production and up to 52.5% between the other ESs. The potential for multiple ESs could be largely explained in terms of forest structure as being emphasized to sparsely populated, spruce-dominated old forests with large average tree size. Constraining the production of the ESs in the landscape based on the priority maps, however, resulted in sub-optimal choices compared to an optimized production. Even though the land-use planning cannot be completed without involving the stakeholders' preferences, we conclude that the workflow described in this paper produced valuable information on the overlaps and tradeoffs of the ESs for the related decision support.

1. Introduction

Forest bioeconomy stimulates new industries to replace fossil-based materials using forest biomass for products such as bioenergy, chemicals, polymers, and wood-based structures (Puddister et al., 2011; Hannerz et al., 2014). The increased requirements to use forest biomass call for long-term considerations of the sustainability of and possible influences on the ecological, economic, cultural and social resource supply. The numerous goods and services provided by forests, such as habitats, biological diversity, recreational uses and other environmental functions in addition to the biomass and wood-based products, are broadly referred to as forest Ecosystem Services (ESs) (Costanza et al., 1997; Daily et al., 1997).

Excluding forest areas managed for the provision of specific ESs such as protection of water resources or erosion control (Krieger, 2001), the primary management objectives of a typical Scandinavian boreal forest are most often related to providing timber, habitats, recreational amenities (e.g., Kangas et al., 1992, 2008), and more recently, carbon storage or sequestration (Pukkala, 2016). These ESs can be categorized as in Table 1 following the classification of the Millennium Ecosystem Assessment (MEA, 2005). Even though an aggregate provisioning of several and parallel ESs is usually preferred over exclusive objectives related to single ESs (Hänninen et al., 2011), Table 1 illustrates the dimensions of the multiple criteria decision problem at hand: how to allocate a forest area to the production of various ESs, which differ in terms of rivalry and excludability (Wunder and Jellesmark Thorsen, 2014), require different forest management practices (Pukkala, 2016), and provide different benefits depending on the properties of the forest site and the objectives of its owner. When the preferences

* Corresponding author. Present address: Natural Resources Institute Finland (Luke), Economics and Society, Yliopistokatu 6, P.O. Box 68, FI-80101 Joensuu, Finland.

E-mail address: jari.vauhkonen@luke.fi (J. Vauhkonen).

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Table 1
Forest ecosystem services considered by our study, categorized according to MEA (2005).

Category	Example service (indicator; unit)	Stand-level forest attributes used for modeling the indicator values (citation)
Supporting service	Biodiversity management (conservation value based on expert opinion; index value)	Species composition, mean diameter, growing stock volume, site fertility (Lehtomäki et al., 2015)
Provisioning service	Timber production (soil expectation value; €/ha)	Mean diameter, basal area, age, site fertility, species-specific growing stock volume, number of trees, operational environment (temperature, interest rate, timber prices) (Pukkala, 2005)
Regulating service	Carbon storage (estimated amount of carbon; t/ha)	Total biomass converted to carbon (IPCC, 2003)
Cultural service	Recreational value (recreational amenity and suitability for berry picking; index values)	Mean diameter, basal area, age, site fertility, species-specific growing stock volume, number of trees (Pukkala et al., 1988; Ihalainen et al., 2002)

of the decision maker are known, rather generic tools can be applied to support the decision making based on the available data. Two broad categories of methods are presented in the literature (cf., Kangas et al., 2008): multiple criteria decision analysis (MCDA) for discrete and optimization for continuous problems, the applications of which are reviewed in a forestry context by Uhde et al. (2015) and Pukkala (2008), respectively, and by Langemeyer et al. (2016) regarding ES assessments in general.

To integrate multiple ESs in forest management planning, the benefits provided by the different services must be numerically described, assessed in the same scale and modeled according to measurable forest attributes (Pukkala, 2008). Although estimating the benefits in terms of monetary values is common (Troy and Wilson, 2006; Nelson et al., 2009; Bottalico et al., 2016), it may also be criticized due to methodological heterogeneity that produces uncertainties in the obtained results (see, e.g., D'Amato et al., 2016). Alternative methods build upon the Multi-Attribute Utility Theory (MAUT), in which a utility (or priority or benefit) function is a mathematical transformation that associates a utility with each alternative so that all alternatives may be ranked (Cohon, 1978). Such functions are most often used to estimate the preferences of a decision maker (e.g., Keeney and Raiffa, 1976). However, by quantifying all alternative forest management objectives in terms of the utility functions, both the qualitative and quantitative objectives can be analytically evaluated and compared with respect to the impacts on the overall and objective-specific utility (Kangas, 1993; Pukkala and Kangas, 1993). Utility functions that use forest mensurational parameters as predictors have been formulated for forest planning situations including habitat (Kangas et al., 1993a; Kurttila et al., 2002), landscape (Kangas et al., 1993b; Pukkala et al., 1995), or multiple ES related objectives (Pukkala and Kurttila, 2005; Hurme et al., 2007; Schwenk et al., 2012). Deriving utility functions with spatial criteria based on Geographical Information Systems (GIS) has also been proposed for both the MCDA (Store and Kangas, 2001) and optimization (Packalén et al., 2011).

Information on the production possibilities may have been available for political decision making of very large areas (e.g., Backéus et al., 2005), but rarely in the operational (compartment) scale due to the high data acquisition costs involved in conventional field inventories. Recent developments of remote sensing (RS) technologies have brought spatially explicit estimates of various forest inventory, structure and habitat related parameters available for vast areas (Tomppo et al., 2008a, 2008b, 2014; Maltamo et al., 2014; Barrett et al., 2016). For instance, generalizing field plot measurements using coarse- or medium-resolution RS and other numeric map data, referred to as Multi-Source National Forest Inventory (MS-NFI; Tomppo et al., 2008a) has been used to generate pixel-wise (Tuominen et al., 2010) or aggregated (Mäkelä et al., 2011) maps of biomass-related attributes, carbon (Akujärvi et al., 2016; Mononen et al., 2017), biological diversity (Lehtomäki et al., 2009, 2015; Räsänen et al., 2015), habitats (Vatka et al., 2014; Björklund et al., 2015) or berry yields (Kilpeläinen et al., 2016). Applying RS data to analyze multiple forest ESs, Frank et al. (2015) evaluated the biomass provisioning potential and tradeoffs for other ESs, when the land use of a region located in Germany was expected to change according to climate-adapted management scenarios. Sani et al. (2016) carried out a spatial MCDA based on multi-source data and expert knowledge to rank alternative land uses in a mountain forest in Iran. Matthies et al. (2016) assessed intra-service tradeoffs within the Payments for Ecosystem Services (PES) scheme based on the Finnish MS-NFI data. Schröter et al. (2014) examined tradeoffs between timber production and pooled biodiversity and other ES features using a pixel size of $500 \times 500\ m^2$. Despite the successful examples of using RS-based inventory data for the assessment of multiple ESs, we are not aware of results that would allow formulating management prescriptions at the level of operational management units (e.g., forest compartments).

In summary, even though RS-based data often describe the ESs as indirect proxies (Andrew et al., 2014), such maps may enable to spatially identify areas which differ with respect to the supply of the ESs and thus require different forest management (cf., Pukkala, 2016). Applying the RS-based proxies of the ESs in multi-objective forest management (e.g., Davis et al., 2001) of private forests produces specific, unsolved research questions, in addition to those generally present in integrating ESs in landscape planning (de Groot et al., 2010). In Europe, private forest owners hold 51% of the total forest area (FOREST EUROPE, 2015), this percent increasing toward northern Europe (Finland, Norway, Sweden). The derived management plan should instruct the forest owner on which silvicultural treatments to perform on individual forest compartments, typically 1.5–2 ha in size in Finland (Koivuniemi and Korhonen, 2006), to reach the overall objectives for the forest property. Applying existing models (Table 1) to the RS-based inventory data would allow wall-to-wall assessments of the provisioning potential of multiple ESs presented as a grid of pixels with a fraction-of-hectare scale, i.e., in a considerably more detailed resolution than the current operational compartments. This is expected to allow formulating management units that are more efficient in utilizing the production possibilities of the forest compared to conventional stands with fixed boundaries (Heinonen et al., 2007). In that case, essential questions are (i) to what degree do the alternative ESs overlap in the same area and (ii) what are the trade-offs for selecting one ES over another.

Our purpose was to perform a case study to provide an example of implementing decision analyses of multiple ESs using grid-based forest inventory data. Particular aims were (i) to analyze the degrees of overlap and spatial arrangements of the ESs prioritized to their most feasible locations; (ii) to explain the occurrences of sites with a potential to provide multiple ESs with respect to forest structure; and (iii) assess the degree of tradeoffs for an unconstrained optimal solution due to decisions to preserve a fraction of the landscape to the production of selected ESs based on the information obtained. The prioritization workflow and information sources are discussed based on these experiences.