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Managing a boreal forest landscape for providing timber, storing and sequestering carbon

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ABSTRACT

Human well-being highly depends on ecosystem services and this dependence is expected to increase in the future with increasing population and economic growth. Studies that investigate trade-offs between ecosystem services are urgently needed for informing policy-makers. We examine the trade-offs between a provisioning (revenues from timber selling) and regulating (carbon storage and sequestration) ecosystem services among seven alternative forest management regimes in a large boreal forest production landscape. First, we estimate the potential of the landscape to produce harvest revenues and store/sequester carbon across a 50-year time period. Then, we identify conflicts between harvest revenues and carbon storage and sequestration. Finally, we apply multiobjective optimization to find optimal combinations of forest management regimes that maximize harvest revenues and carbon storage/sequestration. Our results show that no management regime alone is able to either maximize harvest revenues or carbon services and that a combination of different regimes is needed. We also show that with a relatively little economic investment (5% decrease in harvest revenues), a substantial increase in carbon services could be attained (9% for carbon storage; 15–23% for carbon sequestration). We conclude that it is possible to achieve win–win situations applying diversified forest management planning at a landscape level.

1. Introduction

Over the past centuries, humans have had a tremendous impact on their environment, mostly to meet rapidly growing demands for resources along with economic development (Vitousek et al., 1997). These demands have caused severe ecosystem degradation and biodiversity loss (e.g., MEA, 2005; Rapport et al., 1998). Ecosystem services represent direct and indirect benefits that people obtain from ecosystems (MEA, 2005) and our dependence on their consumption is expected to increase in the future with an increasing population and economic growth (Guo et al., 2010). Therefore, studies about trade-offs between ecosystem services are urgently needed to inform decision-makers and managers of natural resources to take appropriate management actions. As a result, international, continental and national policies have been formulated such as the Intergovernmental Platform on Biodiversity and Ecosystem Services, the European Union Biodiversity Strategy for 2020 and the Finnish national strategy (www.ipbes.net, European Commission, 2010; Finnish Government Resolution, 2012).

Many crucial ecosystem services are provided by forests (Gamfeldt et al., 2013; García-Nieto et al., 2013; Vanhanen et al., 2012). The boreal biome represents approximately one-third of all remaining global forests (Bradshaw et al., 2009; Hansen et al., 2010) and constitutes approximately 45% of the world's stock of growing timber (Vanhanen et al., 2012). Moreover, boreal forests store about one third of the global terrestrial carbon in forests (Pan et al., 2011). Therefore, the absence of boreal forests from global policy agendas on climate change mitigation (e.g., REDD+ program) represents an important

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missed opportunity that should be corrected (Moen et al., 2014). Most commercial forests worldwide have been intensively managed for maximizing the provision of timber, while maintaining biodiversity and other ecosystem services such as water and climate regulation, soil retention and recreational values have received less attention (Gerasimov et al., 2012; Guariguata et al., 2012). Management based on a single ecosystem service is potentially problematic, as it might undermine the long-term provision of other ecosystem services (Balvanera et al., 2014; Rodríguez et al., 2006). For example, in northern Europe, intensive forest management for timber production might reduce water quality (Eriksson et al., 2011). Moreover, intensive timber extraction has caused profound ecological changes in forests like simplification of stand structure (e.g., homogenization of tree's age and composition), reduction of dead wood, altered disturbance dynamics (e.g., fire suppression) and the loss and fragmentation of old growth forests (Brumelis et al., 2011; Hanski, 2005; Siitonen, 2001). Thus, the biggest challenge in forest management is to simultaneously maintain the provision of timber, biodiversity and other ecosystem services (e.g., de Groot et al., 2010).

Forests help to regulate climate and, more specifically, mitigate climate change by sequestering CO_2 from the atmosphere and storing it in different biomass pools (e.g., Powers et al., 2013). *Carbon storage* represents the carbon stock (the amount of carbon fixed in the system at a given time; size of storage pools) whereas *carbon sequestration* represents the carbon flux (the amount of carbon exchange between atmosphere and forests between two points in time) (Powers et al., 2013). Even though values of *carbon storage* and *sequestration* will tend to coincide in the long term because all carbon fixed through photosynthesis will eventually be released back to the atmosphere (Liski et al., 2001), they represent different aspects of climate regulation when considering forest management for a short period of time. Trees sequester carbon as they grow, so a critical aspect in carbon sequestration is the rate of tree growth (van Kooten et al., 1995). Usually fast-growing tree species sequester more carbon at the beginning of their lives, whereas carbon sequestration rates for slow-growing trees will be higher later on (Nghiem, 2014). Since about 12.5% of anthropogenic carbon emissions from 1990 to 2010 are due to land-use change and deforestation (Houghton et al., 2012) sustainable forest management can play an important role in climate change mitigation. Forest management practices can greatly affect whether forests act as net carbon sources or sinks (e.g., Birdsey et al., 2006).

Finland is the most forested country in Europe and in the boreal zone (UNEP FAO and UNFF, 2009) with around 86% of its territory covered by forests and most of Finland's forests are under commercial management (Finnish Forest Research Institute, 2011). There is a long history of forestry in Finland and this expertise can be seen as an opportunity to develop and implement management practices that promote ecosystem services besides timber production (Moen et al., 2014). For example, the frequency and intensity of thinning play very important roles in timber production and carbon sequestration (Cao et al., 2010; Hynynen et al., 2005) as well as in berry production (Miina et al., 2010). Regulating the rotation length is also an effective way to increase forest carbon sequestration (Hynynen et al., 2005; Liski et al., 2001) and berry production (Miina et al., 2010). Therefore, investigating the effects of different land-use and management decisions on different ecosystem services is vitally important.

In this study, we examined trade-offs between a provisioning ecosystem service (timber) and regulating ecosystem service (carbon storage/sequestration) across a large boreal forest production landscape in central Finland. Using market prices, we estimated the net present value of harvest revenues to measure the economic value of timber production as a provisioning service. However, we used the biophysical amount of carbon to measure regulating services, as the carbon markets are still not established for boreal forests. Our main aim is to identify forest management regimes which improve simultaneously both ecosystem services studied. We go beyond previous studies and incorporate forest dynamics by simulating forest growth in a landscape with about 30,000 stands during 50 years to obtain future forest growth and yield projections. Forest stands are simulated considering seven alternative management regimes ranging from the recommended management (business as usual) to setting aside entire forests stands. The effects of several forest management regimes on multiple ecosystem services in a dynamic context have been rarely assessed (an exception to this is given in e.g., Pukkala et al., 2011). We also apply multiobjective optimization for analysing trade-offs between these different objectives (Miettinen, 1999). The explicit analyses of trade-offs can identify where the current management actions are inefficient to provide multiple goods or services, such as timber production or carbon storage. These analyses can also identify situations where carbon storage can be increased without any, or with only minimal, reductions in the production of timber, or vice versa. Specifically, we address the following questions: (i) What is the potential of the forest landscape and the optimal combinations of management regimes to simultaneously produce economic revenues and regulate climate? (ii) Is there a difference between the two carbon measures regarding to their trade-offs with timber production? This is an interesting question as carbon storage and sequestration reflect different aspects of climate regulation.

2. Material and methods

2.1. Study area

Our study area is a typical boreal production forest landscape located in Central Finland (62°14′N, 25°43′E) (Fig. 1). The total area is 687 km^2 and forest on mineral soils covers 55%, peat lands 13%, lakes 16% and farmland settlement some 15% of the area. Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), birch (*Betula pendula* and *Betula pubescens*) and mixed stands dominate the forest consisting of 29,706 stands of an average size of 1.45 ha (stand size ranges between 0.06 and 17.5 ha). Past forest management practices have resulted in a bimodal age structure of forest stands with a large proportion being less than 40 years of age, and another large part being between 70 and 90 years old (see the complete distribution of stand age in Fig. S1 in Supplementary material).

2.2. Forest data, management regimes and forest growth simulations

We extracted data for forest growth modelling from the data administered by the Finnish Forest Centre, a governmental administrative organization for legal control and enhancement of forestry in private land. The data are organized as forest stands that are basic units for forest inventories. We considered seven alternative management regimes for each stand (see Table 1): (1) *BAU* (Business as usual): in this management regime thinning and final harvest are conducted according to current recommendations (Yrjölä, 2002) which results in more or less homogeneous monoculture of trees; (2) *SA* (Set aside) represents a permanent conservation strategy; (3) *EXT10* (Extended rotation by ten years): postponing final harvest produces some additional mortality (more dead wood) and larger and older trees. This strategy represents a short-term conservation strategy; (4) *EXT30* (Extended rotation by thirty years) represents a long-term conservation strategy; (5) *GTR30* (Green tree retention) represents a conservation oriented management regime that attempt to mimic and restore