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A forest optimisation model including carbon flows: Application to a forest in Norway

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ABSTRACT

We analyse which management to choose in order to increase the carbon benefit from the 1.342 million ha forest area in Hedmark County, Norway, and the cost of doing this compared to traditional profit maximising behaviour. The model used in the analysis is a dynamic forest management optimisation model which includes the main carbon flows and benefits from the forest area: tree growth and mortality, litter accumulation, decomposition of dead wood and harvest residues, soil processes, end-use of wood products, and saved greenhouse gas emissions from using wood products instead of more energy intensive materials and fossil fuels.

The overall harvest from the region is restricted to the present level, in order to see which carbon benefits can be achieved while keeping a steady supply of timber to the forest industry. Under this restriction, maximising carbon benefit decreases the net present value of timber revenue from the region by 21%. There is more planting and less thinning compared to when timber revenue is maximised. If substitution effects, i.e. saved greenhouse gas emissions from use of wood products, are included in the analysis, it is optimal with more planting and thinning, although the changes are small in this case study because harvest level is held constant. On the other hand, net present value of carbon benefit (in ton CO_2-equivalent) is increased by 1.4–1.6 times when substitution effects are included. Changing forest management is a cost effective mitigation option. For a cost of € 0–10 per ton discounted CO_2-equivalent, the net present value of carbon benefit from the area can be increased with 0.2–0.3 million tonnes CO_2-equivalents on average in every year of the 120 years long planning horizon taking discounting into account (annuity).

1. Introduction

Global warming is a much debated and challenging issue, and mitigation of greenhouse gas emissions is seen as part of a long term solution. More information is needed on the mitigation options we have available, and in this context there is considerable interest for forests as carbon sinks and how forest management and land use can contribute to the reduction of accumulation of greenhouse gases in the atmosphere (IPCC, 2000, 2007). In addition, forests do not only store carbon, they provide a renewable resource that can be used instead of more energy intensive building materials or fossil fuels (e.g. Hektor, 1998; IPCC, 2007; Petersen and Solberg, 2005; Raymer, 2006; Scharai-Rad and Welling, 2002). What is the size of potential greenhouse gas benefits from forests? How and to what degree can humans influence greenhouse gas emissions through forest management? What will it cost? These are the questions behind the research presented in this paper.

Several studies have looked at the size of carbon storage in forests, either historically or in the future, as reviewed in Nabuurs et al. (2007). Others have examined the effect of various rotation lengths (Ericsson, 2003; Liski et al., 2001; Seely et al., 2002), thinning regimes (Karjalainen, 1996), or management options (Chen et al., 2000; Masera et al., 2003; Price et al., 1997; Schlamadinger and Marland, 1996; Shvidenko et al., 1997). What all these studies have in common is that forest management, i.e. harvest age, thinning regime, and regeneration scheme, are exogenously given. Only Backéus et al. (2005, 2006), Hoen and Solberg (1994), and Pohjola and Valsta (2007) have determined forest management endogenously in their models. Since forest management is the factor people can influence it is important to study which forest management to choose if the aim is to increase carbon fixation or there is a price on CO_2.

Some of the studies have included substitution effects, or greenhouse gas savings, from using wood instead of fossil fuels (Chen et al., 2000; Ericsson, 2003; Schlamadinger and Marland,

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1996; Shvidenko et al., 1997) or more energy intensive materials (Schlamadinger and Marland, 1996). However, since forest management in these analyses is based on predetermined management schedules, there is no information on how strongly substitution effects may influence optimal forest management from a carbon perspective.

As reviewed in Richards and Stokes (2004), changing forest management can be a cost-effective mitigation option, although methodology and assumptions differ between studies. Including cost-effectiveness and marginal cost of changing forest management in studies of carbon benefit is important in order to find the least expensive mitigation options.

This paper presents a case study of optimal forest management in Hedmark County in Norway and describes the dynamic forest management optimisation model used in the analysis. The aim of the case study is to find how much the carbon benefit from the area can be increased while maintaining a steady supply of timber, and what this would cost. Forest management is determined endogenously, and costs, revenues, and main aspects of carbon flows in forests are taken into account. These include tree growth and mortality, accumulation of litter, decomposition of dead trees and harvest residues, soil processes, end-use of wood products, and saved greenhouse gas emissions due to substitution (by using wood products as substitute for more energy intensive materials or by using wood as energy instead of fossil fuels). The model represents a substantially revised version of the model used in Hoen and Solberg (1994) by including substitution effects, a process based soil model, and annual production and mortality of needles, leaves, branches, and fine roots.

2. Model description

2.1. General

The model, GAYA-J/C, consists of two models; (1) the GAYA forest stand model which simulates a wide range of realistic stand treatment schedules for each stand in the forest and their corresponding net present value and carbon flow, and (2) the J optimising system, which, based on linear programming, optimises the management of all forest stands seen together, under exogenously specified constraints and objective function. GAYA acts as a matrix generator for J, defining for each forest stand a possible set of alternative treatment schedules, and J finds the optimal forest management according to the chosen objective function and restrictions, i.e. forest management is endogenous.

Compared to the previous version used in Hoen and Solberg (1994) the new model contains a more detailed soil module, annual production and mortality of needles, leaves, branches, and roots, and account for substitution effects in production of wood products, wood energy, and in waste handling. The substitution effects are net saved emissions, i.e. greenhouse gas emissions from alternative products minus greenhouse gas emissions from wood products. The carbon part of the model is also reprogrammed in matrix notation, which makes it more transparent and easier to update.

GAYA projects possible developments for each forest stand on a 5-year basis based on growth, yield, natural mortality, and seven different stand treatments: no treatment, release thinning in young growth, thinning, fertilization, clear felling, clear felling with retention of seed trees, and planting or natural regeneration depending on the cutting regime. For each of these treatments, several different options regarding intensity and timing are simulated based on the feasibility requirements shown in Table 1. These requirements are defined in accordance with criteria for sustainable forest management in Norway (Hoen et al., 1998), for instance, stands older than 160 years cannot be harvested.

Table 1
A priori feasibility requirements for forest management in the simulations.

Forest management alternatives	Feasibility restrictions
No management	–
Release thinning in young growth	Number of stems per ha min 2500, dominant height 2–8 m, can be performed max 2 times
Thinning	Number of stems per ha min 1200, dominant height 12–18 m, basal area min 15 m^2 per ha, can be performed max 2 times
Clear felling	Age of stand 60–160 years
Natural regeneration	1500 trees per ha after 20 years
Planting	800–4000 plants per ha with an interval of 100 plants per ha

The set of all simulated stand treatment schedules give the input/output coefficients in the linear programming model J. The general linear programming formulation for a forest management problem consisting of h stands is

$$\text{Max}\, O = \mathbf{c}^{\mathbf{t}}\boldsymbol{x}$$

where O is the objective function, e.g. net present value, $\mathbf{x}$ is the number of ha to be treated with a specific management schedule (this is the decision variable in the problem), and $\mathbf{c}$ is the net present value of the sequence of net payments related to each activity represented in $\mathbf{X}$.

The objective function is subject to constraints that ensure that:

- the total area remains constant,
- the number of ha treated with a specific management schedule cannot be negative, and
- the level of total harvested quantity, net income, or carbon fixation are set to reflect the research question.

The basic carbon accounting is done in GAYA as described in Sections 2.2–2.5. All results are calculated as tons CO_2. For each simulated forest treatment schedule, total storage and emissions of CO_2 is summed up for each period. It is this total flow of CO_2 for each forest management alternative that is used in the linear programming model.

The future value of the forest at the end of the planning horizon, both in monetary terms and in terms of carbon benefit, is found with exogenously given forest management programmes. These future values are included in the linear programming problem to control for the possibility of unrealistic forest management in the last period.

CO_2 fixation and release, as well as substitution effects, are discounted to a net present value with specified interest rates based on the assumption that the marginal damage of greenhouse gas emissions is constant over time (non-constant damage costs can easily be incorporated). The discount rate is assumed the same as for costs and revenues. GAYA-J/C is a deterministic model, i.e. future prices, interest rates, growth, and mortality are specified functions with no stochastic elements included.

2.2. Fixation of CO_2 in biomass

Three processes influence the carbon flow related to a forest rotation; (1) the fixation process, (2) the emission process, and (3) the substitution effect when wood products are used instead of fossil fuels or energy intensive materials. To model this flow we have to keep track of the development over time of the biomass and carbon content in living and dead trees, as well as in wood products.

CO_2 from the atmosphere is fixated in the trees as they grow. This is modelled with growth and yield functions (Braastad, 1966,