



## Research article

## Trade-offs between forest carbon stocks and harvests in a steady state – A multi-criteria analysis

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## ARTICLE INFO

## Article history:

Received 6 June 2017

Received in revised form

16 December 2017

Accepted 30 December 2017

## Keywords:

Carbon balance

Long-rotation forestry

Bioenergy

Substitution benefits

Steady-state forest management

Multi-criteria analysis

## ABSTRACT

This paper provides a perspective for comparing trade-offs between harvested wood flows and forest carbon stocks with different forest management regimes. A constant management regime applied to a forest area with an even age-class distribution leads to a steady state, in which the annual harvest and carbon stocks remain constant over time. As both are desirable – carbon stocks for mitigating climate change and harvests for the economic use of wood and displacing fossil fuels – an ideal strategy should be chosen from a set of management regimes that are Pareto-optimal in the sense of multi-criteria decision-making. When choosing between Pareto-optimal alternatives, the trade-off between carbon stock and harvests is unavoidable. This trade-off can be described e.g. in terms of carbon payback times or carbon returns.

As numerical examples, we present steady-state harvest levels and carbon stocks in a Finnish boreal forest region for different rotation periods, thinning intensities and collection patterns for harvest residues. In the set of simulated management practices, harvest residue collection presents the most favorable trade-off with payback times around 30–40 years; while Pareto-optimal changes in rotation or thinnings exhibited payback times over 100 years, or alternatively carbon returns below 1%. By extending the rotation period and using less-intensive thinnings compared to current practices, the steady-state carbon stocks could be increased by half while maintaining current harvest levels. Additional cases with longer rotation periods should be also considered, but were here excluded due to the lack of reliable data on older forest stands.

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## 1. Introduction

Sustainably managed commercial forests are an important source of renewable biomass while simultaneously sequestering atmospheric carbon (Koponen et al., 2015). Forests can mitigate climate change in two ways:

1) the harvested flow of biomass carbon displaces a) fossil fuels with wood fuels, and b) materials with high fossil-carbon emissions from manufacturing (e.g. concrete or steel) with wood products;

2) the biomass carbon stock of both forests and long-lived wood products sequester carbon from the atmosphere.

There are trade-offs and synergies between the above wood-use and carbon-sequestration options related to managed forests. How should such trade-offs be valued?

In the ‘short-term’ – up to 2050 or even 2100 – the carbon-stock changes of long-rotation forests seem to be of greater magnitude than the substitution benefits from wood-based bioenergy (Mitchell et al., 2012; Holtsmark, 2013, 2015), with the exception of small-diameter harvest residues (Repo et al., 2011, 2012). Studies related to boreal forests at the country level (Soimakallio et al., 2016; Kallio et al., 2013; Pingoud et al., 2016), regional (Helin et al., 2016) or stand level (Pingoud et al., 2012) also indicate that long-rotation forestry in general – the management and harvest of slowly growing forest biomass stocks for materials and energy – increases atmospheric carbon stocks when compared with almost

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any baseline with less-intensive thinnings or longer rotations. The same conclusion applies even when high fossil-fuel substitution benefits could be achieved with the harvested biomass and, in addition, a substantial share of the biomass could be sequestered into long-lived wood products.<sup>1</sup> Economic analyses using the Faustmann model for finding optimal rotation lengths have come to similar conclusions if changes in the forest carbon stock are priced (van Kooten et al., 1995), particularly if the carbon price increases over time (Ekholm, 2016).

A major reason for the above results is the foregone carbon sequestration. When trees in the growing phase are cut (e.g. in thinnings) their potential carbon sink will be lost, which is compensated only in the long-term by the faster growth of remaining trees and the substitution benefits of the harvested biomass flow, utilized as energy or wood-based materials. It is critical to note that the above results do not imply that the forests at regional or country level would be a carbon source,<sup>2</sup> only that their carbon sequestration is weaker with respect to any no-harvest or less-harvest baseline, and this weakening cannot be compensated by the substitution benefits of the higher supply of harvested wood.

A complementary perspective to the transient, i.e. short-term, carbon balance is to consider the carbon balance of steady-state forest management, where the size and age class distribution of the considered forest area remain constant over time. The forest area produces a sustained biomass yield and climate benefit, and different steady-states can be compared against each other in terms of their climate benefits. This perspective, similar to Torssonen et al. (2016) is the subject of the present article. The steady-state condition, termed normal forest in the forestry literature (see e.g. Leslie, 1966), can be pictured in a simplest way as a forest with an even distribution of age classes, where the oldest age class is harvested annually, thus yielding the same harvest each year.

Here, we present steady-state forest management as a problem of maximizing both the biomass carbon stock and harvests, provide two measures for characterizing their trade-offs, and illustrate the concept with simulation results that pertain to forests in mineral soil sites in Southern Finland. The considered management regimes differ in their rotation lengths, thinning intensity and the collection of harvest residues, and result in different steady-state levels of carbon stock and annual biomass yield. While the approach presented cannot answer what is an optimal trade-off between carbon stocks and harvest flows, it renders this trade-off explicit and helps to avoid sub-optimal forest management strategies.

The system boundary of our analysis includes the carbon stocks of wood biomass and the fossil carbon stocks, whose emissions are avoided through use of renewable wood biomass. In a previous study (Pingoud et al., 2010), forest steady-states, together with their wood use chains, were compared applying two indicators: 1) the biomass-carbon stock of forests and wood products in service and 2) the estimated annual fossil-carbon substitution benefits of the wood-use cycles.<sup>3</sup> In this article an indicator integrating these two factors is presented. In the current study the focus is on forest management based on comprehensive data on commercial forestry

practices in Southern Finland. The substitution benefits of wood production are considered but the carbon stock of wood products is excluded. An assessment of the potential end use of wood products for each forest management alternative would have required a specific analysis beyond the scope of this article.

## 2. Methods

We consider here managed forests in a steady state: a forest area is composed of a large number of stands with a uniform age-class distribution for which a constant management regime and clear-cutting cycle is applied repeatedly *ad infinitum*. Such a steady state is often termed *normal forest* (see e.g. Leslie, 1966), and for which the amount of annual harvests and the forest carbon stock remain constant over time. An example of a management cycle of a single stand with a rotation with two thinnings and final fellings is depicted in Fig. 1a. Applying this management strategy for a collection of stands with uniform age-class distribution would lead to the above regional-level steady state.

A management regime such as the one represented in Fig. 1a results in an annual average standing carbon stock and an average annual harvest over the life of a stand for that specific regime. When applied under the steady-state condition, these are equal to a steady-state harvest  $h$  (tC/ha/year = metric tonnes of carbon per hectare per year) and biomass carbon stock  $C$  (tC/ha). This combination generates one point in Fig. 1b. Simulations with multiple management regimes generate a set of such points. The frontier of this set of points separates the set of feasible points (the region under and to the left of the curve) from the infeasible region. Fig. 1b presents the frontier as a smooth concave relationship. Later, in Fig. 2, our numerical simulation results approximate this curve with a piecewise linear surface.

A forest management regime affects both the annually harvested amount of wood and the carbon stock of the forest. Both of these are desirable and should thus be maximized. From the perspective of these two criteria, an ideal forest management regime would maximize both stock and flow; and make voluntary trade-offs between the two criteria when necessary.

In a multi-objective setting, such as the setting described here, an ideal strategy is said to be Pareto optimal when improving one criterion is impossible without worsening the other criterion. The outer boundary of this feasible region is a Pareto curve  $C_p$ , and all points inside the feasible region are inferior to those at the Pareto curve: when starting from an interior point, it is always possible to improve either of the criteria without worsening the other, ending up at the Pareto curve.

The steady-states at the Pareto curve  $C_p$  involve inherently a trade-off between the carbon stock and harvests. The marginal level of this trade-off at a steady-state  $(h,C)$  on  $C_p$  equals the slope of the tangent ( $dC_p/dh$ ) at the point  $(h,C)$  (Fig. 1 b).<sup>4</sup> The choice over the preferred marginal trade-off fixes the slope of the tangent of the Pareto curve, and thus also the corresponding optimal steady-state point on  $C_p$ . That is, choosing a desired level of the trade-off determines the optimal forest management regime.

We provide an interpretation with two characterizations for the trade-offs between steady-states. A change in management regimes that shifts the steady-state on the Pareto curve and decreases the steady-state forest carbon stock also enables an increase in the harvests. Such carbon stock loss between Pareto-optimal steady-states can be portrayed as a one-time investment, which provides an additional and perpetual flow of biomass carbon from the forest.

<sup>1</sup> On the substitution benefits of wood construction and carbon sequestration into long-lived wood products, see, e.g., Sathre and O'Connor, 2010; Pingoud et al., 2012; Gustavsson et al., 2006; Forsell et al., 2010, pp. 319–324.

<sup>2</sup> They can still be a carbon sink as a whole. For example, Finland and Sweden are countries with intensive long-rotation forestry and major forest industries, but simultaneously an annually increasing growing stock volume (Koponen et al., 2015).

<sup>3</sup> Pingoud et al. (2010) was a limited case study, where the logs were used as building material of two specific wood-framed multi-store houses, one in Finland and the other in Sweden. The greenhouse gas balance of these two building cases was based on a detailed life-cycle study (Gustavsson et al., 2006).

<sup>4</sup> In economic terms, the Pareto curve can be called a production possibilities frontier while the slope is the marginal rate of transformation.

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