Forest Ecology and Management 378 (2016) 193–205

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Using forest ecosystem simulation model EFIMOD in planning uneven-aged forest management

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ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form 27 July 2016
Accepted 27 July 2016

Keywords:
Simulation modelling
Forest management
Selection cuttings
Uneven-aged stands
Spruce forest
Timber production

ABSTRACT

Uneven-aged forest management is suggested to be a sustainable management alternative in boreal forests, but knowledge on applicable harvest intensities is very limited as majority of the studies has focused on even-aged management practices. The ecosystem model EFIMOD was used to assess the effect of selection cuttings on ecosystem production, carbon sequestration and volume increment in spruce stands. The model was calibrated and validated against experimental data from 20 permanent forest plots in southern Finland where stand responses to uneven-aged management had been monitored for 25 years. The simulated scenarios started with planting trees on bare land, simulation of first decades according to even-aged management, and a subsequent transformation into uneven-aged stand structure and management. Simulated selection cutting scenarios contained variations of both harvest interval (10–30 years) and postharvest stand density (basal area 8–16 m^2 ha^{-1}). We hypothesized that longer harvest intervals and higher post-harvest basal areas will positively affect the net ecosystem production, nitrogen use efficiency, and forest carbon sequestration. The results presented here are for a period of 90 years. Simulations showed that net ecosystem production (NEP) increased from 0.25 to 0.5 kg m^{-2} a^{-1} of carbon with longer harvest intervals and higher postharvest density, and was generally less than that at undisturbed development. Nitrogen use efficiency (NUE) varied from 100 kg NPP per kg consumed N for heavy cuttings to 300 kg NPP per kg consumed N for light removal of trees. Changes in soil carbon stocks were negative for most scenarios (5–20% decline in terms of total soil C), and the decline was most pronounced with lowest postharvest density and short harvest intervals. The volume of harvested timber was between 320 and 400 m^3 ha^{-1} for a 60-year period. Longer harvest intervals resulted in increased timber production. Stem volume growth (5–7 m^3 ha^{-1} a^{-1}) was equally affected by both harvesting parameters. The cumulative volume of deadwood of 80–120 m^3 ha^{-1} was substantially higher with the longest harvest interval (30 years) than with the shorter alternatives where it comprised 40–60 m^3 ha^{-1}. The simulations provide novel results on different harvesting options for uneven-aged forest management of boreal Norway spruce stands. These results fill a gap in knowledge on ecosystem responses to alternative management regimes and support the development of sustainable management practices.

1. Introduction

Vast boreal forests are globally important carbon sinks, because they provide ecosystem services essential to local communities, and they are widely used for commercial timber production (Nasi et al., 2002). Net primary production and timber production in boreal forests are affected by climatic and edaphic factors, tree species composition, and forest management regimes that control tree size distribution and development of stand structure through time. The prevailing silvicultural system in boreal forests has been the even-aged management of monocultures, which is favoured due to logistical reasons (in Canada and Russia) or determined in forest legislation as a method to organize sustained-yield forestry (e.g., in Finland) (Kuuluvainen et al., 2012). However, this system may not be the economically the most profitable alternative (Pukkala et al., 2013; Rämö and Tahvonen, 2014, 2015; Tahvonen et al., 2010). Additionally, the even-aged monocultures are

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http://dx.doi.org/10.1016/j.foreco.2016.07.041
0378-1127/

suggested to be vulnerable to disturbances and the consequences of climate change (O'Hara et al., 2007; Seidl et al., 2011). The low structural diversity of the tree stands is not optimal for biodiversity (e.g., MacArthur and MacArthur, 1961) and ecosystem productivity (Dănescu et al., 2016).

Studies on alternative management methods are still sparse, and a general theory and knowledge of silvicultural possibilities other than even-aged management in boreal forests has been poorly developed. Recent economic analyses of forest management regimes (e.g., Tahvonen et al., 2010) and advances in forest modelling (e.g., Mäkelä et al., 2012; Mäkipää et al., 2014) have responded to the high societal need for such information (Valkeapää and Karppinen, 2013) and opened the avenue for further studies on management alternatives including uneven-aged or continuous cover forest management.

There is a large experimental research legacy on even-aged forest stands treated with thinnings from below or light thinnings from above with observation periods covering numerous decades (Huuskonen et al., 2014) and models based on them (e.g., Gobakken et al., 2008; Hynynen et al., 2005; Wikström et al., 2011). Uneven-aged management is characterized by a much greater degree of complexity and dynamics. In selection management, harvesting removes mostly large trees from the upper canopy layers, leaving behind smaller trees with a variable degree of suppression that respond to the increased availability of resources with delay. Constant promotion of tree vigour with repeated harvesting and relatively low standing volume is proposed to be essential in selection management. Therefore, preharvest volume, harvest interval and removal percentage, and vigour of the remaining trees constitute a set of entwined growth factors to be accounted for when analysing and predicting tree and stand growth in selection management. Forest management focuses on establishing forest stand conditions that enhance wood increment and maximize forest income. In irregularly structured stands, intensity of inter-tree competition varies depending on the tree size distribution (Peltoniemi and Mäkipää, 2010). In stands with multiple tree cohorts and canopy layers, light use efficiency (LUE) can be higher than in stands with one tree cohort, and the effect on stand productivity is suggested to be dependent on the shade tolerance of the tree species (Gspaltl et al., 2013). Far less is known about the belowground competition (which is even more important in north boreal forests) and nitrogen use efficiency of stands with multiple tree species with uneven tree size distributions. When the net ecosystem production and timber yield of a multispecies uneven-aged stand is evaluated, it is essential to have an understanding and a spatially explicit model that accounts for both above-ground competition for light and below-ground competition for soil resources.

Modern experiment-based studies in forestry have often been accompanied by forest simulation models that are used to assess and compare different management strategies (Pretzsch et al., 2008; Pukkala et al., 2009; Shanin et al., 2011; Söderbergh and Ledermann, 2003).

In this study, we used the ecosystem model EFIMOD (Komarov et al., 2003). It is built on population ecology (Odum, 1959) and matter-balance principles (Chapin et al., 2002), and it can capture important ecological processes in a forest stand: soil decomposition processes, growth processes and light and root competition that enables us to simulate ecosystem response to fast and severe environmental changes. The model is individual-tree based and utilizes the exact spatial location of each tree. This feature allows us to simulate cuttings (harvesting) of any strength, with the ability of 'fine-tuning' a treatment such as individual tree selection in which case a local competition cannot be ignored. In this study, EFIMOD was tested against experimental data from a unique experimental set with spruce forests actively managed with single-tree selection for 25 years and intensively monitored for growth and regeneration parameters (Eerikäinen et al., 2007, 2014; Saksa and Valkonen, 2011).

The overall objective of the study was to assess the influence of harvest treatments in selection cuttings on net ecosystem production (NEP), nitrogen use efficiency (NUE), carbon sequestration, and timber production by means of simulation modelling. The simulations provide novel results for uneven-aged forest management by quantifying differences between various harvest regimes, i.e. we show how ecosystem will response to varied harvest interval and post-harvest basal area (harvest intensity).

We hypothesize that (i) the highest net primary productions are obtained with long harvest intervals, which also results on largest annual volume growth, since nitrogen use efficiency is highest in fully stocked stands; (ii) long harvest intervals result in highest timber production, but the proportion of harvested timber of the total timber volume will be relatively low, since the volume of growing stock and natural mortality are high; (iii) increase in the post-harvest basal area results in increasing NEP, forest carbon sequestration and nitrogen use efficiency, but decrease in the harvested timber volume due to larger natural mortality.

The investigation of ecosystem response to harvesting by simulation models represents an alternative option to experimental thinnings that might be applied in uneven-aged management of boreal Norway spruce stands to improve practices for balancing economic and ecological performances. In the study, we first calibrate ecosystem model EFIMOD by experimental wood yield data from 20 harvest treatment plots in southern Finland and test its validity against the data. Second, we compare effects of varied harvest treatments on NEP, NUE, forest C sequestration and timber yields by simulation of ecosystem dynamics. Third, we discuss the applicability of our results to practical uneven-aged forest management.

Our study was intended to fill a gap in the current knowledge on quantitative indicators of sustainability of uneven-aged forest management and evaluate their performance by several simulation experiments.

2. Materials and methods

2.1. Short description of the EFIMOD model

The EFIMOD is a spatially explicit, individual-tree based model that simulates the biological turnover in tree-soil systems (Komarov et al., 2003), which was recently improved by adding a root competition model (Shanin et al., 2015). EFIMOD operates with an annual time step. A simulated stand consists of individual trees which interact with neighbouring trees. Each tree forms a shadow zone and nutrition zone, the sizes of which depend on the tree size. The shape of the rooting zone of an individual tree is defined by the availability of nitrogen in the soil and its interaction with neighbouring trees. Zones of nutrition can overlap for neighbouring trees, and available nitrogen is consumed proportionally to the mass of fine roots of the neighbouring trees in these overlapped areas and the age of the tree. Belowground competition is species-specific and depends on the dispersion of roots and their density per square unit in different soil layers. Thus, two possible types of tree increment can be calculated: one due to light and another due to soil nitrogen availability. The calculation requires species-specific estimates of leaf or needle and fine root biomass, maximal biological productivity of leaves or needles, and the specific nitrogen consumption rate. The minimal value of these two increment parameters is taken as the annual increment, following Liebig's law of the minimum. The annual net production of each tree is distributed among five compartments (stem, branches,