Current Forestry Reports (2018) 4:150–160
https://doi.org/10.1007/s40725-018-0080-9

INTEGRATING FORESTRY IN LAND USE PLANNING (P BETTINGER, SECTION EDITOR)

Incorporating Carbon and Bioenergy Concerns Into Forest Management

Atsushi Yoshimoto[1] · **Patrick Asante**[2] · **Shizu Itaka**[3]

Abstract

Purpose of Review The primary focus of this paper is to review articles that incorporate forest carbon sequestration or bioenergy into an optimization framework for forest management at the stand and forest levels and to highlight the gaps in the literature. Forest management is seen as a cost-effective strategy to reduce carbon emission, and optimization techniques are a powerful tool to assist in developing an optimal strategy.

Recent Findings Our review of literature shows a gap in research on the use of optimal management schemes to investigate the impact of silvicultural techniques such as site preparation, genetic improvement, and fertilization on carbon sequestration. For operational planning, spatial information is helpful in developing an optimal mitigation strategy. However, there is a gap in literature when it comes to the application of exact solution techniques to solve spatially constrained harvest scheduling problems that encourage carbon sequestration and timber production, while taking into account forest management prescriptions. The review further shows that assessing the impacts of using carbon sequestration and bioenergy strategies to mitigate the impact of greenhouse gas-induced climate change is complex due to the interaction between the forest sector, energy, and other industrial product sectors.

Summary We suggest that more research should be directed towards using optimization techniques and an integrated system approach that tracks carbon flow in multiple sectors as a strategy to reduce carbon emissions. This strategy should encourage higher wood utilization and increase use of long-lived harvested wood products as well as bioenergy from waste wood.

Keywords Forest carbon sequestration · Bioenergy · Optimization · Forest management

Introduction

Traditionally, forests have been utilized to produce market-based wood products. To achieve this goal, the objective of forest management has been to seek optimal series of treatments (i.e., such as clear-cut, thinning, weeding, pruning, regeneration at the forest stand level) and location of harvest blocks and timing at the forest level, which meet the management objectives, e.g., maximization of the net present value induced from all forestry activities. In recent times, this traditional way of managing forest has changed because today's society assigns a great deal of importance to non-market forest-related products. There is a lot more emphasis on managing forests to preserve water quality, wildlife habitats, esthetic values, and carbon sequestration. These non-market products are often regarded as products from "forest ecosystem services" [1]. Methodologies from operations research have been utilized to evaluate such non-market products within the optimization framework of forest management [2•, 3, 4].

In response to the threat from global climate change, forest carbon sequestration and woody bioenergy have been seen as a cost-effective strategy for mitigating the effects of greenhouse gas (GHG)-induced climate change [5]. The interest in using this strategy in forest management has been growing among scientists, policymakers, and governments [6–9]. There are principally two viable ways in which forests can be manipulated to mitigate the effects of GHG emissions.

This article is part of the Topical Collection on *Integrating Forestry in Land use Planning*

✉ Atsushi Yoshimoto
yoshimoa@ism.ac.jp

[1] Department of Statistical Modeling, Institute of Statistical Mathematics, 10-3 Midori-cho, Tachikawa, Tokyo 190-8562, Japan

[2] Ministry of Forests, Lands, Natural Resource Operations & Rural Development, Government of British Columbia, PO Box 9515 Stn., Victoria, BC V8W 9C2, Canada

[3] Center for Social Data Structuring, Research Organization of Information and Systems, 10-3 Midori-cho, Tachikawa, Tokyo 190-8562, Japan

One way is to increase carbon storage in forests and/or long-lived harvested wood products. The other is the use of forest biomass for generating bioenergy as direct substitutes for fossil fuels [10]. In both situations, carbon offset occurs by preventing the emissions from fossil fuels which would otherwise have been used [6, 11].

IPCC [12] defines carbon sequestration as an increase in carbon stocks in any non-atmospheric reservoir. It is widely recognized that forest plays an important role in the global carbon cycle by sequestering and storing carbon. It is this role of forests that influenced participants of the Kyoto Protocol to allow countries to count forest carbon sequestration towards a country's emission reduction commitment [13]. Forest carbon sequestration can be enhanced by employing forest management or silvicultural tools in the "appropriate" way through an optimization framework [14]. Afforestation, site preparation, genetic improvement, fertilization, thinning, selective harvesting, etc., are viewed as effective management strategies in increasing carbon sequestration and therefore reducing GHG emissions in the atmosphere [9, 15]. However, there are concerns associated with the use of forest carbon sequestration in mitigating the effects of GHG-induced climate change. These concerns are centered on how to properly account for carbon sequestration in forest management and the effectiveness of using carbon incentives to encourage forest managers to increase carbon sequestration [2•, 16].

There is also growing interest in using forest bioenergy as a renewable, environmentally friendly alternative to energy derived from fossil fuels. Through a variety of processes, biomass can be converted to solid, liquid, or gaseous biofuels. Greater use of these wood-based biofuels could help ease society's dependence on fossil fuels and, in the process, reduce net GHG emissions. In addition, policies that encourage bioenergy production also ensure efficient utilization of forest resources, since they encourage the use of harvest residue, waste from salvage operations, and mill processing residue.

The framework for assessing total GHG emissions of forest bioenergy is the life cycle assessment (LCA). This process begins by assessing all emissions associated with silvicultural activities, biomass harvest, through to the transportation of harvested biomass to a bioenergy processing facility and the conversion of biomass into bioenergy [17]. When forest bioenergy displaces energy from a fossil fuel, it eliminates GHG emissions from producing and burning the fossil fuel. The difference in LCA emissions between forest bioenergy and a fossil fuel is what is termed the GHG benefit of displacing this fossil fuel with forest bioenergy [8]. It is this potential that encouraged scientists, policymakers, and governments to consider the use of forest bioenergy in mitigating the impact of GHG-induced climate change.

In recent years, there has been a debate over the ability of forest bioenergy to mitigate the impact of GHG-induced climate change. There is no clear consensus among scientists on this issue. Some scientists are of the view that forest bioenergy enhances global warming while others maintain that forest bioenergy can play a key role in climate change mitigation [18]. Although bioenergy have been promoted as a means to enhance energy independence and reduce GHG emissions, their developments have also been a cause for deep concern. Land conversion is a great concern [19]. For example, some Asian countries have converted thousands of hectares of forest land to palm oil plantations for the purpose of bioenergy production [20]. There are also those who are concerned that increased removal of biomass from the forests for bioenergy production will reduce carbon storage in both the biomass pool and the dead organic matter (DOM) pool [21].

Although the above concerns are important to policymakers and scientists, the focus of this paper is centered on reviewing the concerns of forest carbon sequestration and bioenergy through the lens of using optimization techniques within a forest management framework. We begin this review paper with a brief overview of literature about carbon sequestration and bioenergy in forestry. Then, we review articles that use optimization techniques to incorporate forest carbon sequestration and bioenergy at the stand as well as forest levels. We then conclude the paper by highlighting gaps in research and pointing out areas that need future research and attention.

Brief Overview of the Literature

In this section, we give a brief overview of the literature on forest carbon sequestration and the use of forest bioenergy. Forest carbon sequestration and forest bioenergy can play a critical role in mitigating the effect of GHG-induced climate change.

Forest Carbon Sequestration

Research articles related to forest carbon sequestration have increased especially in last two decades. Silviculture and forest management practices have the ability to increase forest carbon sinks and reduce emissions from carbon sources [22–28]. Helms [29] defined silviculture as "the art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society on a sustainable basis." He also defined forest management as the practical application of principles from a variety of disciplines, including biology, ecology, and economics, to the regeneration, density control, use, and conservation of forests. Silviculture and forest management can be used as a tool to increase carbon storage and therefore reduce the impact of GHG-induced climate change. A growing number of studies have identified silvicultural and forest management methods that could enhance the mitigation potential of managed forests [3, 4, 30–34].

An advantage of using silviculture or forest management to mitigate the impact of climate change is that it is a relatively cost-effective means of offsetting emissions from other sources at least temporarily. Such an approach could provide time while more efficient technologies for emission reduction are developed and implemented [5, 23]. There is also a large body of literature on the cost of carbon sequestration that concludes that the marginal costs of carbon sink enhancement can be considerably lower than those of carbon emission reduction [4, 5, 34–41].

In the forest economics literature, several authors [42–51] have shown that payments for carbon sequestration can have substantial impact on the rotation length of even-aged forests. These researchers showed that incentives can be used to increase carbon sequestration and therefore help to mitigate the effect of greenhouse gas-induced climate change.

Forest Bioenergy

In December 2015, world leaders finalized a historic global agreement to combat climate change in Paris [52]. They agreed to achieve GHG neutrality in the second half of this century and to hold global warming well below 2 °C relative to pre-industrial levels. In Paris, the IPCC noted that forest bioenergy can play a critical role in mitigation but face several challenges or concerns. Bioenergy as used in this paper refers to energy derived from biomass, which can be deployed as solid, liquid, and gaseous fuels for a wide range of uses, including transport, heating, electricity production, and cooking. Forest bioenergy production can have both positive and negative impacts on a range of environmental, social, and economic objectives that are not always fully compatible.

Bioenergy opportunities have been promoted as a means to reduce GHG emissions. It has also been championed by many policymakers and scientists because of "carbon neutrality". Searchinger et al. [53] showed that it is carbon neutral because its use does not result in fossil carbon being released into the atmosphere. They argue that all the carbon contained in the bioenergy was absorbed from the atmosphere by photosynthesis in trees years earlier. This means that when we burn a biomass, we simply release the carbon back into the atmosphere without any overall effect on atmospheric CO_2 levels. In contrast, they argue that fossil fuels contain carbon that has been locked up underground for thousands of years. However, several researchers have shown that burning of biomass for bioenergy does indeed increase the level of CO_2 in the atmosphere, and it is not balanced out by photosynthesis [8, 54, 55].

In managing forest for bioenergy, GHG are released more than the carbon captured at the initial stage of forest growth. As time goes on, net GHG emissions in the forest bioenergy become smaller as harvested stands increase in growth and capture more carbon. A point is reached when the change in forest carbon equals the accumulated GHG benefit of using forest bioenergy in place of fossil fuel. This stage of the cycle is known as carbon neutrality [8, 56]. It is only after passing this stage, can we say there is a net benefit or forest bioenergy has reduced atmospheric GHG emission compared with the reference fossil fuel.

Using biomass or bioenergy to reduce carbon emission has been researched since the 1990s [57–59]. Researchers have shown that manufactured wood products can store carbon for several decades in buildings and are therefore good tools for reducing carbon emissions [60].

Considering Carbon and Forest Bioenergy for Optimal Forest Management

The key to forest management is the ability to manipulate forest management activities such as planting, fertilization, thinning, or clear-cutting to achieve an optimum outcome. This optimum outcome can be achieved with the help of optimization techniques to seek an optimal management scheme. Optimization techniques and methods have been applied to the solution of forest management planning problems for over more than three decades, and during this time, the nature of the problems have evolved. More recently, these techniques have been applied to problems that consider optimal management of carbon or bioenergy at both the stand and forest levels. This is relevant because decisions in forest management are carried out at either the stand level or the forest level. Traditionally, forest planning is divided into a hierarchy of planning phases. Strategic planning is carried out to make decisions about sustainable harvest levels while taking into account policy and regulatory constraints over relatively long term. The goal of tactical planning on the other hand is to schedule harvest operations to specific areas and timing in the immediate few years and on a finer time scale than in the strategic plan. Forest stand-level and forest-level models on carbon and bioenergy issues can be grouped into strategic and tactical planning models as shown in Table 1. In the sections that follow, we review papers which have employed optimization techniques to manipulate the forest to increase forest carbon sequestration at the stand and forest levels. We also use stand-level analysis to demonstrate how an optimization technique like dynamic programming can be used to optimize the production of biofuel and carbon sequestration in logs.

Carbon Storage Through Forest Stand-Level Optimization

Stand-level planning is concerned with the specification of development paths, i.e., series of silvicultural activities for a given stand. At the stand level, an optimum forest carbon

Table 1 Carbon and bioenergy concerns in optimal forest management

Management level	Management perspective	
	Strategic approach	Tactical approach
Stand-level planning	Englin and Callaway (1995) [61], van Kooten et al. (1995) [43], van Kooten et al. (1997) [5], Couture and Reynaud (2002) [62], Spring et al. (2005)a [63], Spring et al. (2005)b [64], Chladná (2007) [45], Gutrich and Howarth (2007) [44], Daigneault et al. (2010) [50], Asante et al. (2011) [2•], Asante and Armstrong (2012) [16], Asante and Armstrong (2016) [48]	Yoshimoto et al. (2005) [3], Yoshimoto and Marušák (2007) [49]
Forest-level planning	Díaz-Balteiro and Romero (2003) [65], Neilson et al. [66], Bourque et al. (2007) [14], Hennigar et al. (2008) [4], McCarney et al. (2008) [67], Baskent and Kucuker (2010) [68]	Dong et al. (2015) [69••], Wan-Yu et al. (2017) [70]

management can only be achieved when sufficient and realistic stand-level paths are specified. Various studies have used optimization techniques to show how a forest stand can be manipulated to increase carbon sequestration at the stand level. In most of these studies, the central focus has been to control or delay the harvest decision so as to increase carbon storage or the desired outcome. In the forest economics literature, most of the researchers have investigated the effect of carbon payment on optimal rotation lengths when both timber and carbon values are considered [2•, 16]. Much of this work has been built on variations of the model developed by Hartman [71], which demonstrated that optimal rotations may be extended beyond timber only management regimes when flows of non-timber value are associated with the standing forest. Most of the studies that use the Hartman framework to examine the economics of forest carbon sequestration at the stand level treat carbon benefits as a function of a change in biomass [3, 5, 16, 43, 49]. The main objective of these papers is usually to address how incentives to sequester carbon affect the optimal rotation age. When these economic incentives are internalized by forest landowners, the optimal age of timber harvesting is usually increased [42]. The problem or concern of this approach is that the forest manager is limited in his/her ability to manipulate the control variable at the stand level. The forest manager can only cut the stand or leave the stand uncut. These models are strategic in nature.

Dynamic programming is one of mathematical programming techniques that can be used to seek an optimal solution for stand-level management problems. Details on the development of dynamic programming models can be found in Yoshimoto et al. [72]. Dynamic programming models can be used to produce either strategic-level plans or tactical-level plans. In recent years, dynamic programming has also been used to manipulate a forest stand to increase forest carbon sequestration at the stand level. Spring et al. [63] formulated and solved a stochastic dynamic program to maximize the expected net present value of returns from timber production and carbon value in a forest stand subject to stochastic fire. They modeled the decision problem using stand age as the state variable: timber production and carbon storage were both treated as functions of stand age. The same authors [64] also used stochastic dynamic programming to determine the rotation age considering timber production, water yield, and carbon sequestration under stochastic fire occurrence. Other researchers have also used stochastic dynamic programming to investigate the optimal forest management with carbon sequestration credits and fire risk [50, 62]. Also, researchers like Chladná [45] have used stochastic dynamic programming to examine the optimal forest stand harvest decision when timber and carbon prices are stochastic. Chladná [45] used stand volume per hectare, timber price, and carbon price as state variables. Other researchers include the following: Yoshimoto and Marusák [49], who optimized timber and carbon values in a forest stand using dynamic programming in a framework where both thinning and final harvest were considered, and Asante et al. [2•] and Asante and Armstrong [48], who used dynamic programming to examine how landowners will change the rotation age for clear-cutting when faced with different starting DOM pools under carbon incentives. Unlike the models developed within the Hartman framework, dynamic programming allows forest managers the option to work with more than one control variable so as to increase carbon sequestration. It is important to note that although the aforementioned researchers have shown that controlling the rotation age can lead to an increase in carbon sequestration, there is a concern that holding trees longer (over mature trees) makes them susceptible to risk of natural disasters such as fire.

Carbon Storage Through Forest-Level Optimization

Forest-level planning determines the best combination of development paths in all stands, considering constraints and objectives for the forested landscape as a whole. Forest-level plans can be grouped as strategic or tactical (Table 1). To increase carbon sequestration at the forest level or mitigate the risk of losing carbon, forest managers can manipulate forests using silvicultural management practices, such as planting genetically improved stocks.

Many researchers have used mathematical programming techniques or optimization techniques to maximize carbon storage at the forest or landscape level. Bourque et al. [14] used goal programming to maximize total carbon sequestration in the forest landscape and in wood products generated from harvesting. Goal programming was also used by Díaz-Balteiro and Romero [65] and Neilson et al. [66] to optimize forest carbon storage at the forest landscape level. Other researchers have used linear programming as a tool to optimize carbon sequestration [4, 67, 68]. McCarney et al. [67] used linear programming to investigate the relationships and trade-offs between forest carbon management, sustained timber yield, and the production of wildlife habitat. Hennigar et al. [4] developed a linear programming model to maximize carbon storage in both forest and wood products at the forest level. A linear programming model was also developed to integrate water, carbon, and timber values into a forest management plan [68]. Although the aforementioned researchers have shown that forest managers can use goal programming and linear programming as a tool to manipulate a forest to increase carbon sequestration at the forest level, the concern is that these approaches are limited to their ability to solve only strategic-level problems. These models are not able to answer questions like where to cut or where to leave uncut in order to achieve the strategic-level goal. Such tactical-level decisions are best addressed using mixed-integer programming or integer programming or heuristics.

Other researchers have addressed forest planning problems that consider carbon sequestration values and spatial concerns at the forest level [68, 70]. Wan-Yu et al. [69••] used an improved simulated annealing heuristic approach, which iteratively searches for a "near-optimal" solution to solve a spatial forest-thinning planning problem involving carbon sequestration and emissions. Their model determines 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. Dong et al. [69••] also developed a spatial forest planning process by which one could assess either a carbon stocks objective, a timber production objective, or a spatial objective related to the arrangement of forest management activities. The concern with these heuristic solution approaches is that they lack information on the quality of the solutions. The final or "near-optimal" solution generally does not have optimal attributes, but is guaranteed to be the best among the generated group of solutions. They give us a "good feasible solution" within a reasonable timeframe, but do not guarantee optimality of the solution [72]. An exact solution technique on the other hand can guarantee optimality of the solution or provide optimal attributes on the derived solution even when it is not optimal, such as gap[1] information.

What is missing in this area of research is the use of exact solution techniques for solving carbon issues within the framework of spatially constrained harvest scheduling under area restrictions, which has gained a great deal of attention in the last two decades. Although there have been advances in computational capabilities, it is still difficult to use the existing exact solution techniques to solve spatially constrained harvest scheduling problems with area restrictions that can consider carbon benefits.

Carbon Sequestration and Biofuel Production Through Stand-Level Optimization

Seeking an optimal solution using a dynamic programming model for the production of forest bioenergy and logs at the stand level often results in an extreme solution of either bioenergy production only or log production only. This is because an optimal solution is often dependent upon price difference between bioenergy and logs. In this section, we use a stand-level optimization model to illustrate some decisions available to a landowner who chooses to manage his/her forest stand for bioenergy and carbon sequestration services. For illustration purposes, we assume an even-aged sugi (*Cryptomeria japonica*) forest stand in Fukuoka, Japan. Growth and yield information for this forest is from a stand density management diagram used in Yoshimoto and Marušák [49].

We make the assumption that this forest gives two types of benefit: log production and biofuel production. It is also assumed that log production comes with the benefit of carbon sequestration. Using a dynamic programming model with the MSPATH algorithm, it is possible to find the best combination of carbon sequestered in logs and biofuel production. The optimality equation of MSPATH is represented by Eq. (1) (see [72]),

$$\begin{aligned} f_i^* &= \max_{\{T_{i-j,i},t_j\}} \{ f_{i-j,i}(T_{i-j,i}) \} \\ f_{i-j,i}(T_{i-j,i}) &= V_i^R(T_{i-j,i}) + V_i^T(T_{i-j,i}) - V_{i-j}^* + f_{i-j}^* \end{aligned} \tag{1}$$

in order to search for an optimal amount of thinning and elapse time, t_j, for thinning or final harvest. Variables are defined as follows:

$T_{i-j,\,i}$, amount of thinning at time t_{i-j} with elapse time t_j from time t_i ($t_{i-j} = t_i - t_j$);
$V_i^R(T_{i-j,i})$, net present value of return from harvesting a forest stand at time t_i after thinning $T_{i-j,\,i}$ at time t_{i-j};
$V_i^T(T_{i-j,i})$, net present value of return from thinning $T_{i-j,\,i}$ implemented at time t_{i-j};
t_j^*, optimal elapse time t_j targeting the state at time t_i;
$T_{i-j,i}^*$, optimal amount of thinning over an optimal elapse time t_j^* targeting the state at time t_i;

---

[1] The relative difference between the solution reported and an upper bound value of the optimal solution value.

$V_i^* = V_i^R\left(T_{i-j,i}^*\right)$, net present value of return from harvesting a forest stand at time t_i after thinning $T_{i-j,i}^*$ at time t_{i-j}.

Let us seek the optimal combination of log production and biofuel production by changing the utilization percentage of log from stem as well as the price of oil. The amount of carbon sequestered was estimated by using Eq. (2),

$$Wc = \rho_0 \times V \times E \times C_0 \tag{2}$$

where Wc (Ct) is the amount of carbon sequestered, ρ_0 is wood density (g/cm^2), V is stem volume (m^3), E is an expansion factor, and C_0 is a coefficient of carbon content (g/Ct). Given the parameter value from [49], here, carbon sequestered in wood biomass was calculated using Eq. (3),

$$Wc = 0.3772 \times V \times 1.7 \times 0.5 \tag{3}$$

Conversion coefficient from woody biomass to biofuel amount was assumed to be 173.3 l of "A"-type crude oil equivalent per 1 m^3 of woody biomass. Equation (4) was used to estimate the benefit from biofuel sources,

$$V_{i-j,i}^{bio} = 173.3 \cdot P^{bio} \cdot (1-\alpha) \cdot T_{i-j,i}^* \tag{4}$$

where $V_{i-j,i}^{bio}$ is the benefit from biofuel use from thinned volume, $T_{i-j,i}^*$ with the price of "A" crude oil, P^{bio} and utilization ratio for log production from standing tree, α. Thus, the benefit from log production becomes,

$$V_{i-j,i}^{\log} = P^{\log} \cdot \alpha \cdot T_{i-j,i}^* \tag{5}$$

Note that $V_i^R\left(T_{i-j,i}\right)$ and $V_i^T\left(T_{i-j,i}\right)$ in Eq. (1) take into account the benefits from biofuel and carbon sequestration in logs as in Eqs. (4) and (5) from harvesting a forest stand after thinning.

In order to seek the best combination of carbon sequestered in log production and biofuel production, the utilization ratio was changed from 0 to 65%, where 0% means no timber production and 65%, which is commonly applied in Japanese forestry for log production from a stem. The price of "A" crude oil was also varied from 0 to 100 yen/l. The response surface over time for a number of different utilization ratios is presented in Fig. 1. For most of the utilization ratios, it is optimal to harvest around 60 and 65 years. The results show that the utilization ratio has little or no impact on the optimal rotation. This was unexpected, as it means that the different utilization ratios have about the same carbon emission reduction effect or the same impact of mitigating the effect of greenhouse gas-induced climate change.

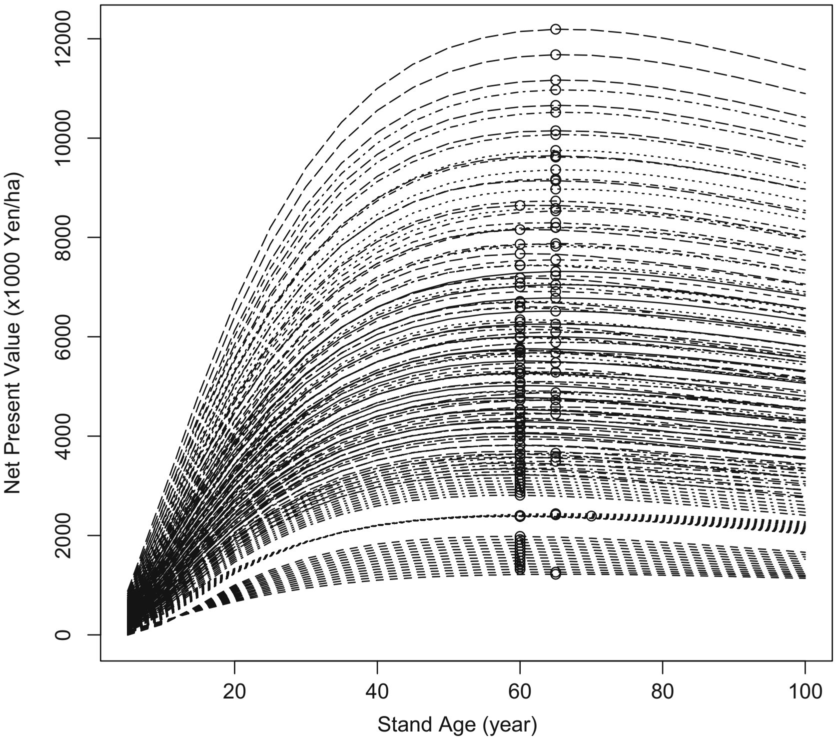
Figure 2 displays a combination of log utilization ratio (labeled "log usage") and net present value over different "A" crude oil prices. In general, the results presented in Fig. 2 suggest that net present value declines with increasing ratio of log utilization when the price of "A" crude oil is greater than or equal to 30 yen/l. The results also suggest that net present value increases with increasing ratio of log utilization when the price of "A" crude oil is less than or equal to 20 yen/l. That is, we have two extreme solutions, depending upon the price of "A" crude oil. It may be noteworthy to comment that if price uncertainty of "A" crude oil and log price be taken into account for optimization, portfolio type of research would be needed to seek the best allocation of woody materials, carbon sequestration, and biomass energy use, over rather long-term planning. This is because an optimal allocation of woody materials for these uses would not change so frequently over time as well as infrastructure of bioenergy uses.

Conclusion and Future Direction

Carbon and bioenergy concerns have been discussed and analyzed in this paper. Most studies simply estimate the amount of carbon sequestration or carbon emissions from woody biomass. From a practical viewpoint, forest management is about evaluating alternative treatments for long-term forest management plans, while taking into account tactical decisions, as opposed to just quantifying carbon stocks. Today's forest manager is driven by the necessity to seek an optimal management plan based not just on maximizing profit from timber production, but maximizing benefits from a wide range of ecosystem services like carbon sequestration. These conflicting objectives are best resolved and evaluated through the use of exact optimization techniques.

The key to forest management is the ability to manipulate forestry activities as control variables, and optimization techniques are a tool that allows forest managers to achieve this objective. Optimization techniques and methods are powerful tools, which have been applied to problems considering carbon and bioenergy at both the stand and forest levels. This review of literature shows two main types of optimization models at the stand level: (1) a variation of the model developed by Hartman and (2) dynamic programing model, which have been used as a tool to manipulate a forest to increase carbon sequestration. Of the two approaches, dynamic programming gives a manager more flexibility to control treatments to increase carbon sequestration over the given forest dynamic models. For forest-level analysis, linear programming and goal programming are limited to their ability to solve only strategic-level problems. To address spatial concerns in forest carbon management at the forest or landscape level, mixed-integer programming technique is appropriate and of necessity, though heuristics can help to generate "feasible solutions" as long as problems are mathematically formulated.

Fig. 1 Response surface to seek the optimal rotation age (circle is the optimal rotation age)



After reviewing papers on forest carbon sequestration and bioenergy, we are of the opinion that future research needs to be directed towards an integrated system approach through the optimal management framework that encourages higher utilization, increase use of long-lived harvested wood products (HWP), and increase use of bioenergy from waste wood. Several researchers have affirmed this fact by showing that higher utilization and increased use of HWPs and bioenergy from waste wood are very effective in mitigating climate change [10•, 73, 74]. Xu et al. [10•] showed that the greatest mitigation potential can be

Fig. 2 Change in net present value over log utilization ratio (log usage) with respect to different oil prices

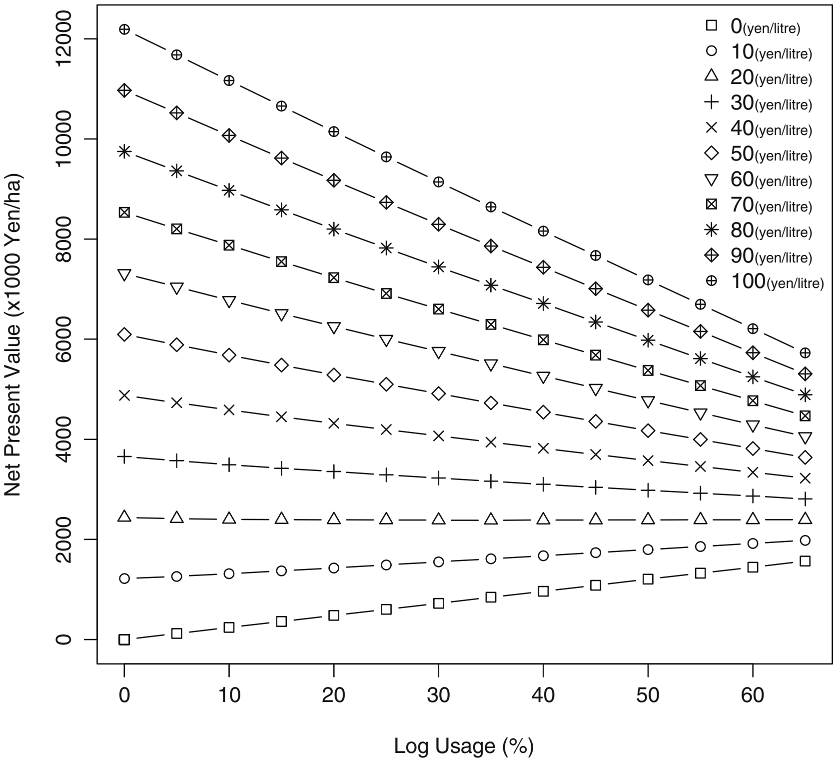


Table 2 Carbon measurement to investigate the impact of forest management prescription on carbon sequestration

Forest management prescription	With non-optimization technique	With optimization technique
Afforestation	Bashkin and Binkley (1998) [75], Guo and Gifford (2002) [76], Paul et al. (2002) [77], Vesterdal et al. (2002) [78], Byrne and Farrell (2005) [79], Jandl et al. (2007) [80]	Bourque et al. (2007) [14], Hennigar et al. (2008) [4], McCarney et al. (2008) [67], Olschewki and Benitez (2010) [47], Yemshanov et al. (2015) [81], Yemshanov et al. (2005) [82], McKenney et al. (2004) [83]
Site preparations	Johnson (1992) [84], Johansson (1994) [85], Örlander et al. (1996) [86], Schmidt et al. (1996) [87], Mallik and Hu (1997) [88], Jandl et al. (2007) [80], Fonseca et al. (2014) [89], Wang et al. (2016) [90]	
Genetic improvement	Jayawickrama (2001) [91], Nowak and Crane (2002) [92], Millar et al. (2007) [93], Aspinwall et al. (2012) [94]	
Fertilization	Johnson (1992) [84], Mäkipää (1995) [95], Nadelhoffer et al. (1999) [96], Canary et al. (2000) [97], Johnson and Curtis (2001) [98], Shan et al. (2001) [99], Sampson et al. (2006) [100], Eriksson et at. (2007) [93], Jandl et al. (2007) [80], de Vries et al. (2009) [101], Kilpeläinen et al. (2016) [102]	Shrestha et al. (2015) [51]
Thinning	Wollum and Schubert (1975) [103], Vesterdal et al. (1995) [78], Jandl et al. (2007) [80], Finkral and Evans (2008) [104], Alam et al. (2013) [105], Zubizarreta-Gerendiain et al. (2016) [106]	Bourque et al. (2007) [14], Yoshimoto and Marušák (2007) [49], Wan-Yu et al. (2017) [70]
Selection harvesting or harvesting at different intensities	Olsson et al. (1996) [107], Davis et al. (2009) [108], Kuehl et al. (2013) [109], Kamangadazi et al. (2016) [110]	Neilson et al. (2006) [66], Bourque et al. (2007) [14], Hennigar et al. (2008) [4], Schwenk et al. (2012) [111], Dong et al. (2015) [69••], Mao et al. (2017) [112]

achieved by improving the harvest utilization, shifting the commodity mix to HWPs, and using harvest residues for bioenergy. They showed that implementing two or more strategies simultaneously would achieve more mitigation than having only one individual strategy. However, they showed that combined strategies may not necessarily be cost-effective or lead to more socio-economic benefits. Their study also revealed that strategies may or may not affect each other when combined. In particular, they showed that higher utilization strategy and the bioenergy strategy were not "additive" because higher utilization in harvest caused fewer harvest residues left on site, which resulted in a smaller supply for local bioenergy. In contrast, they reported that the HWP strategy and the bioenergy strategy were additive, as shifting the wood product mix for a given harvest volume did not affect the amount of harvest residues. Therefore, the choice of a combined strategy depended on the interaction between mitigation actions and policy goals [10•].

We also reviewed papers which either employed optimization techniques to investigate or simply quantified the impact of forest management prescriptions on carbon sequestration so as to identify the gaps in literature (Table 2). From Table 2, it can be seen that there is a gap in literature when it comes to using optimization techniques to investigate the impact of forest management treatments such as site preparation, genetic improvement, and fertilization on carbon sequestration. Therefore, future research needs should be directed to overcome this gap. Another gap in literature is the use of an exact solution technique to solve a spatially constrained harvest scheduling problems that encourages carbon sequestration and timber production, taking into account the management prescriptions identified in Table 2. We suggest an exact solution technique because, although these spatial constraints do address environmental concerns in forest management plans, they do so at a cost to the forest landowner in terms of lost timber revenue [113]. To guarantee an optimal solution, these types of problems are best solved using an exact optimization technique as opposed to a heuristic solution technique which does not have optimal attributes, but is guaranteed to be the best among the generated group of solutions [72].

Compliance with Ethical Standards

Conflict of Interest Atsushi Yoshimoto, Patrick Asante, and Shizu Itaka declare that they have no conflict of interest.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Nicholson E, Mace GM, Armsworth PR, Atkinson G, Buckle S, et al. Priority research areas for ecosystem services in a changing world. J Appl Ecol. 2009;46:1139–44.

2.• Asante P, Armstrong GW, Adamowicz WL. Carbon sequestration and the optimal forest harvest decision: a dynamic programming approach considering biomass and dead organic matter. J For Econ. 2011;17:3–7. **In this paper, the authors used a dynamic programming as an optimization tool to determine the optimal harvest decision for a forest stand in the boreal forest of western Canada that provides both timber harvest volume and carbon sequestration services.**

3. Yoshimoto A, Yanagihara H, Nomoto M. Carbon sequestration and optimal thinning regimes from forest stand optimization modeling. FORMATH. 2005;4:71–91. http://formath.jp/book/vol04/fulltext/vol04_4.pdf. Accessed 17 July 2018.

4. Hennigar CR, MacLean DA, Amos-Binks LJ. A novel approach to optimize management strategies for carbon stored in both forests and wood products. For Ecol Manag. 2008;256:786–97.

5. van Kooten GC, Grainger A, Ley E, Marland G, Solberg B. Conceptual issues related to carbon sequestration: uncertainty and time. Crit Rev Environ Sci Technol. 1997;27(Special):65–82.

6. Baral A, Guha GS. Trees for carbon sequestration or fossil fuel substitution: the issue of cost vs. carbon benefit. Biomass Bioenergy. 2004;27:41–55.

7. Miner RA, Abt RC, Bowyer JL, Buford MA, Malmsheimer RW, O'Laughlin J, et al. Forest carbon accounting considerations in US bioenergy policy. J For. 2014;112:591–606.

8. Ter-Mikaelian MT, Colombo SJ, Chen J. The burning question: does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting. J For. 2015;113(1):57–68.

9. Timmons DS, Buchholz T, Veeneman CH. Forest biomass energy: assessing atmospheric carbon impacts by discounting future carbon flows. GCB Bioenergy. 2016;8:631–43. https://doi.org/10.1111/gcbb.12276.

10.• Xu Z, Smyth, CE, Lemprière TC, Rampley GJ, Kurz WA. Climate change mitigation strategies in the forest sector: biophysical impacts and economic implications in British Columbia, Canada. Mitig Adapt Strateg Glob Chang. 2017:1–34. https://cfs.nrcan.gc.ca/publications?id=37881. **The researchers in this paper examined the climate change mitigation potential of the forest sector and concluded that the greatest mitigation potential can be achieved by improving the harvest utilization, shifting the commodity mix to longer-lived wood products to increase carbon storage, and using harvest residues for bioenergy. They were able to show that implementing two or more strategies simultaneously would achieve more mitigation than having only one individual strategy.**

11. Richards KR. A brief overview of carbon sequestration economics and policy. Environ Manag. 2004;33:545–58.

12. IPCC. Land use, land-use change, and forestry. Cambridge: Cambridge University Press; 2000. http://www.ipcc.ch/ipccreports/sres/landuse/

13. UNFCCC. Report of the ad hoc working group on further commitments for annex i parties under the Kyoto Protocol to the conference of the parties serving as the meeting of the parties to the Kyoto Protocol in the fifth session. FCCC/KP/AWG/2009/L15. 2009. Available at http://www.unfccc.int/resource/docs/2009/awg10/eng/l15.pdf.

14. Bourque CP, Neilson ET, Gruenwald C, Perrin SF, Hiltz JC, Blin YA, et al. Optimizing carbon sequestration in commercial forests by integrating carbon management objectives in wood supply modeling. Mitig Adapt Strateg Glob Chang. 2007;12:1253–75.

15. Sedjo RA. Forest carbon sequestration: some issues for forest investments. Washington: Resources for the Future; 2001.

16. Asante P, Armstrong GW. Optimal forest harvest age considering carbon sequestration in multiple carbon pools: a comparative statics analysis. J For Econ. 2012;18:145–56.

17. Zhang Y, Mckechnie J, Cormier D, Lyng R, Mabee W, Ogino A, et al. Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. Environ Sci Technol. 2010;44:538–44.

18. Berndes G, Abt B, Asikainen A, Cowie A, Dale V, Egnell G, Lindner M, Marelli L, Paré D, Pingoud K, Yeh S. Forest biomass, carbon neutrality and climate change mitigation. From Science to Policy 3. European For Inst. 2016;3–27.

19. Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science. 2008;319:1235–8.

20. Yusof B, Chan KW. The oil palm and its sustainability. J Oil Palm Res. 2002;16(1):1–10.

21. Mckechnie J, Colombo S, Chen J, Mabee W, Maclean HL. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. Environ Sci Technol. 2011;45:789–95.

22. Apps MJ, Bhatti JS, Halliwell DH, Jiang H, Peng CH. Simulated carbon dynamics in the boreal forest of Central Canada under uniform and random disturbance regimes. In: Lai R, Kimble JM, Stewart BA, editors. Global climate change and cold regions ecosystems. Boca Raton: Lewis Publishers; 2000. p. 107–22.

23. Metz B, Davidson O, Swat R, Pan J. Climate change 2001: mitigation: contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2001.

24. Liski J, Pussinen A, Pingoud K, Mäkipää R, Karjalainen T. Which rotation length is favourable to carbon sequestration? Can J For Res. 2004;31:2004–13.

25. Liski J, Lehtonen A, Palosuo T, Peltoniemi M, Eggers T, Muukkonen P, et al. Carbon accumulation in Finland's forests 1922–2004—an estimate obtained by combination of forest inventory data with modeling of biomass, litter and soil. Ann For Sci. 2006;63:687–97.

26. Kauppi PE, Rautiainen A, Korhonen KT, Lehtonen A, Liski J, Nöjd P, et al. Changing stock of biomass carbon in a boreal forest over 93 years. For Ecol Manag. 2010;259:1239–44.

27. Vilén T, Gunia K, Verkerk PJ, Seidl R, Schelhaas MJ, Lindner M, et al. Reconstructed forest age structure in Europe 1950–2010. For Ecol Manag. 2012;286:203–18.

28. Noormets A, Epron D, Domec JC, McNulty SG, Fox T, Sun G, et al. Effects of forest management on productivity and carbon sequestration: a review and hypothesis. For Ecol Manag. 2015;355:124–40.

29. Helms JA. The dictionary of forestry. Bethesdam: Society of American Foresters; 1998.

30. Hoen HF, Solberg B. CO_2-taxing, timber rotations, and market implications. Crit Rev Environ Sci Technol. 1997;27:151–62.

31. Binkley CS, Apps MJ, Dixon RK, Kauppi PE, Nilsson LO. Sequestering carbon in natural forests. Crit Rev Environ Sci Technol. 1997;27(Special):23–45.

32. Nabuurs GJ, Dolman AJ, Verkaik E, Kuikman PJ, van Diepen CA, Whitmore AP, et al. Article 3.3 and 3.4 of the Kyoto Protocol: consequences for industrialized countries' commitment, the monitoring needs, and possible side effects. Environ Sci Policy. 2000;3:123–34.

33. Sampson RN, Scholes RJ. Additional human-induced activities—article 3.4. In the Intergovernmental Panel on Climate Change (IPCC) Special Report on Land Use, Land-Use Change, and Forestry, R.T. Watson, I.R. Noble, B. Bolin, N.H. 2000.

34. Morison J, Matthews R, Miller G, Perks M, Randle T, Vanguelova E, et al. Understanding the carbon and greenhouse gas balance of forests in Britain. Edinburgh: Forestry Commission; 2012.

35. Sedjo RA, Wisjiekwskio J, Sample AV, Kinsman JD. The economics of managing carbon via forestry: assessment of existing studies. Environ Resour Econ. 1995;6:139–65.

36. Stavins RN. The cost of carbon sequestration: a revealed preference approach. Am Econ Rev. 1999;89:994–1009.

37. Richards K, Stokes C. A review of carbon sequestration cost studies: a dozen years of research. Clim Chang. 2004;63:1–48.
38. van Kooten GC, Eagle AJ, Manley J, Smolak T. How costly are carbon offsets? A meta-analysis of carbon forest sinks. Environ Sci Pol. 2004;7:239–51.
39. van Kooten GC, Laaksonen-Craig S, Wang Y. Carbon offset credits via forestry activities: a meta-regression analysis. Can J For Res. 2009;39:2153–67.
40. Manley J, van Kooten C, Moeltner K, Johnson D. Creating carbon offsets in agriculture through no-till cultivation: a meta-analysis of costs and carbon benefits. Clim Chang. 2005;68:41–65.
41. Phan THD, Brouwer R, Davidson M. The economic costs of avoided deforestation in the developing world: a meta-analysis. J For Econ. 2014;20:1–16.
42. Plantinga A, Birdsey R. Optimal forest stand management when benefits are derived from carbon. Nat Resour Model. 1994;8:373–87.
43. van Kooten GC, Binkley CS, Delcourt G. Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. Am J Agric Econ. 1995;77(2):365–74.
44. Gutrich J, Howarth RB. Carbon sequestration and the optimal management of New Hampshire timber stands. Ecol Econ. 2007;62(3–4):441–50.
45. Chladná Z. Determination of optimal rotation period under stochastic wood and carbon prices. Forest Policy Econ. 2007;9(8):1031–45.
46. Foley TG, Richter D, Galik CS. Extending rotation age for carbon sequestration: a cross-protocol comparison of North American forest offsets. For Ecol Manag. 2009;259:201–9.
47. Olschewki R, Benitez PC. Optimizing joint production of timber and carbon sequestration of afforestation projects. J For Econ. 2010;16:1–10.
48. Asante P, Armstrong G. Carbon sequestration and the optimal forest harvest decision under alternative baseline policies. Can J For Res. 2016;46(5):656–65.
49. Yoshimoto A, Marušák R. Evaluation of carbon sequestration and thinning regimes within the optimization framework for forest stand management. Eur J For Res. 2007;126(2):315–29.
50. Daigneault AJ, Miranda MJ, Sohngen B. Optimal forest management with carbon sequestration credits and endogenous fire risk. Land Econ. 2010;86(1):155–72.
51. Shrestha P, Stainback GA, Dwivedi P. Economic impact of net carbon payments and bioenergy production in fertilized and non-fertilized loblolly pine plantations. Forests. 2015;6:3045–59.
52. United Nations. Paris Agreement 2015. Available online at http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.
53. Graham RL, Liu W, English, BC. The environmental benefits of cellulosic energy crops at a landscape scale. Environmental enhancement through agriculture: proceedings of a conference. Centre for Agriculture, Food and Environment, Tufts University, Massachusetts; 1995.
54. Searchinger TD, Hamburg SP, Melillo J, Chameides W, Havlik P, Kammen DM, et al. Fixing a critical climate accounting error. Science. 2009;326:527–8.
55. Haberl H, Sprinz D, Bonazountas M, Cocco P, Desaubies Y, Henze M, et al. Correcting a fundamental error in greenhouse gas accounting related to bioenergy. Energy Policy. 2012;45:18–23.
56. Mitchell SR, Harmon ME, O'connell KEB. Carbon debt and carbon sequestration parity in forest bioenergy production. Glob Change Biol Bioenergy. 2012;4:818–27.
57. Harmon ME, Ferrell WK, Franklin JF. Effects on carbon storage of conversion of old growth forests to young forests. Science. 1990;247:699–702.
58. Hall DO, Mynick HE, Williams RH. Carbon sequestration versus fossil fuel substitution: alternative roles for biomass in coping with greenhouse warming PUICEES Report No. 225. Princeton: Center for Energy and Environmental Studies, Princeton University; 1990.
59. Marland G, Schlamadinger B. Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. Biomass Bioenergy. 1997;13(6):389–97.
60. Gustavsson L, Sathre R. Variability in energy and carbon dioxide balances of wood and concrete building materials. Build Environ. 2006;41:940–51.
61. Englin J, Callaway J. Environmental impacts of sequestering carbon through forestation. Climate Change. 1995;31:67–78.
62. Couture S, Reynaud A. Forest management under fire risk when forest carbon sequestration has value. Ecol Econ. 2011;70:2002–11.
63. Spring D, Kennedy J, Mac Nally R. Optimal management of a flammable forest providing timber and carbon sequestration benefits: an Australian case study. Aus J Agric Resour Econ. 2005a;49(3):303–20.
64. Spring DA, Kennedy JOS, Mac Nally R. Optimal management of a forested catchment providing timber and carbon sequestration benefits: climate change effects. Glob Environ Chang. 2005b;15(3):281–92.
65. Díaz-Balteiro L, Romero C. Forest management optimisation models when carbon captured is considered: a goal programming approach. For Ecol Manag. 2003;174:447–57.
66. Neilson ET, MacLean DA, Arp PA, Meng FR, Bourque CP, Bhatti JS. Modeling carbon sequestration with CO2Fix and a timber supply model for use in forest management planning. Can J Soil Sci. 2006;86:219–33.
67. McCarney GR, Armstrong GW, Adamowicz WL. Joint production of timber, carbon, and wildlife habitat in the Canadian boreal plains. Can J For Res. 2008;38:1478–92.
68. Baskent EZ, Kucuker DM. Incorporating water production and carbon sequestration into forest management planning: a case study in Yalnicam planning unit. Forest Syst. 2010;19(1):98–111.
69.•• Dong L, Bettinger P, Lui Z, Qin H. Spatial forest harvest scheduling for areas involving carbon and timber management goals. Forests. 2015;6:1363–79. **In this paper, the authors developed a heuristic spatial forest planning process by which one could assess either a carbon stocks objective, a timber production objective, or a spatial objective related to the arrangement of forest management activities.**
70. Wan-Yu L, Chun-Cheng L, Ke-Hong S. Spatial the forest-thinning planning problem with carbon sequestration and emissions. Forest Policy Econ. 2017;78:51–66.
71. Hartman R. The harvesting decision when a standing forest has value. Econ Inq. 1976;14:52–8.
72. Yoshimoto A, Asante P, Konoshima M. Stand-level forest management planning approaches. Curr Forestry Rep. 2016;2:163–76.
73. Nordström EM, Forsell N, Lundström A, Korosuo A, Bergh J, Havlí k P, et al. Impacts of global climate change mitigation scenarios on forests and harvesting in Sweden. Can J For Res. 2016;46(12):1427–38. https://doi.org/10.1139/cjfr-2016-0122.
74. FAO (Food and Agriculture Organization of the United Nations). Forestry for a low-carbon future: integrating forests and wood products in climate change strategies. FAO Forestry Paper. 177: 1–151. http://www.fao.org/3/a-i5857e.pdf. Accessed 6 Sept 2016.
75. Bashkin MA, Binkley D. Changes in soil carbon following afforestation in Hawaii. Ecology. 1998;79:828–33.
76. Guo LB, Gifford RM. Soil carbon stocks and land use change: a meta analysis. Glob Chang Biol. 2002;8:345–60.
77. Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK. Change in soil carbon following afforestation. For Ecol Manag. 2002;168:241–57.

78. Vesterdal L, Ritter E, Gundersen P. Change in soil organic carbon following afforestation of former arable land. For Ecol Manag. 2002;169:137–47.
79. Byrne KA, Farrell EP. The effect of afforestation on soil carbon dioxide emissions in blanket peatland in Ireland. Forestry. 2005;78:217–27.
80. Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, et al. How strongly can forest management influence soil carbon sequestration? Geoderma. 2007;137:253–68.
81. Yemshanov D, McCarney GR, Hauer H, Luckert MK, Unterschultz J, McKenney DW. A real options-net present value approach to assessing land use change: a case study of afforestation in Canada. Forest Policy Econ. 2015;50:327–36. https://doi.org/10.1016/j.forpol.2014.09.016.
82. Yemshanov D, McKenney DW, Hatton T, Fox G. Investment attractiveness of afforestation in Canada inclusive of C sequestration benefits. Can J Agric Econ. 2005;53:307–23. https://doi.org/10.1111/j.1744-7976.2005.00021.x.
83. McKenney DW, Yemshanov D, Fox G, Ramlal E. Cost estimates for carbon sequestration from fast growing poplar plantations in Canada. Forest Policy Econ. 2004;6(3–4):345–58.
84. Johnson DW. Effects of forest management on soil carbon storage. Water Air Soil Pollut. 1992;64:83–121.
85. Johansson MB. The influence of soil scarification on the turn-over rate of slash needles and nutrient release. Scand J For Res. 1994;9:170–9.
86. Örlander G, Egnell G, Albrektsson A. Long-term effects of site preparation on growth in Scots pine. For Ecol Manag. 1996;86:27–37.
87. Schmidt M, Macdonald S, Rothwell R. Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Can J Soil Sci. 1996;76:531–40.
88. Mallik A, Hu D. Soil respiration following site preparation treatments in boreal mixedwood forest. For Ecol Manag. 1997;97:265–75.
89. Fonseca F, de Figueiredo T, Martins A. Carbon storage as affected by different site preparation techniques two years after mixed forest stand installation. Forest Systems. 2014;23(1):84–92.
90. Wang J, Wang H, Fu X, Xu M, Wang Y. Effects of site preparation treatments before afforestation on soil carbon release. For Ecol Manag. 2016;361:277–85.
91. Jayawickrama KJS. Potential genetic gains for carbon sequestration: a preliminary study on radiata pine plantations in New Zealand. For Ecol Manag. 2001;152:313–22.
92. Nowak DJ, Crane DE. Carbon storage and sequestration by urban trees in the USA. Environ Pollut. 2002;116:381–9.
93. Millar CI, Stephenson NL, Stephens SL. Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl. 2007;17(8):2145–51.
94. Aspinwall MJ, McKeand SE, King JS. Carbon sequestration from 40 years of planting genetically improved loblolly pine across the southeast United States. For Sci. 2012;58(5):446–56.
95. Mäkipää R. Effect of nitrogen input on carbon accumulation of boreal forest soils and ground vegetation. For Ecol Manag. 1995;79:217–26.
96. Nadelhoffer KJ, Emmett BA, undersen P, jønaas OJ, oopmans CJ, Schleppi P, et al. Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. Nature. 1999;398:145–8.
97. Canary J, Harrison R, Compton J, Chappell H. Additional carbon sequestration following repeated urea fertilization of second-growth Douglas-fir stands in western Washington. For Ecol Manag. 2000;138:225–32.
98. Johnson DW, Curtis PS. Effects of forest management on soil C and N storage: meta analysis. For Ecol Manag. 2001;140:227–38.
99. Shan JP, Morris LA, Hendrick RL. The effects of management on soil and plant carbon sequestration in slash pine plantations. J Appl Ecol. 2001;38:932–41.
100. Sampson DA, Waring RH, Maier CA, Gough CM, Ducey MJ, Johnsen KH. Fertilization effects on forest carbon storage and exchange, and net primary production: a new hybrid process model for stand management. For Ecol Manag. 2006;221:91–109.
101. de Vries W, Solberg S, Dobbertin M, Sterba H, Laubhann D, van Oijen M, et al. The impact of nitrogen deposition on carbon sequestration by European forests and heathlands. For Ecol Manag. 2009;258:1814–43.
102. Kilpeläinen A, Alam A, Torssonen P, Ruusuvuori H, Kellomäki S, Peltola H. Effects of intensive forest management on net climate impact of energy biomass utilisation from final felling of Norway spruce. Biomass Bioenergy. 2016;87:1–8.
103. Wollum AG, Schubert GH. Effect of thinning on the foliage and forest floor properties of ponderosa pine stands. Proc Soil Soc Am. 1975;39:968–72.
104. Finkral AJ, Evans AM. The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. For Ecol Manag. 2008;225:2743–50.
105. Alam A, Kellomaki S, Kilpelainen A, Strandman H. Effects of stump extraction on the carbon sequestration in Norway spruce forest ecosystems under varying thinning regimes with implications for fossil fuel substitution. GCB Bioenergy. 2013;5:445–58.
106. Zubizarreta-Gerendiain A, Pukkala T, Peltola H. Effects of wood harvesting and utilization policies on the carbon balance of forestry under changing climate: a Finnish case study. Forest Policy Econ. 2016;62:168–76.
107. Olsson B, Staaf H, Lundkvist H, Bengtsson H, Rosén J. Carbon and nitrogen in coniferous forest soils after clear-felling and harvests of different intensity. For Ecol Manag. 1996;82:19–32.
108. Davis SC, Hessl AE, Scott CJ, Adams MB, Thomas RB. Forest carbon sequestration changes in response to timber harvest. For Ecol Manag. 2009;258:2101–9.
109. Kuehl Y, Li Y, Henley G. Impacts of selective harvest on the carbon sequestration potential in Moso bamboo (Phyllostachys pubescens) plantations. For Trees Livelihoods. 2013;22:1–18.
110. Kamangadazi F, Mwabumba L, Missanjo E. The potential of selective harvesting in mitigating biomass and carbon loss in forest co-management block in Liwonde Forest reserve, Malawi. Scholars Acad J Biosci. 2016;4:716–21.
111. Schwenk WS, Donovan FM, Keeton WS, Nunery JS. Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis. Ecol Appl. 2012;22(5):1612–27.
112. Mao F, Zhou G, Li P, Du H, Xu X, Shi Y, et al. Optimizing selective cutting strategies for maximum carbon stocks and yield of Moso bamboo forest using BIOME-BGC model. J Environ Manag. 2017;191:126–35.
113. Augustynczik ALD, Arce JE, da Silva ACL. Spatial forest harvest planning considering maximum operational area. Cerne. 2015;21:649–56.