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Does biofuel harvesting and continuous cover management increase carbon sequestration?

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ABSTRACT

The study used an existing forest planning system to analyze the influence of fuel feedstock harvesting and type of forest management on the carbon balance of forestry. The carbon balance module simulated changes in the carbon storage in living biomass, dead organic matter and products. Carbon releases from timber harvesting, transporting and manufacturing were included in the carbon balance, as well as the substitution, recycling and reuse effects of different types of wood products (avoided releases from fossil fuels due to the use of wood). Prediction models were developed for the initial pools of wood products and dead organic matter. The results show that collecting branches, stumps and coarse roots for bioenergy improves the carbon balance very little during the first 30 years of biofuel harvesting. This is because decreased carbon balance of forest soil partially cancels the positive substitution effects of fuel feedstock harvesting. Using high thinnings and continuous cover management, instead of low thinnings, clear felling and artificial regeneration have an immediate positive effect on the carbon balance. This is because the sizes of the wood product and living biomass pools increase, and manufacturing releases decrease.

1. Introduction

One of the ecosystem services of forests is carbon sequestration. A measure of 'net sequestration' is carbon balance, which is the difference between sequestrated and released carbon. A positive balance means that forestry is carbon sink and negative balance implies that forestry is carbon source. According to international carbon standards (Verified Carbon Standard, 2013), the carbon balance should include changes in the carbon content of (1) living biomass, (2) dead organic matter, and (3) wood-based products. In addition, carbon releases of harvesting, transporting and manufacturing should be included in the balance.

Besides these standard components of the carbon balance of forestry, substitution effects may also be considered in the calculations (Schelhaas et al., 2004; Backéus et al., 2005, 2006; Pukkala, 2011). A substitution effect means that the use of wood decreases the consumption of fossil fuels, and this decrease can be included as a positive component in the carbon balance. Substitution effects are substantial for bioenergy since most wood-based biofuels replace fossil oil and carbon. A substitution rate of 0.8 has been widely used in the literature (e.g., Díaz-Balteiro and Rodriguez, 2006; Pukkala, 2011). A substitution rate of 0.8 means that carbon releases from fossil fuels are reduced by 80% of the carbon content of biofuel. Wihersaari (2005) calculated that substitution rates higher than 0.75 are justified for forest biofuel.

Construction wood also reduces the use of fossil fuels and therefore has positive substitution effects. This is because construction wood reduces the use of energy in cement and steel industry. A substitution rate of 0.4 has been used earlier for construction wood (Pukkala, 2011; Pukkala et al., 2011).

Some wood-based materials can be recycled for the same use. Recycling reduces the rate at which carbon is released back to the atmosphere and can be easily included in calculations by decreasing the decomposition rate of the product. Paper products and waste wood from demolished buildings can be used as biofuel, which has the same substitution effect as fuel feedstock collected from the forest. Recycling and reuse improve the carbon balance of forestry through reduced product decomposition rate and via positive substitution effects. Recycling and reuse are seldom explicitly included in international carbon standards (Verified Carbon Standard, 2013).

As a summary, the main components of the carbon balance of forestry are the following items:

- Change in the carbon storage of living biomass
- Change in the carbon storage of dead organic matter
- Change in the carbon storage of products
- Harvesting, transporting and manufacturing releases
- Substitution effects of primary use
- Substitution effects of recycling and reuse

Calculating the carbon balance of forestry implies that changes in three carbon pools (living biomass, dead organic matter, wood products)

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are simulated. Changes in living biomass can be calculated with several existing forest simulators. Decomposition of dead organic matter (also called soil organic matter) can be simulated for instance by using simple decay curves (Yatskov et al., 2003), Yasso07 model (Liski et al., 2009; Tuomi et al., 2011a, 2011b), or the fairly similar method of the Co2Fix model (Masera et al., 2003; Schelhaas et al., 2004). Inputs to the dead organic matter pool consist of dead trees, harvesting residues and annual litter fall.

Product decomposition can be simulated for instance by using the following formula

$$B_t = B_0 e^{-kt} \quad (1)$$

where B_t is the remaining dry mass after t years since manufacturing, B_0 is the dry mass at the moment of manufacturing, and k is the decay rate, which is different for different product types. Other decomposition functions have also been presented in literature (Karjalainen et al., 1994; Schelhaas et al., 2004; Mäkinen et al., 2006; Verified Carbon Standard, 2013). The same formula (Eq. (1)) has also been used to simulate the decomposition of dead organic matter (Yatskov et al., 2003). Inputs to the wood product pool consist of those parts of cut trees that are taken away from the forest and used as raw materials for wood-based products. Most models for the decomposition of products and dead organic matter result in fairly similar, descending curve.

Each of the three pools should be initialized, i.e., their amounts in the beginning of simulation should be estimated. The living biomass pool can be initialized by using inventory data in combination with biomass models (e.g., Repola, 2009) or biomass expansion factors (e.g., Lehtonen et al., 2004). The other pools can be initialized by prediction models, imputation, or running the model several times for the same stand and management schedule and using the ending pool as the initial pool of the new simulation. The latter method has been used in stand-level analyses (Pukkala, 2011) but it may become complicated in large scale forest level analyses.

Initialization of dead organic matter and product pools is often found complicated and this step is therefore ignored or circumvent. International carbon standards (Verified Carbon Standard, 2013) avoid initialization by calculating the carbon balance for two alternatives: baseline and project (Schelhaas et al., 2004). Both balances are calculated without initialization, and carbon credits are based on the difference between project and baseline. This difference is the same whether or not dead organic matter and wood product pools are initialized (assuming that the decomposition rate of the initial soil organic matter pool does not depend on management). However, this kind of calculation does not tell whether forestry is carbon sink or carbon source. Therefore, carbon credits may be obtained even when carbon is released. This happens when both the baseline and the project have negative balances but project is better than baseline.

A potential way to improve the carbon balance of forestry is uneven-aged management and other forms of continuous cover forestry such releasing advance regeneration in high thinnings. Previous research suggests that high-thinnings and uneven-aged management may result in better carbon balance than even-aged plantation forestry (Pukkala, 2011; Pukkala et al., 2011). This is because mainly large trees are harvested, with a larger proportion of wood going to construction purposes and long-lived products. However, collecting harvest residues (branches and tree tops) for biofuel is the easiest in clear-felling, and stumps can be harvested only in clear-felling sites. If the substitution effects of these sources of bioenergy are included in the carbon balance, it can be hypothesized that clear-felling becomes superior to continuous cover forestry.

Few studies have included all the relevant components of carbon balance in the comparisons of forest management alternatives. This study aimed at presenting a detailed methodology for calculating forest's carbon balance in the context of forest management planning. The method was used to compare the carbon balances of rotation forestry and continuous cover forestry and to analyze the influence of fuel feedstock harvesting on carbon balance. The economics and profitability of timber production was measured by the net present value of all future costs and incomes. Earlier studies (e.g., Díaz-Balteiro and Rodriguez, 2006; Pohjola and Valsta, 2007; Pukkala, 2011) have used monetary units also for carbon benefits, allowing the researchers to maximize the total net present value arising from timber production and carbon sequestration. This study used multi-objective optimization approach, in which timber benefits were described with net present value and carbon benefits were measured by using carbon balance, i.e., the difference between sequestrated and released carbon.

2. Methods

2.1. Carbon balance calculator

The dynamics of living biomass was simulated using the individual-tree growth models of Pukkala et al. (2013), programmed in the Monsu simulation–optimization software (Pukkala, 2004). The same models can be used in both even- and uneven-aged management (Pukkala et al., 2013). Ingrowth, i.e., the gradual regeneration of stands, was simulated, in addition to tree growth and survival. The taper models of Laasasenaho (1982) were used to calculate assortment volumes of removed trees, and the models of Repola (2009) were used to calculate the biomasses of tree components other than stem (branches, foliage, stump, coarse roots). Stem biomass was calculated by multiplying stem volume by the basic density of wood. A species-specific proportion (around 0.5) of dry biomass was assumed to be carbon (Table 1).

Dead trees, harvest residues and annual litter production were inputs to the dead organic matter pool. The biomass of small trees removed in the tending operations of young stands was also moved to the dead organic matter pool. Litter production was calculated from biomass using turnover rates (Table 2), which were adopted from literature (e.g., Peltoniemi et al., 2004; Liski et al., 2006). Since there were no biomass models for fine roots, fine root biomass was assumed to be a certain proportion of foliage biomass (Vanninen and Mäkelä, 1999; Helmisaari et al., 2007). The decomposition of dead organic matter (soil organic matter) was simulated using the Yasso07 model (Liski et al., 2006; Tuomi et al., 2011a, 2011b). The model simulates the transitions between acid-soluble, water-soluble, ethanol-soluble, non-soluble and humus components (AWENH-components) of the organic matter, as well as the decomposition of each component.

In the Yasso07 model, decomposition rate depends on the mean annual temperature, annual precipitation and temperature amplitude of the region, as well as on the size (diameter) of the deadwood piece. Because size affects decomposition rate, the dead organic matter pool was divided into 5 sub-pools according to the size of the piece of dead organic matter. Trunks, stumps and coarse root systems were added to one of the following sub-pools on the basis of the dbh of the tree: 0–10 cm, 10–20 cm, 20–30 cm and over 30 cm. The remaining biomass components were added to size class 0 cm. The decomposition of each pool was simulated separately (Fig. 1). The initial compositions (proportions of AWEN fractions) of different dead matter inputs were obtained from the Appendix table of Yasso07 Manual (Liski et al., 2009). As an example, in pine branches their shares are: A 45%, W 2%, E 10%, N 43%. There are substantial differences between tree species and biomass components but in most cases A is the largest component and is N the second. The mass of component A decreases rapidly in decomposition, and N becomes soon the largest component.

Harvested trees were divided into the following components: saw log; pulp wood; firewood (fuel feedstock made of stems); fuel feedstock from branches and tree tops; and fuel feedstock from stumps and coarse roots. Saw logs and pulpwood pieces were further divided into four end product categories: (1) sawn wood and plywood, (2) mechanical mass,