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Modelling the spatial forest-thinning planning problem considering carbon sequestration and emissions

Wan-Yu Liu [a,*], Chun-Cheng Lin [b], Ke-Hong Su [b]

[a] Department of Forestry, National Chung Hsing University, Taichung 402, Taiwan
[b] Department of Industrial Engineering and Management, National Chiao Tung University, Hsinchu 300, Taiwan

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ABSTRACT

Appropriate forest thinning is beneficial for growing forests and protecting ecological environments. To determine a beneficial approach in both economic and environmental aspects, carbon sequestration and emissions caused by forest-thinning activities can be traded. However, previous research on forest planning has not considered a detailed and sophisticated calculation for forest thinning and carbon sequestration. Hence, this study proposes a spatial forest-thinning planning problem involving carbon sequestration and emissions, which determine forest-thinning schedules over a planning period so that the total thinned timber volume over the period and the revenue from carbon sequestration and emissions can be maximized under certain spatial constraints. For this research, we first created a novel mathematical programming model, which can generally solve only small-scale problems. Therefore, this study also proposes an improved simulated annealing heuristic approach (ISA), which iteratively searches for a near optimal solution with two improved designs: a spatial local search operator and a neighborhood search scheme. The simulation results obtained using 300 forestland instances revealed that the proposed ISA can achieve better results through the proposed spatial local search operator, and run more efficiently through the proposed neighborhood search scheme. In addition, the decision regarding carbon sequestration and emissions was verified to be clearly advantageous for the cycling and sustainability of forest resources.

1. Introduction

Forests are one of the most crucial ecological components in the earth's biosphere, playing a key role in reducing atmospheric CO_2 levels, providing habitat for animal communities, regulating hydrological turbulence, and protecting the soil. Forest planning includes numerous forest management activities; for instance, forest harvesting and renewal (Liu and Lin, 2015), forest conservation (avoiding excessive deforestation) (Fotakis, 2015), forest restoration (including afforestation and reforestation), forest tending, the management and usage of nonwood forest products in forests, and the establishment and tending management of urban forests. The forest planning in this study involves identifying a balance between economic and environmental benefits in forest harvesting. Forest harvesting or planning is generally characterized by a computationally complex mathematical model, because it concerns various economic and environmental factors, such as different management units and time periods, adjacency and green-up constraints associated to environmental objectives and regulations, the amount of timber to be harvested, whether the forestland is to be developed into a tourist area, the water supply, the range and size of the biological habitat, and ecological maintenance (Kazana et al., 2003; Arabatzis, 2010).

Forest planning includes temporal and spatial dimensions. Aside from the planning time period, the temporal dimension considered in recent studies has shifted to including the tree growth time (Myronidis and Arabatzis, 2009; Fotakis et al., 2012), because the model that considers the temporal dimensions of both planning periods and tree growth time is more complete. For the spatial dimension, the adjacency constraint (Wilkinson and Anderson, 1985; Murray, 1999; Kurttila, 2001) restricts two adjacent forest areas from being harvested concurrently. Note that the adjacency constraint considered in this study is the URM (unit restriction model) (Murray, 1999), and another frequently-used model is the area restriction model (ARM), which incorporates the construction of clusters from stands. In addition, the adjacency constraint usually involves with the green-up constraint (Nalle et al., 2005), which allows only the forests that grow for more than a minimum time period or until a certain tree height to be harvested. Forest-planning problems with various objectives and constraints have been modelled and solved using mathematical programming methods (Hoganson and Rose, 1984; Hof and Joyce, 1993; Borges and Hoganson, 1999). However, mathematical programming methods cannot mitigate large-scale problems because they are involved with

* Corresponding author.
E-mail address: wyliu@nchu.edu.tw (W.-Y. Liu).

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integer variables so that they are generally computationally complex, i.e., they could not be solved efficiently by software on ordinary computers. Hence, various heuristic and metaheuristic approaches have been proposed; for instance, the nonsorting genetic algorithm II (Deb et al., 2002; Ducheyne et al., 2004, 2006), Monte Carlo integer programming (Boston and Bettinger, 1999), threshold accepting (Dueck and Scheuer, 1990), the great deluge algorithm (Dueck, 1993), the evolutionary algorithm (Liu et al., 2006; Mathey et al., 2007), simulated annealing (SA) (Ohman and Eriksson, 2002; Borges et al., 2014; Dong et al., 2015a), and the cultural algorithm (Liu and Lin, 2015). These approaches for forest planning generally adopt a scheme that circumvents local optimal solutions while searching for solutions. Among these approaches, SA has been shown to produce among the best solutions efficiently for some forest-planning problems with spatial concerns (Bettinger et al., 2002; Boston and Bettinger, 1999; Liu et al., 2006; Lockwood and Moore, 1993; Ohman and Eriksson, 2002; Ohman and Lamas, 2005).

Dong et al. (2015b) considered the forest-planning problem with carbon sequestration, in which the utility function consists of the harvested timber volume, carbon stocks, and spatial aggregation of the management activities. Their simulation considered forests of four ages (i.e., the actual, young, normal, and older), and the SA was applied to search for the maximal utility for forests at four ages. They found that the older forest landscape has the highest average utility value. Their work is of interest because it integrates the harvested timber volume, carbon stocks, and spatial aggregation of the management activities in a utility function. Note that these factors have been receiving much attention from ecological environmental and landscape aspects. The authors provided forest managers a comprehensive analysis to understand the performance of the three factors of different forest landscapes.

This study proposes a novel spatial forest-planning problem involving forest thinning and carbon trading, which have never been considered in previous research. These two concerns are respectively explained as follows:

Forest harvesting is further classified into clearcutting, thinning, and selective harvesting. Forest clearcutting involves nearly all trees in an area to be harvested being felled. The advantage of clearcutting is that it allows the convenience for mechanical logging by using large ground-based equipment (e.g., excavators), and does not require identifying the trees that should be felled. However, forest clearcutting could negatively impact the soil, with potentially harmful effects on sapling (young tree) growth, water conservation due to erosion, the landscape, and animal dwellings. In addition, certain countries or areas do not allow any forest clearcutting (e.g., Taiwan). However, forest thinning involves the selective removal of trees. Generally, only trees that have achieved the standard to be cut (i.e., when some tree branches or stems impede the growing space of other trees) can be felled, whereas the others are left to grow. Selective harvesting also involves the selective removal of trees. The difference of selective harvesting from forest thinning is that the former harvests mature, overripe, and defective trees and reserves a sufficient number of healthy trees with commercial value; the latter moderately trims trees to tend trees and improve adjustment of growing space. Note that the method in this study can be applied to both thinning and selective harvesting under assumptions for problem simplification; only thinning is mentioned in the rest of this paper.

Appropriate forest thinning is beneficial, because it allows uncut trees to have more space to grow, so that more timber can be harvested (Assmann, 1970, 1961); the ecological environment can be protected (Beck, 1983; Haveri and Carey, 2000); forest resources can keep growing and be reused; and sustainable forest management can be achieved. Therefore, timber harvesting in some countries or regions involves forest thinning. However, to the best of our knowledge, conventional spatial forest-planning problems have not provided detailed and sophisticated calculation for forest thinning and carbon concerns.

Long-term forest planning should consider not only economic aspects but also ecological environments and social responsibility (Kangas and Kangas, 2005). Greenhouse gas (GHG) is one of the reasons for global warming. The main GHGs are water vapor (about 60–70%) and CO_2 (about 26%). Relatively speaking, humans are more able to control CO_2 emissions (from controlling the amount of human's burning fuels, deforestation, and biological respiration). Thus, CO_2 emissions receive a lot of attention, and are regarded as one of the major methods to mitigate global warming. Except for external forces (e.g., being absorbed by trees), atmospheric CO_2 levels are not easily reduced. As human activities are one of the reasons for CO_2 emissions, the amount of CO_2 emissions increase with a rising global population. Hence, certain green projects have been proposed for CO_2 adsorption (Hassall and Associates, 1999, p. 23), and have fostered an emerging carbon-trading market through which the sequestration and emissions of carbon are commodities that can be traded. Based on the Kyoto Protocol and the Paris Agreement, those countries that signed the agreements has a regulated yearly quota of CO_2 emissions, and will be encouraged if its carbon emissions do not exceed the quota.[1] In the forest carbon-trading market, if forestland owners (sellers) afforest or reforest their land, they will obtain some quota of carbon sequestration (carbon certificates). When a firm (buyer) exceeds its regulated quota of CO_2 emissions, it can purchase the carbon sequestration quota from the sellers to offset its own insufficient quota to achieve the goal of reduction of carbon emissions. Thus, the sellers will obtain carbon benefits except for timber revenues. Conventional forest-planning problems rarely considered forest carbon trading. Recently, Dong et al. (2015b) have considered the forest planning problem with carbon sequestration. However, their work did not consider transforming carbon sequestration and emissions into the total net present value (NPV) to be traded, and did not focus on forest thinning.

This study proposes a spatial forest-planning problem that simultaneously considers forest thinning and carbon trading. Because a forestland is divided into multiple grids in which forests of each grid are assumed to be the same age (Borges et al., 2014), this problem involves determining a forest-thinning schedule for each year over a planning period (i.e., to determine the timber volume thinned in each grid at the end of each year), so that both the total harvested timber volume over the period and the revenue from carbon trading are maximized under the adjacency constraint (in which forests in two adjacent grids cannot be thinned concurrently) and the even timber flow constraint (in which the timber volume thinned this year must be no <90% and no >110% of that thinned the previous year).

Note that the ratio of the timber harvested for heavily thinning achieves up to 36% (Štefančík and Bošeľa, 2014). If adjacent grids apply the heavily thinning, the wildlife and habitat could be destroyed. Therefore, this study considers the adjacency constraint for forest thinning. To simplify this problem, the number of treatment schedules (TSs) is assumed according to the analogy by Borges et al. (2014); each TS determines a timber volume thinned in each grid at the end of each year. Next, solving this problem involves identifying the TS applied in each forest grid. To address this problem, we first establish a mathematical programming model for it. Because SA has been shown to yield good performance in solving large-scale forest-planning problems (Bettinger et al., 2002; Boston and Bettinger, 1999; Liu et al., 2006; Lockwood and Moore, 1993; Ohman and Eriksson, 2002; Ohman and Lamas, 2005), we improve the SA to solve this problem. The main features of the proposed problem and approach are listed as follows:

- This study integrates the spatial forest-planning problem with a detailed and sophisticated mathematical formulation for forest thinning and carbon trading.
- Although the proposed SA approach is based on the SA approach for

[1] UNFCC, Paris Agreement – Status of Ratification. Available at: http://unfccc.int/2860.php