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Developing alternative forest spatial management plans when carbon and timber values are considered: A real case from northeastern China

Lingbo Dong[a], Wei Lu[b], Zhaogang Liu[a,*]

[a] College of Forestry, Northeast Forestry University, Harbin 150040, China
[b] College of Forestry, Agricultural University of Hebei, Baoding 071000, China

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ABSTRACT

Forest ecosystems play an important role in mitigating global climate change, and this role has recently been further reinforced by the Paris Agreement. However, our knowledge with respect to the trade-offs between timber production and carbon sequestration in forest ecosystems is still seriously deficient. Therefore, the overall goal of this study is to quantitatively analyze the effects of a set of economic and ecological constraints on the joint production capacity for forest timber and carbon by alternative forest management strategies for a large forest in northeastern China. The proposed forest planning models integrate four alternative forest management strategies, namely, the timber-oriented management strategy (TMS), the carbon-oriented management strategy (CMS), the multiobjective management strategy (MMS), and the resource-restricted management strategy (RMS). Four different planning scenarios for each strategy were further generated by successively adding one additional constraint, which mainly included the even-flow of timber production, the adjacent constraints of harvest activities, and the minimum targets of carbon sequestration, over a 50-year planning horizon. The results showed that increasing the prices of carbon resulted in positive quadratic polynomial total and carbon net present values (NPVs), positive logistic carbon sequestration and stocks, and negative logistic harvest of timber and its NPV for optimal forest management plans, in which the carbon price of $100 per ton was a significant threshold for balancing the harvest of timber and carbon sequestration. In addition to the CMS, our tested spatial and nonspatial constraints all showed significant effects on optimal forest management plans when a realistic carbon price (i.e., $20 ton^{-1}) from the carbon trading market in China during 2014–2017 was employed, in which decreases of approximately 29.34% and 25.08% were observed for total NPV when twenty-percent deviations in harvest volume between any two consecutive periods were employed. Additionally, two periods of green-up constraints could further reduce the total NPV by approximately 17.87% and 15.73% for TMS and MMS, respectively, when compared with their base scenarios. However, increasing the minimum carbon target by one percent reduced the total NPV by approximately $29.44 per hectare per year when evaluated for RMS. Our optimization framework not only can be replicated in other regions with similar characteristics but also contributes to the ongoing debate about the trade-offs between carbon sequestration and wood production benefits.

1. Introduction

Forest management operations usually have significant effects on the structure and function of forest ecosystems. Therefore, there is an obvious need to model the effects of various forest management prescriptions on the evolution of forest ecosystems over time to choose optimal management alternatives. Forest management optimization can provide the most desirable forest plans (i.e., the temporal and spatial configuration of management actions) in terms of the global objectives and constraints of the entire forest enterprise; additionally, it can be used to quantitatively analyze the potential uncertainty and risk of complex forest decision-making processes, including forest inventory errors, growth prediction errors, the performance of various product markets, the preferences of decision makers, the unpredictability of natural hazards, and the effects of climatic changes (Pasalodos-Tato et al., 2013; Bettinger et al., 2013). In recent decades, public concerns about forest management have gradually transformed from traditional timber production goals to ecosystem-based services (e.g., carbon sequestration, biodiversity, wildlife habitat) and recreational (e.g., landscape aesthetics, oxygen production) values. However, the interactions

* Corresponding author.
E-mail addresses: farrell0503@126.com (L. Dong), sanpangzi1228@126.com (W. Lu), lzg19700602@163.com (Z. Liu).

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among these multitudinous goods and services of forest ecosystems can either be viewed as a trade-off or a synergy (Cademus et al., 2014), which are usually present in typical nonlinear relationships. Meanwhile, some additional nonlinear constraints are also necessary when other additional objectives are integrated, and the interactions between the objective and predefined spatial constraints are also ambiguous. Thus, considering more objectives may significantly increase the complexity of traditional harvest scheduling models, and analyses of these problems are also becoming more time consuming and resource demanding.

Recently, the role of forest ecosystems in mitigating global climatic changes has been further supported by the Paris Agreement (Framework Convention on Climate Change, 2015), which was approved by approximately 175 countries worldwide in 2015. Therefore, each country that ratified the Paris Agreement should implement appropriate policies and provide positive incentives for reducing emissions, for preventing deforestation and forest degradation, and for increasing the carbon stocks of forests (Framework Convention on Climate Change, 2015). However, the carbon benefits provided by forest ecosystems are generally considered to conflict with traditional timber production; thus, incorporating carbon objectives into the forest management planning process has created large challenges in forestry research and development. In recent years, some papers have successfully integrated carbon objectives into forest planning models. For example, Backéus et al. (2006), Bourque et al. (2007), Hennigar et al. (2008), Raymer et al. (2011) and Chen et al. (2011) incorporated carbon objectives into forest harvest scheduling models using traditional mathematical programming (i.e., linear programming, goal programming). Krcmar et al. (2005), Yousefpour and Hanewinkel (2009) and Baskent and Keles (2009) further incorporated other forest management objectives (e.g., biodiversity, water and oxygen) beyond timber and carbon benefits into forest planning models using linear programming. These studies have increased our knowledge of the trade-offs between timber production and carbon sequestration in forest ecosystems, but they focused only on nonspatial planning problems. Obviously, the specific management prescription implemented in any given management unit (or stand) may have significant effects on the adjacent units, e.g., the clear-cutting prescription of one stand may increase the risk of wind damage (Zeng et al., 2007; DuPont et al., 2015) or bark injury (Behjou, 2014) in a neighboring stand. Therefore, it is nearly impossible to simultaneously address several important social concerns in forest management practices without considering the spatial details.

Planning problems can usually be classified into two categories, i.e., spatial planning models and nonspatial planning models, based on whether they contain the necessary spatial information. Generally, nonspatial forest planning models are formulated with continuous variables (i.e., the percentage or hectares of a specific stand); in contrast, spatial forest planning models mostly focus on basic management units (or stands), in which the decision variables are typically represented by binary variables that can take only the values of 0 or 1. There are various ways in which forest harvest spatial constraints can be integrated into forest planning processes (McDill and Braze, 2000); however, the unit restriction model and the area restriction model are two of the most frequently used spatial constraint types in the forestry literature (Bettinger et al., 2002; Crowe and Nelson, 2005; Öhman, 2011; Tóth et al., 2013; Borges et al., 2015). These two approaches may be suitable for different planning problems (Murray, 1999), and selecting an approach mainly depends on the size of the stand relative to the maximum opening area. Generally, if the average size of the management units (or stands) across the forest landscape is similar to the maximum opening area, then two arbitrary neighboring units cannot be simultaneously harvested under the unit restriction model planning approach; however, in the area restriction model planning approach, two or more neighboring units can be harvested in the same period (or in adjacent periods) as long as their combined area does not exceed the maximum opening area (Murray, 1999). In fact, the unit restriction model can be treated as a special case of the area restriction model; thus, the area restriction model is typically a much more powerful and complex approach than the unit restriction model. The effects of various harvest adjacency constraints on a set of important forestry planning problems have been evaluated by several previous studies that mainly focused on forest economic and commodity production (Boston and Bettinger, 1999; Tóth et al., 2013), wildlife habitat preservation (Bettinger et al., 2002; Öhman, 2011), forest landscape maintenance (Baskent and Jordan, 2002), and water production (Baskent and Keles, 2009). The study by Dong et al. (2015a,b), to the best of our knowledge, is the only study that has included carbon benefits in the consideration of harvest adjacency constraints (i.e., area restriction model) in forest planning. However, Dong et al. (2015a,b) focused only on the results of a set of different age-class structures and did not consider the effects of various economic- and ecological-oriented forest management strategies on the carbon sequestration function of forest ecosystems.

The overall goal of this study is to quantitatively analyze the effects of a set of economic and ecological constraints on optimal management plans that include four alternative forest management strategies for a large forest in northeastern China. Our hypotheses were as follows: 1) a threshold carbon price might exist that affects the balance between harvesting timber and keeping trees to sequester carbon and 2) spatial constraints may have much larger effects than nonspatial constraints on joint economic profitability when forest timber and carbon objective are considered simultaneously. Therefore, the specific objectives are to 1) develop a spatially explicit forest management planning model that simultaneously considers carbon and timber benefits of forest ecosystems; 2) optimize the proposed planning model using a heuristic simulated annealing process; 3) analyze the sensitivity of the optimal management plan to various carbon prices; and 4) evaluate the effects of a set of economic and ecological constraints on the optimal management plans for the alternative forest management strategies. In all analyses, the results are presented and examined based on the amount and the net present value (NPV) of timber production and carbon sequestration over a planning horizon of 50 years.

2. Materials and methods

2.1. Case study area

The study area of Pangu Forest Farm is situated in Heilongjiang Province in the northeastern region of China (Fig. 1). The study area comprises an area of 123,423 ha, and approximately 96.72% of this area is subject to harvest scheduling. The remaining area is mainly composed of settlements, wetlands and mining areas. The forested area has 325 compartments and 6421 subcompartments (or stands) with an average size of 19.21 ha. Each stand has different species, ages, site qualities and stages of development. The forest contains coniferous and broadleaf species along with some forest openings. The main tree species are larch (*Larix gmelinii*) and birch (*Betula platyphylla*). Other species found in this area include *Pinus sylvestris*, *Picea asperata*, *Populus davidiana* and *Salix matsudana*. Of the total initial growing stock of $9.44 \times 10^6\,m^3$, the initial growing stocks are $2.43 \times 10^6\,m^3$ for larch forest (25.67%), $1.62 \times 10^6\,m^3$ for birch forest (17.17%), $3.16 \times 10^6\,m^3$ for mixed coniferous forest (33.46%), $2.02 \times 10^6\,m^3$ for mixed coniferous-broadleaf forest (21.37%), and $0.22 \times 10^6\,m^3$ for mixed broadleaf forest (2.30%). The age-class structure of the planning area is illustrated in Table 1.

2.2. Forest planning model

Forest ecosystems provide a wide range of goods and services, such as provisioning services (e.g., timber and nontimber products), regulating services (e.g., soil protection and water resources), cultural services (e.g., recreation and employment opportunities) and