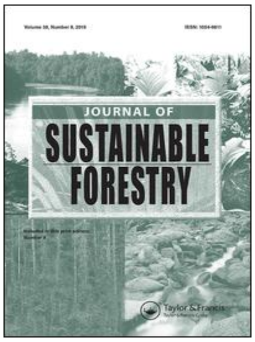

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Calculating the Additional Carbon Sequestration of Finnish Forestry

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ABSTRACT
Forestry sequestrates carbon from the atmosphere and stores it in living tree biomass, dead organic matter (DOM) and wood-based products. A part of the sequestration might be "additional", i.e., increased sequestration compared to the business as usual forestry. This study developed a methodology for calculating the additional part of the carbon sequestration of Finnish forestry. Additionality was defined to be equal to increasing the carbon stocks beyond a reference level, which was equal to the carbon socks of current Finnish forestry. Models were developed for calculating the reference carbon stocks of living tree biomass, DOM and wood-based products, using site fertility and temperature sum as predictors. New models were also developed for initializing the carbon stocks of DOM and wood-based products. These models were used in simulations that predict the future changes of the carbon stocks in a given forest management scenario. The model system developed in this study makes it possible to calculate the future carbon stocks and additional carbon sequestration of any Finnish forest area in alternative forest management scenarios. The use of the system was demonstrated in three case study forests for two different management scenarios.

KEYWORDS
Carbon balance; carbon stock; carbon sink; carbon credit; carbon store

Introduction

Forests sequestrate significant amounts of carbon from the atmosphere (Canadell & Raupach, 2008; Sedjo & Sohngen, 2012). This carbon is stored first in living biomass, from where it moves to the carbon pool of dead organic matter (DOM) in the form of litter, dead trees and harvest residues, or to the carbon pool of wood products.

The carbon sequestration of forests has a significant impact on climate and national carbon budgets, especially in countries with a high cover of forests such as Finland (Official Statistics of Finland, 2019). The carbon balance of forests and forestry can be affected by regulations, taxes, subsidies, and international carbon trade. For example, a recent study (Pukkala, 2020) showed that the carbon sequestration of Finnish forestry can be increased by 70% with a subsidy of 100 euros per ton of carbon sequestrated in the living tree biomass and DOM (27.3 € per ton on CO_2). Subsidies to carbon sequestration have been shown to increase optimal stand densities and rotation lengths (e.g., Assmuth & Tahvonen, 2018; Couture & Reynaud, 2011; Daigenault et al., 2010; Guthrie & Kumareswan, 2009; Pukkala, 2011; Raymer et al., 2011; Van Kooten et al., 1995). The proportion of saw log of harvested

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wood would increase (Assmuth et al., 2017; Pukkala, 2011) and the profitability of continuous cover management would improve as compared to even-aged rotation forestry (Assmuth & Tahvonen, 2018; Pukkala et al., 2011).

A part of the carbon sequestration of forests might be tradable in international carbon markets. This part needs to be "additional", i.e., excess to the carbon sequestration of normal or "business as usual" (BAU) forest management (Gren & Aklilu, 2016). Calculating the additional carbon sequestration needs a definition for the BAU management, or an estimate of the carbon sequestration of the BAU management.

One possibility to define the BAU forest management are silvicultural recommendations (Äijälä et al., 2014); sequestration that is surplus as compared to the recommended silviculture is additional. The problem of this approach is that it is not known to what extent the past or current management corresponds to the recommendations. Forest landowners often sell timber when they need income or timber price is high. Following the recommendations is not of primary importance to the landowner. Besides, the current recommendations are flexible, allowing a wide range of carbon sequestration levels and failing to dictate a single reference level for the sequestration (Äijälä et al., 2014).

Another possibility to define the reference level is economically optimal management. However, this does not correspond to the BAU management either since forests are not always managed for maximal economic profitability (Hyytiäinen & Tahvonen, 2001). Forests are managed for many different purposes, depending on the preferences of the landowners (Häyrinen et al., 2014). If economically optimal management is used as the BAU management, there is a problem of selecting the discount rate. A low rate leads to a low cutting level, high biomass and increasing carbon stocks of forests while a high rate has the opposite effect (Price, 2011; Pukkala et al., 2011).

The current carbon stocks of forests and wood-based products are a result of past management, climate, site productivity and disturbance regime. If a certain type of forestry is practiced for a long time, and the other factors remain constant, the carbon stocks of living tree biomass, DOM and wood-based products will all reach an equilibrium where the inputs to the carbon pools are equal to the outputs. Therefore, another possibility to define additionality is to use the current forest-generated carbon stocks as the reference level. Increasing the carbon stocks beyond their current sizes can be assumed to be an operational definition for additionality.

Calculating the carbon stocks of living tree biomass is insufficient for a fair carbon accounting. For example, the carbon pool of living biomass can be increased quickly by refraining from cuttings. However, this would lead to decreased carbon stocks of wood-based products as inputs would cease but old products are being continuously discarded. The carbon stocks of DOM may also decrease, at least temporarily, since carbon inputs in the form of stumps, roots and branches of harvested trees stop. Later on, inputs to the DOM carbon pool may start to increase again when the litter production and mortality of unharvested forests increase. Monitoring only the carbon pool of living biomass gives a positively biased estimate of the immediate effect of decreased cutting levels on the carbon sequestration of forests. For a non-biased estimate, it is necessary to consider also the carbon pools of DOM and wood-based products.

This study developed a carbon accounting system where additionality is based on the carbon stock levels of the current Finnish forests and forestry. The carbon stocks of the current forestry provide the reference level, to which the carbon stocks of a certain management scenario are compared. The study developed new models for calculating the reference levels of the carbon pools living tree biomass, DOM, and wood-based products.

Another set of models was developed for initializing the stand-level carbon pools of wood-based products and DOM in simulations. There are previous predictive models for this purpose (Pukkala, 2014) but the earlier models may no longer correspond to the latest knowledge on the decomposition dynamics of DOM or the life cycles of wood products. The earlier models for DOM (Pukkala, 2014) are based on simulations with the Yasso07 decomposition model (Tuomi et al., 2011). This model has been updated based on additional data, resulting in the Yasso15 model (Akujärvi et al., 2019; Didion et al., 2016; Ťupek et al., 2019). Also, the models for simulating the uses of harvested timber and the life cycles of wood-based products have been fine-tuned in recent research (Hurmekoski et al., 2020; Pukkala, 2020).

Calculation examples were provided to illustrate the use of the developed models. The total carbon sequestration and its additional part were computed for three case study forests in two different management strategies.

Materials and methods

Defining additional carbon sequestration

In this study, additionality was defined to be an increase in the size of forest-generated carbon stocks, as compared to the carbon stocks of the current Finnish forestry. The current stocks vary with latitude (temperature sum) and soil fertility. It can be assumed that the product carbon pools are larger for fertile sites and southern latitudes since more timber is harvested from these sites. The DOM pools might also be larger on fertile sites due to larger carbon inputs in the form of litter and harvest residues. The effect of latitude on soil carbon pool is less clear since decreasing temperature toward the north decreases carbon inputs but also the decomposition rate of dead organic matter decreases toward the north.

The carbon accounting system proposed in this study further assumes that if the initial carbon stock of the forest is less than the reference level, the forest landowner needs to pay for the deficit (Figure 1). This penalty is due to earlier management that has yielded low carbon stock levels. Correspondingly, the forest landowner is entitled to immediate compensation when the initial carbon stock is higher than the reference level.

Modeling initial dry matter stocks

A 0.05% random sample of all forest stands of the private forests Finland (4887 stands) was drawn from Metsaan.fi/paikkatietoaineistot. This data repository includes data on all private forest stands of Finland, mostly based on airborne laser scanning. The stand data were imported to a forest simulator (Monsu; Pukkala, 2004). The development of each stand was simulated for 100 years to produce data for modeling the dry matter stocks of DOM and wood-based products. In addition to the living tree stock, the software simulated the dynamics of DOM and the life cycles of harvested trees. The details of the simulation model are explained in Pukkala (2020), including all parameters required in the simulation of carbon dynamics.

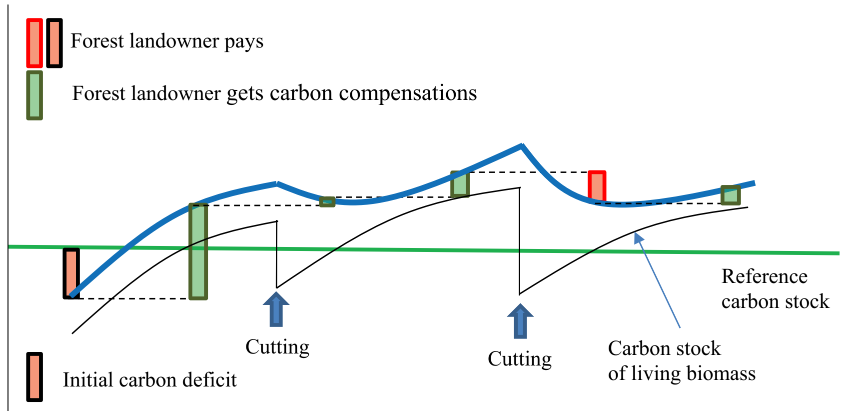


Figure 1. The principle of defining carbon compensations based on the reference level of carbon stocks (green horizontal line). The payments (vertical bars) are based on the changes in the carbon stocks, except the initial payment that is based on the deviation from the reference level. The thin black line is the temporal development of the carbon stock of living biomass, vertical changes representing cutting events. The blue line is the total size of all carbon pools (living biomass, DOM and wood products).

In these simulations, the initial dry matter stocks were calculated using biomass models (Repola, 2009; Repola et al., 2007) and existing predictive models for the dry matter pools of DOM and wood-based products (Pukkala, 2014). Simulation results at the end of the 100 years were used to develop preliminary models for the carbon pools of DOM and wood-based products. Then, another 100-year simulation was conducted where the initial carbon stocks were predicted by using the preliminary models. The final models for the dry matter stocks were based on the results of the second simulation.

The development of all stands under different management scenarios was simulated in 5-year time steps using 10-year sub-periods in the simulation of treatments. Growth, survival and ingrowth were simulated with the models of Pukkala et al. (2013). Decomposition of DOM was simulated using the Yasso15 model (Akujärvi et al., 2019). The carbon dynamics of wood-based products were simulated as described in Hurmekoski et al. (2020) and Pukkala (2020). Forest management was simulated using even-aged silviculture. Stands were assigned randomly to different thinning types, namely thinning from below, thinning from above, and uniform thinning (equal thinning intensity in all diameter classes). Thinning from above often leads to the postponement of final felling, even by several decades. This happens if the stand is uneven-sized and there is plenty of ingrowth. Using thinning from above is therefore a step toward continuous cover management.

The lower limits of the current recommendations for thinning basal area and mean tree diameter for final felling (Äijälä et al., 2014) guided the simulation of cuttings. Alternative schedules were simulated where the cuttings were postponed by 1, 2, 3, … 10 ten-year periods. Also such schedules were simulated where cuttings were not allowed during the 1st, 2nd, 3rd, … or 10th period.

The total number of different 100-year management scenarios was 197141. The ending growing stock characteristics and the ending dry matter pools of these scenarios were used to fit predictive models for the dry matter pools of DOM and wood products, using the site and growing stock variables as predictors.

When the dynamics of the dry matter pool of soil are simulated with the Yasso model (Yasso07 or Yasso15), the pool sizes must be known separately for acid-, water- and ethanol-soluble fractions, as well as non-soluble and humus fractions (Tuomi et al., 2011). These fractions are referred to as AWENH components. The decomposition rate in Yasso simulations depends also on the size of the piece of decomposing material, large pieces decomposing more slowly than small ones.

To produce detailed enough data for Yasso simulations, the models for initial pool sizes were fitted separately for the five AWENH components as well as different sizes of pieces of DOM. The piece sizes were 0 cm, 0–10 cm, and >10 cm. There were more size categories in the simulation but since the dry masses of categories other than 0 cm were rather small, some categories were pooled, and the models were developed only for the three categories mentioned above. In simulations, branch, foliage and root litter as well as the roots and branches of harvested and dead trees were assumed to represent the 0-cm category. The stumps of dead and harvested trees and the stems of dead trees were assigned to the other size categories according to the dbh (diameter at breast height) of the cut or dead tree.

The models for the dry matter pools of wood products were fitted separately for the following product categories: (1) sawed wood, plywood and veneer, (2) mechanical mass products, (3) chemical mass products and (4) bioenergy. The durability of the carbon in different product types varies, the first category (sawed wood, plywood, veneer) being much more durable than the others. Dissolving pulp (used for textiles) was included in the category of chemical mass products.

Newly clear-felled areas are associated with high dry matter pools of DOM and wood products since all dry matter of living trees has recently been moved to the DOM and product pools. However, a part of the new carbon inputs to the DOM and product pools returns quickly back to the atmosphere. Therefore, the sizes of the pools can be assumed to decrease after clear-felling. The dry matter pool of DOM may start growing again when the litter input of the new regeneration exceeds the dry matter loss due to decomposition.

It was also expected that a low stand basal area is associated with high DOM and product pools since low stand basal area is an indication that the stand has been thinned recently. A dense mature stand is associated with a small product pool, and its DOM may be smaller than in a fresh clear-felling site. It was also assumed that improving site fertility and increasing temperature sum increase the size of the product pools created from timber harvested from the stand. Improving site fertility was assumed to increase the size of the DOM pool.

The model forms were developed using data for the major dry matter pools, which were sawed wood for products, and the non-soluble and acid-soluble fractions of DOM. Then, the same model forms were used for all product and DOM categories. The selected model forms were as follows:

$$\text{ProductPool} = \exp(b_0 + b_1 G + b_2/yrs + b_3 H + b_4 ln(TS/1000) + b_5 Mesic + b_6 SubXeric + b_7 Xeric) \tag{1}$$

$$\text{DOMPool} = \exp(b_0 + b_1\sqrt{G} + b_2 G + b_3/(yrs+1) + b_4\sqrt{H} + b_5 ln(TS/1000) + b_6 Mesic + b_7 SubXeric + b_8 Xeric) \tag{2}$$

where G is the stand basal area (m^2 ha^{-1}), H is the mean tree height in meters (or 0.3 m if the mean height is less than 0.3 m), TS is temperature sum (d.d.), and *Mesic, SubXeric* and *Xeric* are indicator variables for mesic, sub-xeric and xeric or poorer site, respectively. If all indicator variables are zero, the site fertility is herb-rich or better. The unit of temperature sum is “degree days” (d.d.), which is the sum of mean daily temperatures minus 5°C of those days on which the mean temperature is higher than 5°C. Variable *yrs* measures time since final felling. It is such a transformation of stand mean height, which takes into account the slower growth rate of trees toward northern latitudes. Variable *yrs* is calculated as $H/(TS/1000)$. For example, when the mean tree height is 2 m, $yrs = 2.86$ with $TS = 700$ d.d., $yrs = 2.0$ with $TS = 1000$ d.d., and $yrs = 1.54$ with $TS = 1300$ d.d.

The unit of the predicted variable is tons of dry matter per hectare. The pool sizes were expressed in dry matter instead of carbon because the Yasso decomposition model operates with dry matter.

The “internal consistency” of the developed model sets was tested by initializing the carbon pools of each stand of three cases study forests with the developed models and simulating the forest development for 50 years using the same growth, mortality, decomposition and product models that were used to produce the simulated modeling data. Forest management and development were simulated in such a way that the total growing stock volume remained constant (at the initial level). Internal consistency requires that the carbon stocks of all three pools should be more or less constant for the whole 50-year simulation period. Any significant decrease or increase in the carbon pool sizes of DOM or products would be an indication that the initialization models over- or underestimate the sizes of the initial dry matter pools.

The three case study forests were created by taking small random samples of stands from latitudes 61–62 degrees (South Finland), 64–65 degrees (Central Finland) and 66–68 degrees (North Finland) using the same stand database as in the other analyses of this study (Metsaan.fi/paikkatietoaineistot). The sampling ratio was selected in such a way that the number of stands in each case study forest was 500–1500.

Modeling reference carbon stocks

After developing models for the initial dry matter pools of products and DOM, another set of models was fitted to calculate the reference levels for the carbon pools of living trees, DOM and wood-based products. The predicted variable of these models was the amount of carbon, in tons per hectare. The models for the reference level provide estimates of the average carbon stocks of Finnish forests. To develop these models, a 2% random sample of all Finnish private forests was drawn from Metsaan.fi/paikkatietoaineistot. This resulted in 180754 stands. The carbon pool of living tree biomass was calculated for each stand using the biomass models of Repola et al. (2007), and Repola (2009) and the species-specific carbon contents of woody biomass (Pukkala, 2014). The carbon pool sizes of DOM and products were calculated with the predictive models developed in this study.

The models for the reference levels of carbon pools predicted the average carbon pool size of Finnish forests (tons of carbon per hectare) as a function of temperature sum and site fertility. The model form was as follows

$$\text{ReferenceCarbonPool} = \exp(b_0 + b_1 ln(TS/1000) + b_3 Mesic + b_4 SubXeric + b_5 Xeric + b_6 Heath) \quad (3)$$

where *Heath* is an indicator variable for sites poorer than xeric.

Case study calculations

The whole system of calculating the temporal development of carbon pools and their deviations from the reference levels was demonstrated in the three case study forests described above. Two 50-year management plans were developed for each forest. In the first plan, there were no cuttings and the second plan maximized the net present value of timber production using a 3% discount rate.

Results

Models for initial dry matter pools

The models for initial dry matter pools predict the amount of remaining dry matter in products prepared of wood harvested earlier from a particular stand. The models (Appendix) show that most of the dry matter is in the sawed wood category, which also includes plywood and veneer products (Figure 2).

The diagram of Figure 2 (top) is a simple simulation of the development of the product pool size as a function of stand development. Mean tree height is used as a proxy of time since previous final felling, and stand basal area (in m^2 ha^{-1}) is assumed to be equal to mean height (expressed in meters). The models predict that the dry matter of energy biomass and

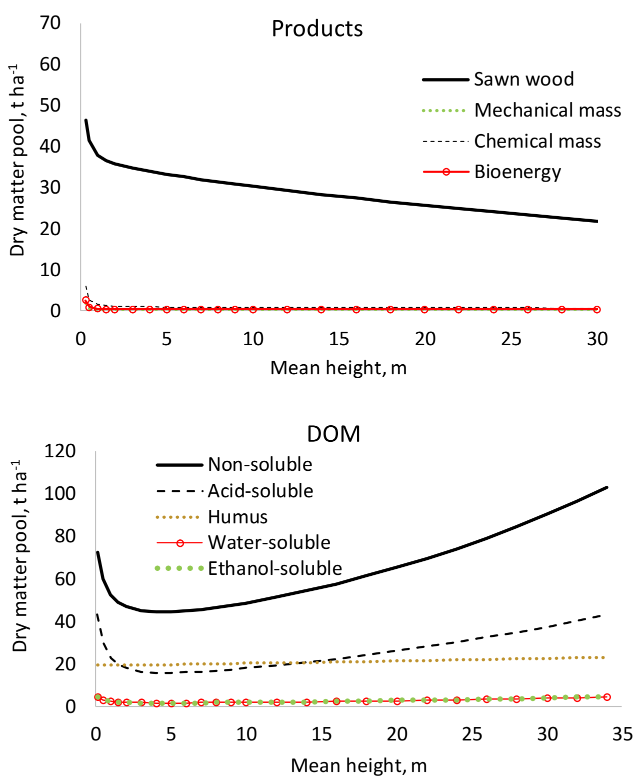


Figure 2. Predicted amount of dry matter in the product (top) and DOM (bottom) pools as a function of tree height. The temperature sum is 1100 d.d. and the site is mesic. Stand basal area (in m^2 ha^{-1}) is equal to mean tree height (in m).

mass products almost disappear soon after final felling but the dry matter pool of sawed wood decreases only about 50% by the time when the trees are 30 m tall and stand basal area is 30 m^2 ha^{-1}. The persistence of the sawed wood pool is because a part of the products has a longer life span than the rotation lengths used in forestry. The sawed-wood pool associated with a particular stand originates from several final fellings and other cuttings of the stand.

The largest component of the DOM pool is the non-soluble fraction (Figure 2 bottom). Water- and ethanol-soluble fractions are negligible and acid-soluble and humus fractions are in-between. The pool sizes are high immediately after final felling (at low mean height), due to the high input in the form of the stumps, roots, branches and tops of harvested trees. The pool sizes start to decrease due to the decomposition of harvest residues. Later on, the pool sizes increase again, due to increased production of litter and coarse woody debris, and decreased decomposition of harvest residues. The humus fraction shows little temporal variation, because humus decomposes slowly and accumulates gradually during long periods.

The sizes of all modeled dry matter pools are visualized in Figure 3. The most significant dry matter pool is "unidimensional" DOM. Dry matter originating from the stems and stumps of small (dbh 0–10 cm) and "large" (dbh >10 cm) trees account for 10–25% of the DOM pool. The size of the product dry matter pool is 10–50% of the DOM pool. The size and proportion of the product pool is the largest immediately after final felling (at low mean height). The size and proportion of the product pool increase with increasing temperature sum because harvested volumes are higher in southern forests.

The pool sizes also depend on site fertility (Figure 4). The product pools of the best-growing sites (herb-rich or better) are two times larger than the pools of poor growing sites (xeric and poorer). The effect of fertility on the DOM pool is less pronounced. The effect of temperature sum on the size of the DOM pool is small. This is most probably due to the combined effect of dry matter inputs and decomposition rate. Both inputs and decomposition rate decrease toward north resulting in nearly similar pool sizes at all latitudes.

Consistency of the models for carbon pools

The models for the initial DOM and product pools were used in simulations for the three case study forests. First, alternative 50-year management schedules were simulated for each stand of each forest by varying the timing of thinning and final felling. Then, such a combination of simulated schedules was selected that maximized the net present value (3% discount rate) under the constraint that the growing stock volume of the forest at the end of each 10 years was equal to the initial volume.

The sizes of all three carbon pools remained rather constant during the whole 50-year period, which is an indication of the internal consistency of the model set (Figure 5). Overestimated sizes of initial pools would result in decreased pool sizes during the 50-year simulation period and underestimated initial pools would have the opposite effect. No such results were found in the simulations. Especially, no illogical and large changes were found during the first decade, during which the decomposition mainly depends on the predicted initial pool size. The DOM pool of the northern case study forest decreased slowly during the 50-year simulation period, but this decrease might be partly attributed to gradual changes in forest composition, which affects for instance, litter production. For example, the proportion of pine increased and the proportion of 40–80 years old stands decreased during the 50 years.

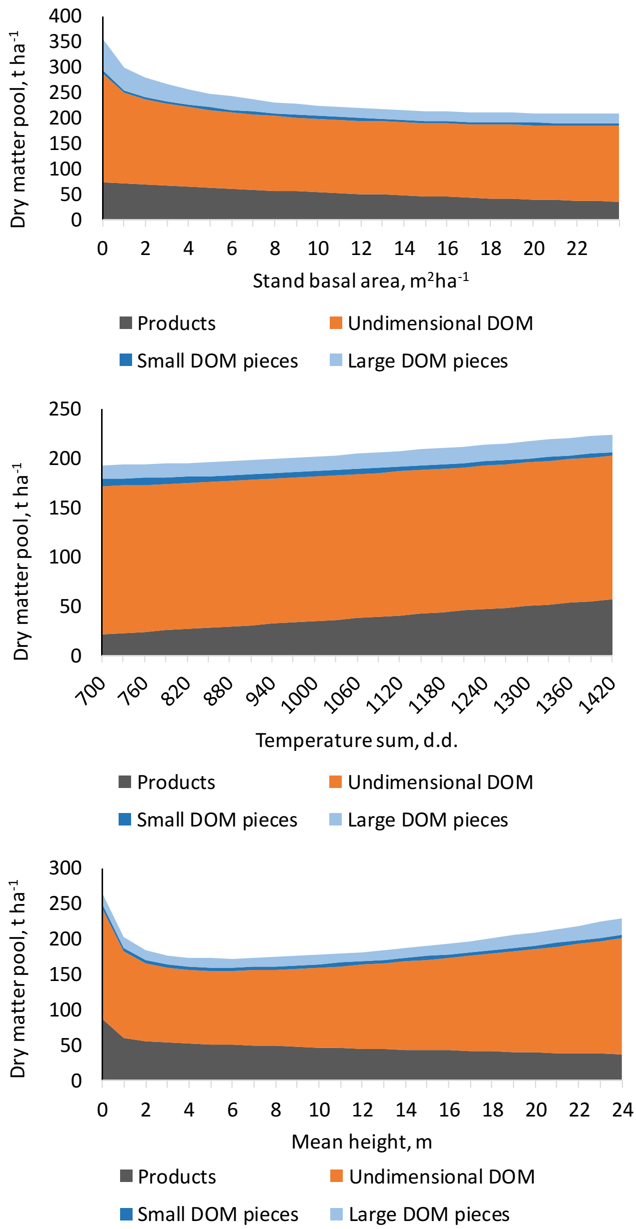
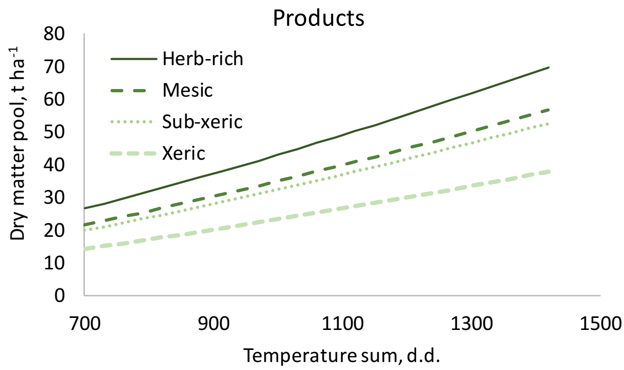


Figure 3. Predicted amount of dry matter in the product and DOM pools. In the top diagram, the mean tree height is 20 m, the site is mesic and the temperature sum is 1100 d.d. In the middle diagram, the mean tree height is 20 m, stand basal area in 20 m^2 ha^{-1} and site is mesic. In the bottom diagram, temperature sum 1100 d.d., site mesic and stand basal area (in m^2 ha^{-1}) is equal to mean height (m).

Models for reference carbon pools

The models for the average pool sizes of the current Finnish forests (Appendix) show that the carbon pool sizes increase with temperature sum and site fertility (Figure 6). The effect of temperature sum is stronger on the pool sizes or living trees and products, compared to



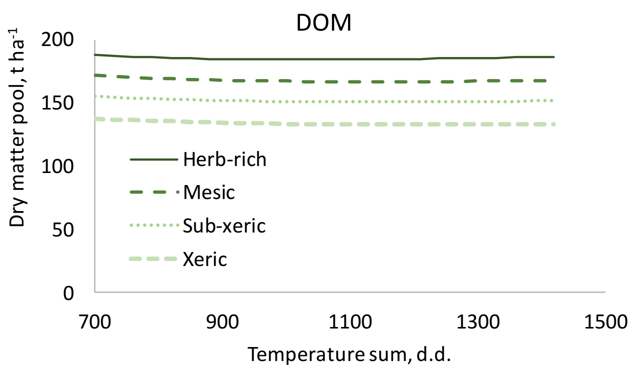


Figure 4. Predicted amount of dry matter in the product (top) and DOM pool (bottom) as a function of temperature sum and fertility class. The stand basal area is 20 m^2 ha^{-1} and the mean tree height is 20 m.

the carbon pool of DOM. The DOM carbon pool is the largest of the three pools. For example, on mesic site in Central Finland (temperature sum 1100 d.d.), the percentages of the three pools are: DOM 51.3%, trees 38.7%, products 10.0%.

Case study calculations

The reference carbon stocks and the future development of the carbon pools were calculated for the three case study forests in two management scenarios. There were no cuttings in the first scenario and the second scenario maximized the net present value calculated with a 3% discount rate. The stand dynamics were simulated with the models of Pukkala et al. (2013). Inputs to the DOM and product carbon pools were calculated as described in Pukkala (2020). The decomposition of DOM was simulated with the Yasso15 model. The carbon dynamics of wood products were simulated with the model of Pukkala (2014) using parameters described in Hurmekoski et al. (2020) and Pukkala (2020).

The initial sizes of the carbon pools were close to the reference level in South and Central Finland, which means that there would be almost no initial payment due to carbon deficit or surplus (Figure 7, right panel). In northern Finland, the pools of trees and products were smaller than the reference level, which means that the forest landowner should pay for the deficit.

In the no-cutting scenario, the carbon stock of living trees increased constantly and the carbon pool of products decreased (Figure 7, left panel). The carbon pool of DOM

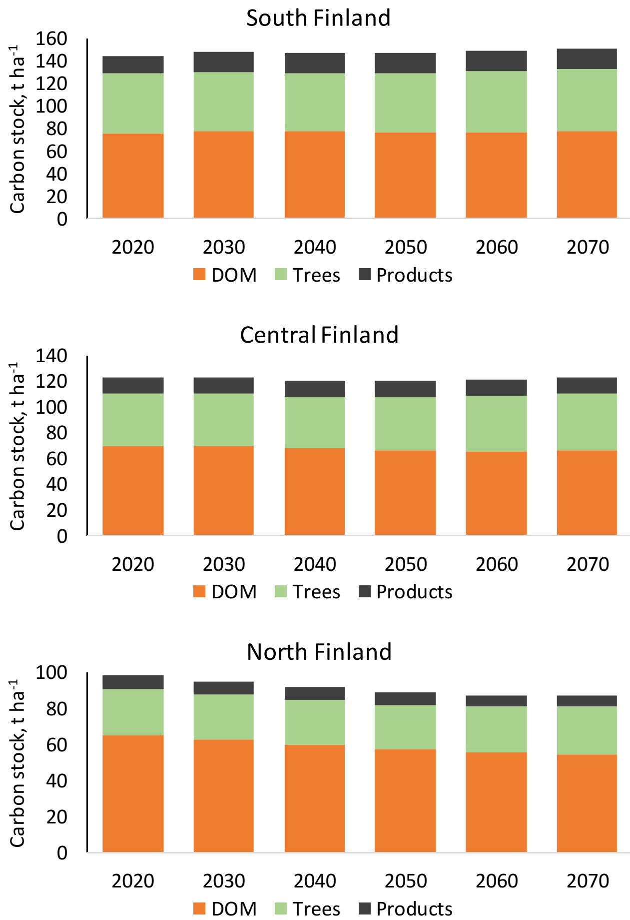


Figure 5. Development of the sizes of the carbon pools of living trees, DOM and wood-based products in three case study forests when the net present value is maximized with the constraint that the growing stock volume at the end of every 10 years is equal to the initial volume.

decreased during the first 10-year period in all case study forests, after which it started to increase. The reason for the initial decline was most probably a decreased input in the form of harvest residues (stumps, roots, branches and tops of harvested trees). Later on, increasing litter production and tree mortality turned the DOM carbon balance positive.

Figure 7 shows that if carbon compensations were based on the carbon pools of living biomass, they would be too high during the first 10-year period, as compared to the total net change in all three pools. Later on, the no-cutting management started to increase the size of the DOM carbon pool, which gradually accounted for an increasing proportion of the total increment of carbon stocks.

The magnitude of the additional 10-year carbon accumulation of the no-cutting scenario was 30 tons per hectare (3 t $ha^{-1}a^{-1}$) in South Finland, 20 tons in Central Finland, and 10 tons in North Finland. With a carbon price of 50 € t^{-1}, the payment to forest landowner would be 150 € $ha^{-1}a^{-1}$ in South Finland, 100 € $ha^{-1}a^{-1}$ in Central Finland and 50 € $ha^{-1}a^{-1}$ in North Finland.

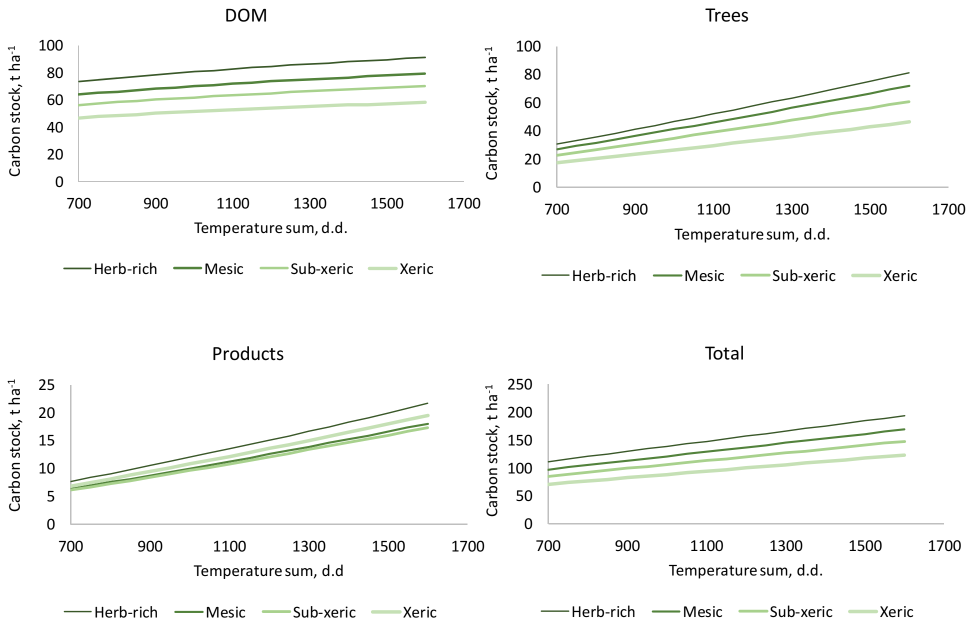


Figure 6. Reference levels of carbon stocks (average carbon stocks of Finnish private forests in 2019).

The other management scenario maximized the NPV of timber production (Figure 8). The initial payments due to deviations from the reference level were the same as in the no-cutting scenario. The changes of the carbon stocks were either increases or decreases, depending on the optimal cutting level of different 10-year periods. Management that maximized the net present value maintained the initial carbon stocks at rather constant levels, and the initial stocks were close to the reference level (except North Finland where the landowner needs to pay for the initial carbon deficit). Therefore, the carbon compensations of the NPV scenarios would be small and to both directions; the landowner would get compensation during some periods but would need to return them during other periods.

Discussion

The system on models developed in this study makes it possible to calculate the carbon balance of any management schedule of any Finnish forest for any period. The calculation may include a single stand, a forest holding, a municipality, or all privately owned stands of Finland (around 10 million stands). All data required in calculations are available in Metsaan.fi/paikkatietoaineistot. As a new element, the system also enables a comparison of the carbon sequestration of a certain planned management scenario and the BAU management. This comparison shows whether the carbon sequestration exceeds or falls short of the threshold of additionality. The carbon models developed in this study describe only the carbon stocks generated by trees. In peatland forests, peat is an additional carbon store, the size of which may increase or decrease.

The methodology suggested in this study does not require any definition for the BAU management. The carbon stocks of the BAU management are calculated without specifying any silvicultural system, cutting level or management objective. Additionality is based on

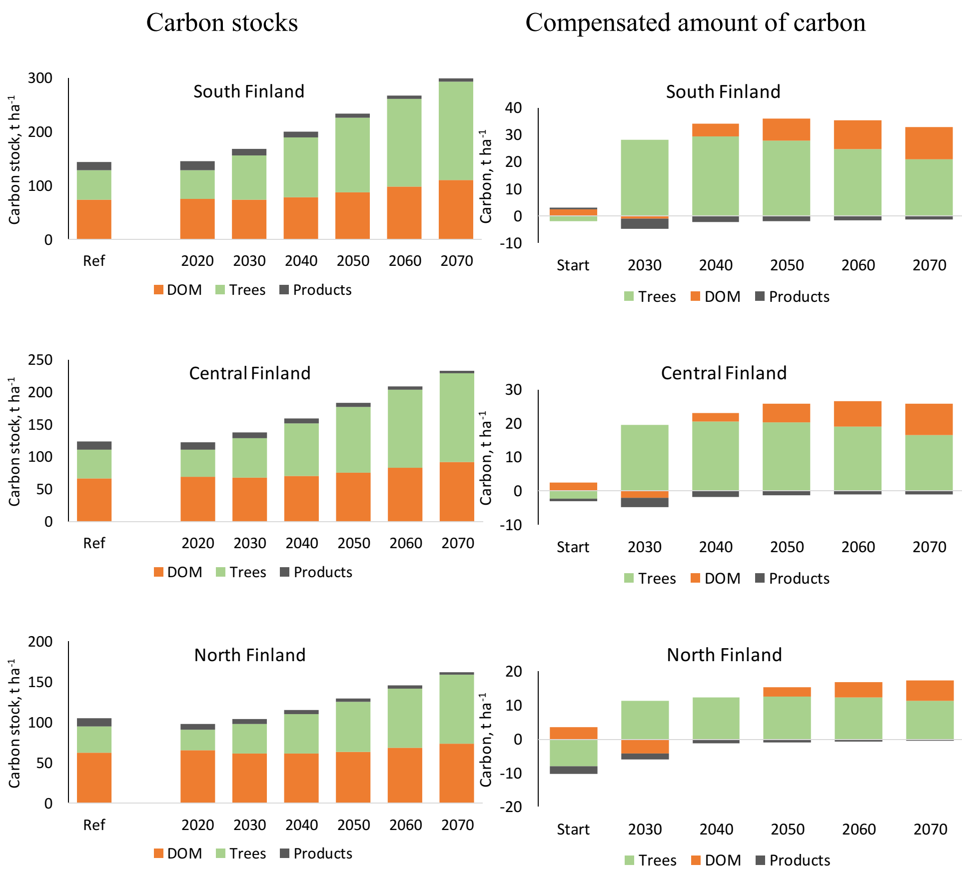


Figure 7. Development of carbon stocks in three case study forests when there are no cuttings. "Ref" is the reference level of carbon stocks. The diagrams on the right panel are the 10-year increases or decreases of the carbon stocks. "Start" is the excess (positive value) or lack (negative value) of initial carbon as compared to the reference level.

the current carbon stocks of Finnish forests, which were assumed to reflect the carbon sequestration of the BAU management under the current climate and disturbance regime.

Even if no carbon compensations are paid, forest landowners may want to know whether their forestry is better than average, or whether their carbon sequestration is "additional". The system described in this study enables such testing. Individual people and organizations who are planning to pay forest landowners to compensate for their carbon footprints may also want to check whether the carbon sequestration of the forest where their payments are going is additional, i.e., improvement from ordinary forest management.

The system proposed in this study simulates the carbon dynamics of living trees, DOM and wood products. All three carbon pools need to be initialized. The initial pool size can be calculated most reliably for living biomass, using inventory data and biomass models. The pool size of tree biomass can also be monitored easily, using for instance, ALS-based forest inventory methods (ALS = airborne laser scanning) or field surveys. Model predictions are necessary for the other components, which therefore include more uncertainty.

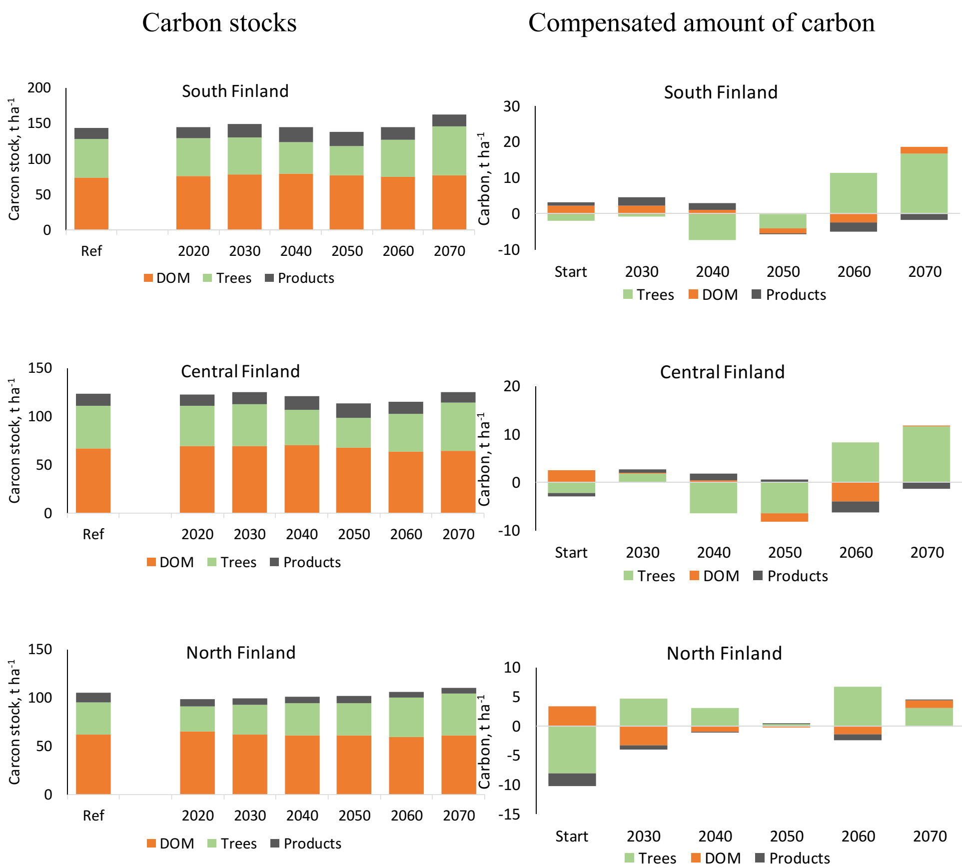


Figure 8. Development of carbon stocks in three case study forests when net present value is maximized with a 3% discount rate. "Ref" is the reference level of carbon stocks. The diagrams on the right panel are the 10-year increases or decreases of the carbon stocks. "Start" is the excess (positive value) or lack (negative value) of initial carbon as compared to the reference level.

However, the inputs and outputs of carbon pools other than living tree biomass can be calculated rather reliably although the true sizes of the pools might be hard to predict accurately. Therefore, calculation of the changes in the carbon pools of DOM and wood-based products might be reliable enough, provided that the pools are initialized in such a way that artifact carbon releases or sequestration due to over- or under-estimated initial pools are avoided. The initialization models developed in this study constitute a model system that is consistent with the current models for stand development, DOM dynamics and product life cycles. The models for the reference pools are also consistent with the other models, making it possible to analyze the additionality of carbon sequestration.

The case study results showed that if the additional carbon sequestration of only living biomass is credited, compensations arising from decreased cutting level would be too high at first. However, in cases where all cuttings are stopped for several decades, the compensations would be eventually too low. This is because of the increasing carbon pool of DOM, which would gradually account for an increasing proportion of the total increment of forest-generated carbon stocks.

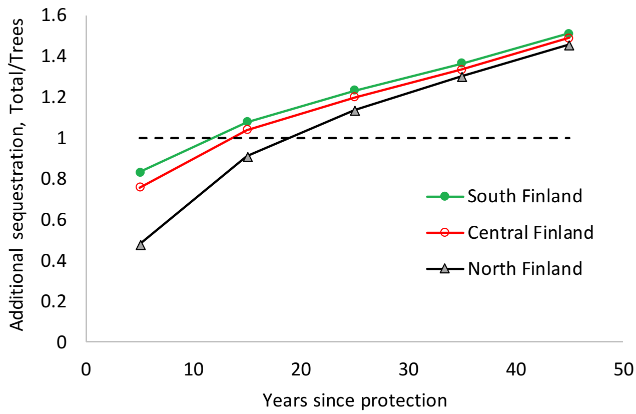


Figure 9. The ratio between the total carbon sequestration (trees, DOM and wood-based products) and carbon sequestration into living tree biomass as a function of time since protection.

Taking into account that measuring and monitoring of the carbon pools of living tree biomass is easy, it is tempting to build carbon crediting systems based on living trees only. To be non-biased, these systems require corrections, which depend on the time and intensity of cuttings. These corrections factors could be calculated by using the models developed in this study. For example, Figure 9 shows that the ratio between the additional carbon sequestration by trees and all carbon pools together changes systematically as a function of time since cuttings were stopped. Figure 9 is based on the no-cutting scenarios shown in Figure 7. In southern and central Finland, the carbon accumulation into trees during the first 10-year period should be multiplied by 0.8 to obtain the total change in all carbon stocks. During the second 10-year period the multiplier should be around 1, from which it increases to about 1.2 for the third 10-year period.

Using the current carbon stock as a threshold for additionality prevents compensations for young plantations where growth and carbon sequestration might be high, but the sizes of the pools are low. Good growth has been made possible by clear-felling the previous tree generation, and releasing most of its carbon to the atmosphere. Correspondingly, when a forest with a high carbon pool enters the compensation market, it is entitled to an initial carbon credit due to the carbon surplus as compared to the reference level. If the surplus is not credited, it would be optimal to the forest landowner to decrease the carbon stocks to the reference level since this cutting would generate income without any decrease in carbon compensations.

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Appendix

Table A1. Parameters of the models for the dry matter pools of wood-based products.

Parameter	Predictor	Sawed wood	Mechanical mass	Chemical mass	Bioenergy
b_0	Intercept	4.047000	−0.851205	−0.103326	−1.191293
b_1	*G*	−0.026740	−0.076262	−0.096778	−0.085597
b_2	1/*yrs*	0.074220	0.805201	0.562171	0.748571
b_3	H	0.010220	0.091064	0.085136	0.093705
b_4	ln(*TS*/1000)	1.401000	−0.168897	1.092730	0.421940
b_5	*Mesic*	−0.209700	−0.382614	0.012586	−0.208939
b_6	*SubXeric*	−0.286000	−1.112986	0.162944	−0.291559
b_7	*Xeric*	−0.613300	−1.536224	−0.283060	−0.710722

yrs = *H*/(*TS*/1000)
Model form: $PoolSize = \exp(b_0 + b_1 G + b_2/yrs + b_3 H + b_4 \ln(TS/1000) + b_5 Mesic + b_6 SubXeric + b_7 Xeric)$
The units are: *Pool*, t ha^{-1}; *G* m^2 ha^{-1}; *H*, m; *TS*, d.d.; *Mesic, SubXeric* and *Xeric* are indicator variables for site fertility classes

Table A2. Parameters of the models for the dry matter pools of undimensional DOM.

Parameter	Predictor	Acid-soluble	Water-soluble	Ethanol-soluble	Non-soluble	Humus
b_0	Intercept	1.977472	−0.321687	−0.512114	3.771108	3.319000
b_1	√*G*	−0.011602	0.016291	0.098156	−0.300864	−0.054140
b_2	*G*	0.017240	0.015484	0.010672	0.034895	0.004883
b_3	1/(*yrs*+1)	2.070936	2.121223	2.373142	0.879274	0.054590
b_4	√*H*	0.237232	0.227348	0.217417	0.291089	0.062810
b_5	ln(*TS*/1000)	−0.835086	−0.849416	−0.922936	−0.271503	0.603500
b_6	*Mesic*	−0.038614	−0.040012	−0.050359	−0.056773	−0.119900
b_7	*SubXeric*	−0.117201	−0.118923	−0.145180	−0.158373	−0.249000
b_8	*Xeric*	−0.175446	−0.174873	−0.191118	−0.267825	−0.457600

yrs = *H*/(*TS*/1000)
Model form: $Pool = \exp(b_0 + b_1\sqrt{G} + b_2 G + b_3/(yrs+1) + b_4\sqrt{H} + b_5 \ln(TS/1000) + b_6 Mesic + b_7 SubXeric + b_8 Xeric)$
The units are: *Pool*, t ha^{-1}; *G* m^2 ha^{-1}; *H*, m; *TS*, d.d.; *Mesic, SubXeric* and *Xeric* are indicator variables for site fertility classes

Table A3. Parameters of the models for the dry matter pools of stumps and stems of small trees (0–10 cm in dbh).

Parameter	Predictor	Acid-soluble	Water-soluble	Ethanol-soluble	Non-soluble	Humus
b_0	Intercept	−0.257503	−2.552059	−2.731000	1.261003	0.515900
b_1	$\sqrt{G}$	−0.027848	−0.028145	−0.007461	−0.020269	0.001219
b_2	*G*	0.000507	0.000496	0.000065	0.001058	−0.000137
b_3	1/(*yrs*+1)	0.376131	0.386856	−0.045360	−0.011542	−0.011360
b_4	$\sqrt{H}$	0.057290	0.058650	−0.003821	0.011205	−0.001622
b_5	ln(*TS*/1000)	−1.597582	−1.594693	−1.749000	−1.350845	0.356800
b_6	*Mesic*	−0.109293	−0.108227	−0.146000	−0.142388	−0.192600
b_7	*SubXeric*	−0.315448	−0.314112	−0.351600	−0.357358	−0.391700
b_8	*Xeric*	−0.553587	−0.552355	−0.578900	−0.595878	−0.596500

yrs = *H*/(*TS*/1000)
Model form: $Pool = \exp(b_0 + b_1\sqrt{G} + b_2 G + b_3/(yrs+1) + b_4\sqrt{H} + b_5 \ln(TS/1000) + b_6 Mesic + b_7 SubXeric + b_8 Xeric)$
The units are: *Pool*, t ha^{-1}; *G* m^2 ha^{-1}; *H*, m; *TS*, d.d.; *Mesic, SubXeric* and *Xeric* are indicator variables for site fertility classes

Table A4. Parameters of the models for the dry matter pools of stumps and stems of large trees (>10 cm in dbh).

Parameter	Predictor	Acid-soluble	Water-soluble	Ethanol-soluble	Non-soluble	Humus
b_0	Intercept	1.5030721	−0.7798507	−1.2499816	2.8419507	0.2241904
b_1	$\sqrt{G}$	−0.7594748	−0.765483	−0.186562	−0.2614734	−0.0373336
b_2	*G*	0.0767962	0.0774085	0.0184351	0.0249927	0.0032109
b_3	1/(*yrs*+1)	0.5409353	0.546307	−0.3345018	−0.3035379	−0.1662712
b_4	$\sqrt{H}$	0.5226466	0.5266622	0.076254	0.1354002	0.0097665
b_5	ln(*TS*/1000)	−0.3650836	−0.3687357	0.4087603	0.7356049	1.1606087
b_6	*Mesic*	−0.2746126	−0.2735458	−0.3162969	−0.359797	−0.3877656
b_7	*SubXeric*	−0.2100956	−0.20686	−0.2707342	−0.441509	−0.5297087
b_8	*Xeric*	−0.3374827	−0.3330458	−0.4837796	−0.6871823	−0.837371

yrs = *H*/(*TS*/1000)
Model form: $Pool = \exp(b_0 + b_1\sqrt{G} + b_2 G + b_3/(yrs+1) + b_4\sqrt{H} + b_5 \ln(TS/1000) + b_6 Mesic + b_7 SubXeric + b_8 Xeric)$
The units are: *Pool*, t ha^{-1}; *G* m^2 ha^{-1}; *H*, m; *TS*, d.d.; *Mesic, SubXeric* and *Xeric* are indicator variables for site fertility classes

Table A5. Models for the reference level of carbon stock (the predicted variable is tons of carbon per hectare).

Parameter	Predictor	Soil	Trees	Products
b_0	Int	4.3914195	3.838114	2.482829
b_1	ln(*TS*/1000)	0.2611933	1.187706	1.257693
b_2	*Mesic*	−0.1399187	−0.120866	−0.182947
b_3	*SubXeric*	−0.264897	−0.288404	−0.221236
b_4	*Xeric*	−0.4500104	−0.564605	0.104854
b_5	*Heath*	−0.4590058	−0.598944	0.1195

Model form: $Pool = \exp(b_0 + b_1 \ln(TS/1000) + b_2 Mesic + b_3 SubXeric + b_4 Xeric + b_5 Heath)$.
The units are: *Pool*, t ha^{-1}; *TS*, d.d.; *Mesic, SubXeric, Xeric* and *Heath* are indicator variables for site fertility classes.

Models for the dry matter stocks of products and dead organic matter (DOM). The unit of the predicted variable is tons of dry matter per hectare, except for models for reference stocks (Table A5) where the unit is tons of carbon per hectare.