BIOGENIC CARBON FOOTPRINT CALCULATOR FOR HARVESTED WOOD PRODUCTS

BACKGROUND DATA & CALCULATIONS

Prepared by:

Simon Gmünder, Michele Zollinger, Jon Dettling |Quantis

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For:

Marty Spitzer | WWF

Marta Stevenson | WWF

Contact:

Simon Gmünder

Senior Consultant

Biogenic-carbon-calculator@quantis-intl.com

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1. Introduction

1.1. Background

How to account for greenhouse gas (GHG) emissions from forest products has been a topic of increasing discussion in recent years. This is especially the case with the European Union Renewable Energy Directive's advancement of forest biomass as a renewable energy alternative (The European Parliament 2009). For managed forest operations, the GHG analysis of forest products frequently assumes carbon neutrality, i.e. the carbon sequestered by biomass is equal to the carbon released by the use of that biomass. This assumption implies that the timespan during which carbon is stored in forest products has negligible effects on climate.

Carbon neutrality is also assumed in other standards and directives. A recent U.S. Environmental Protection Agency (EPA) policy statement declares that future agency regulatory actions will treat biomass from managed forests as carbon neutral when used for energy production at stationary sources (EPA 2018). In addition, several current GHG accounting standards assume carbon neutrality of biogenic carbon emissions and sinks (Roundtable on Sustainable Biofuels 2012; Bessou 2016; European Commission 2017; The European Parliament 2009). The Greenhouse Gas Protocol standard, however, takes into account the timing of emissions by allowing the inclusion of temporary carbon storage — if reported separately (BSI 2012; Ranganathan et al. 2004; ISO 2013).

Currently, accounting for the global warming potential (GWP) of biogenic carbon emissions is rarely done. Common practice is to assume carbon neutrality. However, assuming carbon neutrality ignores that the use of biomass from mature forests could lead to an increase of CO_2 in the atmosphere for a period of time given the potential time lag between wood removal and re-growth, with resulting impacts on radiative forcing (IPCC 2014). A carbon neutrality assumption also ignores the benefit that harvested wood stores carbon during a wood product's life cycle. Assuming carbon neutrality equals climate neutrality neglects the dynamic nature of biogenic carbon emissions and sequestration (Levasseur et al. 2013) (Zanchi et al. 2012; Schulze et al. 2012; McKechnie et al. 2011; Holtsmark 2015a, 2013).

The NCS Guidance recently developed by Quantis includes accounting of biogenic emissions in specific situations/applications, which was piloted with WWF to assess the influence on forest-based products and fuels. This project is a follow-up to support the broader adoption of the biogenic emissions calculation approach for different forest products, using the previously suggested methodology and building upon prior work done by Quantis for WWF on carbon accounting for forest products (Quantis 2018).

1.2. Purpose of the present document

The aim of the Excel-based calculator is to make calculating the biogenic carbon footprint of harvested wood products practical by providing a user-friendly calculator packed with the latest science. The present document describes the methodological choices, background data, and calculation procedure.

2. Methodological background

2.1. Overview of different climate metrics

Recent studies published alternative approaches to the carbon neutrality concept, which consider the carbon dynamics on forest plots and account for the potential benefits of temporary carbon storage. Breton et al. (2018) provides a comprehensive overview of published methodologies and suggests that the dynamic LCA (dLCA) approach (Levasseur et al. 2013) and GWP_{bio} approach (Cherubini et al. 2009) both stand out for their flexibility and impact.

Both approaches consider a dynamic characterization factor (dCF) in relationship to a fixed time horizon relevant for decision-making (see chapter 3.2). In doing so, both approaches avoid the inconsistencies of conventional methods that characterize emissions inventories occurring over several decades beyond the time horizon assumed by the impact characterization method (typically 100 years when using GWP_{100}), and point out that impact scores are highly sensitive to the choice of the time horizon.

One fundamental difference between dLCA and GWP_{bio} is that the former accounts for a complete LCA framework with a high degree of flexibility, while the latter is an emission metric specific to biogenic carbon impacts. GWP_{bio} can be seen as a simplification of the dynamic LCA approach since it models dynamic impacts of biogenic carbon emissions but assumes that fossil carbon emissions related to other processes occur in year zero. Despite methodological differences (described in more detail in Breton et al. 2018), dLCA and GWP_{bio} would expectedly provide equivalent results for forest-based products.

UNEP/SETAC and Life Cycle Initiative (2016) suggest the use of two indicators to report climate change impacts that are complementary. The Global Warming Potential 100 year (GWP_{100}) is focused on the short-term impacts (decadal scale). The Global Temperature Change Potential 100 years (GTP 100) contemplates long-term impacts.

This study focuses only on GWP given its large acceptance for quantifying and reporting short-term climate change impacts. For evaluating long-term effects of the biogenic carbon emissions and removals it is suggested to further elaborate on the calculation of GTP, acknowledging that the GTP quantification is more uncertain than GWP (UNEP/SETAC and Life Cycle Initiative 2016).

2.2. Introduction to GWP_{bio}

The concept of global warming potential (GWP) was introduced as a relative measure of how much energy a GHG traps in the atmosphere over time compared with the amount of energy trapped by a similar mass of carbon dioxide. Hence, the GWP factor of CO_2 is one, and GWP units are typically expressed in kg CO_2eq. Other GHGs are related to CO_2 based on their radiative forcing potential and the atmospheric lifetime. The CO_2 decay curve is described by the Bern cycle model (see the black curve in Figure 1). The Bern carbon cycle model is based on the global carbon cycle and considers that CO_2 molecules emitted to the atmosphere are partially absorbed by the terrestrial biosphere and the ocean. Given the different atmospheric lifetimes of GHGs and that CO_2's is in the order of several thousands of years, GWP is calculated for a specific time horizon such as 20, 100, or 500 years, i.e. discounting all the radiative forcing generated beyond that time horizon.

Absolute GWP mainly depends on three things; the amount of GHGs emitted, the radiative forcing of the GHG, and the atmospheric lifetime of the GHG. In this study, we focus solely on CO_2 molecules emitted to the atmosphere[1], which can be either from "biogenic" or "fossil" sources.

Burning fossil fuels (a non-renewable resource) releases carbon that has been locked in the ground for millions of years (fossil CO_2), while burning biomass (a renewable resource) emits carbon that is part of the short biogenic carbon cycle (biogenic CO_2).

The amount of CO_2 emitted depends on the stoichiometric of the combustion or decomposition process and the carbon content of the feedstock. For example, the combustion of wood for energy usually emits more GHG per unit of energy produced than fossil fuels given the lower energy density, higher quantities of moisture, and less hydrogen (Brack 2017). As such, the amount of biogenic and fossil CO_2 emitted depends on the energy carrier analyzed. Then, once in the atmosphere, the radiative forcing effect of a CO_2 molecule is the same, independent of its biogenic fossil origin.

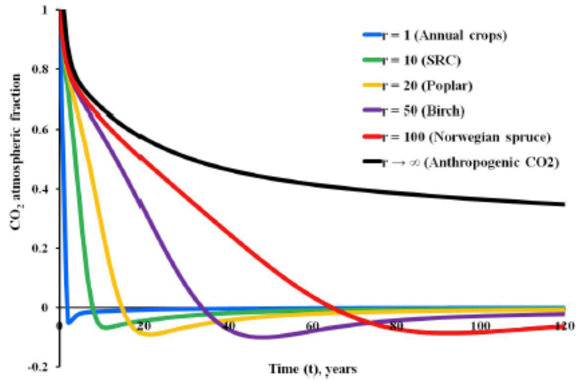
The assumption of carbon neutrality as adopted by most current carbon accounting methods implies that the atmospheric lifetime of biogenic CO_2 emissions equals zero because it is based on the premise that all CO_2 emitted by biomass is recaptured by biomass through photosynthesis. This assumption might be adequate for annual crops where emissions and regrowth typically happen in the same year, but not for forest biomass where the time lag between emissions and uptake can take up to a century for slow-growing forests.

Cherubini et al. (2011a) introduced the concept of GWP_{bio}, which is intended to measure the GWP of a pulse of CO_2 caused by the combustion of biomass, taking into account that harvesting is followed by regrowth of trees in a forest stand and that other dynamic processes are triggered by harvesting. Consequently, the atmospheric lifetime of a biogenic carbon emission is typically higher than zero but is reduced when compared to fossil carbon given the assimilation during plant regrowth.

The GWP_{bio} approach combines the CO_2 impulse response function described by the Bern cycle model and as used in the calculation of GWP with an additional CO_2 uptake curve from forest

[1] Other GHG emissions such as methane are not included in this study for simplicity and especially the CH4 emissions from decomposition and other processes should be included in future studies.

growth in order to assess the radiative forcing resulting from temporary carbon release due to bioenergy produced from existing forests (see Figure 1). Consequently, the GWP of CO_2 emissions from bioenergy production is smaller than the potential warming impact of CO_2 from fossil fuels (Cherubini et al. 2011a) represented by the Bern cycle alone (black curve labeled «Anthropogenic CO_2”). GWP_{bio} depends on the rotation year and the selected time horizon (typically 20, 100 or 500 years) and ranges from 0 (annual crops) to 0.96 (100-year rotation period and 20-year time horizon).



Rotation (years)	GWP TH = 20	GWP TH = 100	GWP TH = 500
1	0.02	0.00	0.00
10	0.22	0.04	0.01
20	0.47	0.08	0.02
40	0.80	0.16	0.03
50	0.87	0.21	0.04
60	0.90	0.25	0.05
80	0.94	0.34	0.06
90	0.95	0.39	0.07
100	0.96	0.43	0.08

Figure 1: CO2 atmospheric decay for selected rotation periods (r, years) and the respective GWP factors depending on the time horizon and the rotation period (right) (Cherubini et al. 2011a).

Several authors have presented estimates of GWP_{bio} for bioenergy from forest products significantly below one (one being GWP for CO_2 from fossil fuels), which indicates that bioenergy from forest products is not climate neutral, but nevertheless preferable to fossil fuels (Guest et al. 2012; Pingoud et al. 2012). However, these studies did not consider the influence of biomass residues on the forest, nor the soil carbon dynamics. Holtsmark (2015a) incorporated methodological improvements related to the model of the considered forest stand and the construction of an explicit baseline scenario (“natural reference scenario”). Contrary to previously published work (Cherubini et al. 2011a, 2012; Guest et al. 2013; Pingoud et al. 2012). Holtsmark applied a more complete dynamic model of the forest stand's main carbon pools, including harvest residues, the pool of natural deadwood, and all parts of growing trees such as branches, tops, stumps, and roots, in addition to the stems. When a 100-year time horizon was applied, the resulting GWP_{bio} estimate was found to be significantly higher than one (contrary to previous studies). This higher value is explained by considering CO_2 emissions from the natural decomposition of harvest residues. Overall, the consideration of the dynamics of the pool of carbon stored in natural deadwood and the inclusion of a “non-harvest” baseline scenario lead to higher GWP_{bio} values.

Hence, Holtsmark concluded that bioenergy from slow-growing forests leads to permanently increased atmospheric carbon concentration, as was concluded in some of the above-mentioned studies (Holtsmark 2015a).

The above-mentioned studies (Holtsmark 2015b; Cherubini et al. 2011b, 2011a, 2012; Guest et al. 2013; Pingoud et al. 2012; Holtsmark 2013) are based on the assumption that the harvested biomass is immediately used (t_0). This might be true for bioenergy, but not for harvested wood products (e.g. construction wood). Guest et al. (2012) calculated the GWP_{bio} as a function of storage time and rotation period (see Figure 2). The higher the rotation period and the lower the storage time, the higher the GWP_{bio} value.

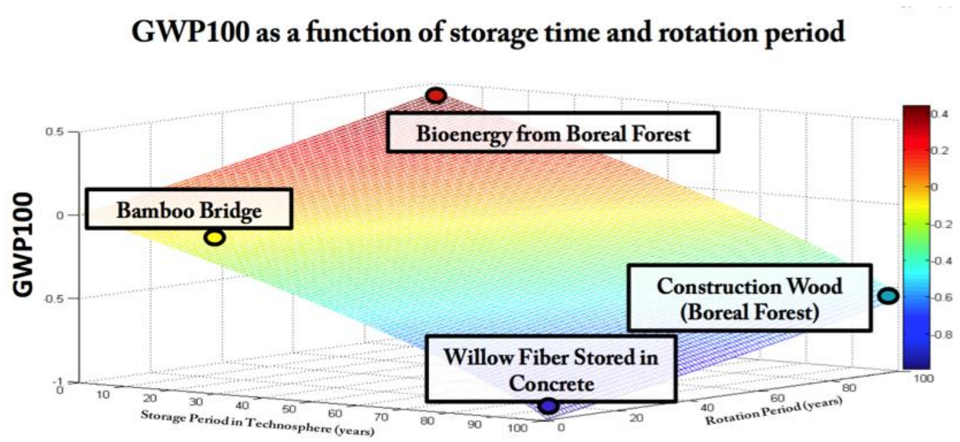


Figure 2: The GWP_{bio} for a 100 year time horizon as a function of the rotation period (years) and the storage period (Guest et al. 2012).

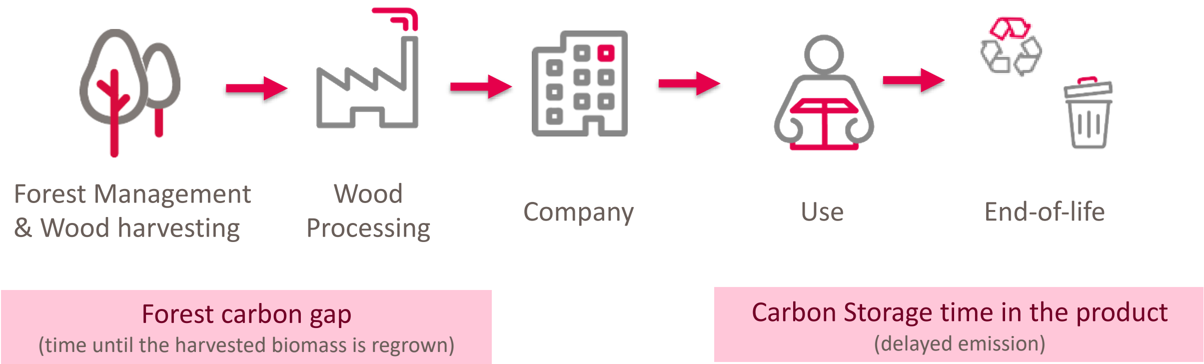
Helin et al. (2016) split GWP_{bio} for forests ($GWP_{bio,\ forest}$) and storage in products ($GWP_{bio,\ product}$) to separate the two effects, which can be summed up to $GWP_{bio\ net}$. An overview of the methodological differences of the recently published approaches is provided next, and further methodological development can be expected in the future.

3. General Framework

3.1. Calculating the biogenic carbon footprint

The global warming impact of forest biomass (GW, in kg CO_2eq) is calculated by taking into account the GW impact of all biogenic carbon emissions and sinks (GW_{bio}) and the "fossil" carbon footprint along the entire value chain of forest products (GW_{fossil}).

The biogenic carbon footprint is measured in kg CO_2eq, and the calculation considers the carbon gap of the forest, as well as storage time benefits of a product.



Forest carbon gap

$GWP_{bio, forest}$: To estimate the $GWP_{bio, forest}$ the dynamics of the carbon stock and the decay of CO_2 in the atmosphere are considered. The dynamic stock models for each carbon pool are described for harvesting and non-harvesting scenarios (reference system) based on where CO_2 fluxes and ultimately, $GWP_{bio, forest}$ is calculated (see chapter 4) (dimensionless).

$C_{extracted}$ Carbon extracted from the forest (in kg C). This factor can be the same as the carbon contained in a final product (default assumption in the calculator) or different depending on wood conversion efficiency and the selected allocation procedure (see chapter 5).

Carbon storage time in the product

$GWP_{bio, product}$ The $GWP_{bio, forest}$ indicators compiled in this study include an inherent assumption that carbon content in the harvested forest biomass is released to the atmosphere within the first year after harvest. In many harvested wood product value chains, this assumption is counterfactual, and correction factors are needed to take into account the benefits of delayed release in long-lived products (Helin et al. 2016). The $GWP_{bio, product}$ correction factors are used to allow transparent separation of the impact of the product storage stage (delayed emission) from the impacts of forest harvesting ($GWP_{bio, forest}$) and/or product substitution ($GWP_{substitution}$). See chapter 0 (dimensionless).

$C_{product}$ Carbon stored in a product (in kg C)

Fossil Carbon Footprint

GW_{fossil} The GW, embedded fossil factor accounts for carbon emissions other than biogenic carbon of the wood product system through its life cycle. Energy usage in transportation, distribution, storage, and processing stages are assumed to be provided by fossil energy, so GHG emissions caused in these process are considered in this analysis. Included based on ecoinvent v3.5 (kg CO2eq)

Products from forest biomass might substitute other products fulfilling the same function (e.g., wood pellet heating vs. fossil fuel heating). In comparative studies, substitution benefits are also quantified, and we refer to the GWP of a compared product system fulfilling the same function as **GWP**, **substitution** (not considered in the calculator).

The GW impact of biogenic carbon emissions and sinks is determined by CO_2 released, calculated based on the carbon content of the (dimensionless) and the molecular weights of CO_2 and C (44/12) and multiplying it by its global warming potential (GWP_{bio}) for a given time horizon (100 years, in our case).

$$GW = GWP_{bio,forest} * C_{extracted} * \frac{44}{12} * + GWP_{bio,product} * C_{product} * \frac{44}{12} + GW_{fossil} \qquad \text{Equation 1}$$

3.2. Defining the time horizon

The climate impact of GHG emissions is based on the cumulative radiative forcing occurring over a time period between the moment when an emission occurs and a time horizon relevant for decision-making (typically 20, 100 or 500 years). No discount is applied within the considered time horizon, whereas a 100% discount is applied beyond.

In most studies a 100-year time horizon, as used under the UNFCC and the Kyoto Protocol, is applied (Røyne et al. 2016). However, it has to be noted that selection of the time horizon is a normative choice that cannot be determined from a scientific perspective and should be defined based on the individual goals and scope of a concrete project.

There are two important aspects to consider when setting the time horizon over which the radiative forcing of each GHGs are cumulated (i.e. integrated over time from zero to the selected time horizon). First, the relative importance of different types of GHG emissions compared to CO_2: the shorter the time horizons, the higher the relative importance of shorter-lived GHGs such as methane. Second, the relative importance of GW impact of the time lag between emission and sequestration of biogenic carbon depends on the time horizon: the longer the time horizon, the smaller its relative importance. If the temporal increase of the (biogenic) CO_2 concentration in the atmosphere is relatively short compared to the assessment time horizon, the climate impacts become insignificant. This is the case for infinite time horizons or for annual crops (short rotation period).

In the calculator, we apply a 100-year time horizon and use the dLCA approach used in the GWP_{bio} calculation (Levasseur et al. 2010). For instance, if a 100-year assessment time period is adopted, then a 100-year time horizon for the impact assessment is chosen. Thus, radiative forcing for emissions occurring at t=0 is calculated over 100 years, while emissions at t=80 are only accounted for radiative forcing modeled over the following 20 years. This is might not be the case in conventional footprint studies[2].

[2] In conventional carbon footprint studies a CO_2 molecule emitted at time 0 and time 50 have the same impact if a 100-year assessment time horizon is used, which leads to an inconsistency between the time horizon of the study (e.g. 100 years) and the assessment of the global warming potential (e.g. 100 years for an emission at year 50 = 150 years). In this case the also a global warming effects occurring after 100 years are considered in the study.

4. Forest carbon gap — $GWP_{bio,\ forest}$

To estimate the $GWP_{bio,\ forest}$ both the dynamics of the carbon stock in the forest and the decay of the CO_2 in the atmosphere are considered. The following assumptions are made:

- The study is limited to managed natural forests and existing forest plantations, where the forest is assumed to regrow after harvesting. Deforestation, followed by land use change (e.g., from natural forest to agriculture), as well as afforestation projects (e.g., conversion of grassland to forest plantation) are outside the scope of this study.
- For the sake of simplicity, we assume that forests are composed of one to three species, and that the same species is regrown after harvesting.
- The removal of forest residues does not affect or reduce stand growth, and also does not amplify the loss of soil carbon after harvest, contrary to the findings from (Holtsmark 2015a).
- The carbon contained in harvested biomass is released immediately as CO_2 emissions, while the potential benefits of temporal storage are considered in the $GWP_{bio,\ product}$ (see chapter 0).

For this study, it was assumed that all carbon emitted by residues are in the form of CO_2 as a result of a perfectly aerobic decomposition (Wiloso et al. 2016). For the sake of simplicity, the potential CH_4 emissions from biomass decay are neglected. This assumption should be reviewed in further studies given the much higher GWP of CH_4 than for CO_2 (IPCC, 2013). In this section, calculations and assumptions are presented.

4.1.1. Forest carbon stock model

The forest carbon stock model includes the dynamics of the forests stand's main carbon pools: above- and below-ground biomass, natural dead wood, and the effect of harvesting on the soil carbon pool. We also consider the effect of harvest residues.

The forest carbon stock model accounts for the dynamics of the forest fraction, as described in Table 1.

Table 1: Forest carbon pool considered in this study (Liu et al. 2017; Holtsmark 2015a).

Carbon Pool		Forest Fraction	Description
Vegetation biomass $G_{(t)}$	Above-ground Biomass (AGB)	Stems $B_{(t)}$	Merchantable stems with bark, which are extracted from the forest
		Other AGB $O_{(t)}$	Harvest residues, which can be extracted or left on the field

Below-ground Biomass (BGB)	BGB $R_{(t)}$	BGB of harvested trees is assumed to be decomposed after harvesting, while BGB of new trees continues to grow
Natural dead organic matter (nDOM) $D_{(t)}$	Litter and dead wood.	Typically left in the forest for decomposition
Soil organic carbon (SOC) $S_{(t)}$		The soil carbon pool is assumed to be reduced and gradually built back to its original state after harvesting (excluded in the default settings of the calculator)

For all calculations, it is considered that at time t = 0, the stand is mature (at the end of the rotation period). Further, it is assumed that after harvesting, new trees start growing and the forest regenerates (responsible forest management).

4.1.1.1. Vegetation biomass G(t)

Biomass accumulation is calculated by the Chapman-Richards growth function (Liu et al. 2017):

$$G_{(t)} = b_1(1 - e^{-b_2 t})^{b_3}$$

Equation 2

Where,

$G_{(t)}$= total living biomass (tC/ha)

t= stand age (years)

b1= asymptote maximum peak biomass yield; tons dry mass per hectare (t d.m./ha) or tons of carbon per hectare (tC/ha)

b2 and b3 = parameter used in modeling tree growth (dimensionless), values for the studied forest types are presented in Table 2.

Table 2: Parameters for the Chapman-Richard function for different forest types.

Forest type	b1	b2	b3	Source
Boreal forest Norway spruce	103.07	0.0245	2.69	(Holtsmark 2015a)
Douglas fir	200	0.02	1.88	(Gholz et al. 1997)
Loblolly pine	131.8	0.101	2.7	(Winrock International 2014)

4.1.1.2. Stems $B_{(t)}$ and other AGB $O_{(t)}$

The stems B(t) are assumed to grow proportional to total living biomass G(t). Stems biomass is calculated as follows (Liu et al. 2017):

$$B_{(t)} = \theta G_{(t)}$$ *Equation 3*

Where,

θ= proportion of the live biomass, values are presented in

Table 3

$B_{(t)}$= stems (trunks) volume (tC/ha)

Table 3: Parameters for the B(t) calculation.

Forest type	θ	Source
Boreal forest Norway spruce	0.48	(Løken et al. 2012)
Douglas fir	0.61	(Rural Technology Initiative 2012)
Loblolly pine	0.63	(Russell et al. 2009)

Branches, tops, and stumps are considered harvest residues from AGB $O_{(t)}$ and can be extracted or left on the forest floor for decomposition. Equation 5 presents the calculation of the other AGB $O_{(t)}$:

$$O_{(t)} = \frac{G_{(t)} - (m+1)B_{(t)}}{m+1}$$

Equation 4

Where,

m= root to shoot ratio, values presented in Table 4

$O_{(t)}$= Other AGB (tC/ha)

Table 4: Root to shoot ratio (m) for different forest types.

Forest type	m	Source

Boreal forest Norway spruce	0.24	(IPCC 2006)
Douglas fir	0.24	(IPCC 2006)
Loblolly pine	0.2	(IPCC 2006)

4.1.1.3. Below ground biomass $R_{(t)}$

The BGB $R_{(t)}$of the forest stand is calculated as follow:

$$R_{(t)} = G_{(t)} - (B_{(t)} + O_{(t)})$$ *Equation 5*

$R_{(t)}$= Below-ground biomass (tC/ha)

4.1.1.4. Total harvest E (t, σ)

At the time of harvesting, the stock of stems $B_{(t)}$ is removed from the stand, as well as a fraction σ of harvest residues (other AGB, $O_{(t)}$)(Holtsmark 2015a). The total harvest is:

$$E(t,\sigma) = G_t + \sigma O_{(t)}$$ *Equation 6*

E (t, σ) = total AGB extracted from stand under the form of stems and other ABG (tC/ha)

4.1.1.5. Decay of harvest residues and below-ground biomass $Dr_{(t)}$

The following function describes the amount of harvest residues $(1-\sigma)O_{(t)}$ that are left on the forest floor and the BGB from harvested trees that is left to decay $R_{(t)}$. This is the fraction of forest biomass that is not extracted from the forest at t=0. The annual decomposition $Dr_{(t)}$ (tC/ha) of $(1-\sigma)(O_t) + R_t$ is based on Holtsmark (2015a):

$$Dr(t,\sigma) = e^{-t\omega}((1-\sigma)(O_t) + R_t)$$ *Equation 7*

The decomposition rate ω for different forest types is presented in Table 5.

Table 3

Table 5: Annual decomposition rates ω for different forest types.

Forest type	ω	Source
Boreal forest Norway spruce	0.04	(Holtsmark 2015a)
Douglas fir	0.031	(Gholz et al. 1997)

Loblolly pine	0.041	(Russell et al. 2014)

Decomposition rates differ for different components of trees. However, Holtsmark (2015) suggests that sensitivity with respect to different decomposition rates for different residue components is not very important to the results.

4.1.1.6. Natural dead organic matter (nDOM) pool

Development of the dead organic matter pool is affected by three processes: litterfall, decomposition, and harvest (Asante et al. 2011).

A fraction of the forest stand dies naturally each year, adding to the nDOM pool. This fraction is related to stem wood $B_{(t)}$ and is expressed at the litter fall rate β. This parameter was set to 0.01357 (Asante et al. 2011).

$$D_{t+1} = \beta B(t) + (1-\omega)D_{(t)} + (1-\omega)D_{(t-1)}$$ *Equation 8*

D_{t+1} = nDOM pool at time t+1 (tC/ha)

DOM is assumed to be decomposed at a rate ω, so the first term of the equation represents the amount of DOM that remains from previous rotations.

4.1.1.7. Soil carbon $S_{(t)}$

Equation 10 represents the dynamic of the soil carbon. It is assumed that as a consequence of forestry activities, a net release of carbon from the soil occurs. Thereafter, the soil carbon pool returns to its initial state. Where S_o is the is the constant amount of soil carbon in the Norway spruce stand (60tC/ha), and s1 (-113.5), s2 (-0.09) and s3 (3.003) are parameters taken from Holtsmark (2015a). Soil carbon $S_{(t)}$ (tC/ha) is calculated as:

$$S_{(t)} = S_0 - s1e^{s2t}(1\text{-}e^{s2t}))^{s3}$$ *Equation 9*

The default calculations do not consider potential SOC emissions given the relatively large uncertainty.

4.1.1.8. Total forest carbon stock $\varphi_{(t)}$

Total forest carbon stock (tC/ha) includes the carbon pool of all living biomass $G_{(t)}$, the pool of harvest residues $Dr_{(t)}$, the nDOM pool $D_{(t)}$ and SOC $S_{(t)}$. Equation 11 is based on Holtsmark (2015a).

$$\varphi_{(t)} = G_{(t)} + D_{r(t)} + D_{(t)} + S_{(t)}$$ *Equation 10*

4.1.2. Forest carbon stock of the reference system

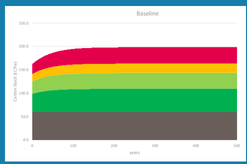
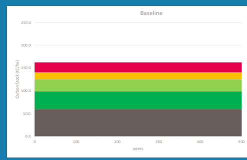
In this study, two forest reference systems are considered:

i) **Net zero reference (default):** this scenario is based on the rationale that a forest is in steady state (no changes in carbon pools) and that only physical carbon emissions due to harvesting and carbon uptakes during biomass regrowth are accounted for (Guest et al. 2013; Cherubini et al. 2011a; Pingoud et al. 2012)

ii) **Foregone sequestration (FS):** this scenario is based on the rationale that forests are typically harvested at maximum mean annual increment (MAI) and would continue to grow if not harvested, but at lower rates. In the foregone sequestration reference system, the burden of an avoided continuous accumulation of carbon is considered (Holtsmark 2015a; Liu et al. 2017).

The main characteristics of the two references are further described in Table 6.

Table 6: Reference systems summary

Criteria	Foregone sequestration (FS)	Net zero
		
Rationale	Footprint is calculated as the impact caused by human intervention compared to the natural state. The assumption is that a harvested forest is not yet in equilibrium and continues to grow until it reaches equilibrium.	Footprint is calculated as the impact caused by human intervention compared to the natural state. Only the time period until the same carbon stock is reached as at the point of harvesting is considered.
Follows physical uptake and emissions	Does not fully consider the physical emissions profile since it accounts for the burden of avoided uptake.	Follows physical emission profile in the atmosphere.
Realistic harvesting scenario	Hypothetical scenario, since forest plantations are cut at rotation periods and forests are typically cut again upon reaching maturity.	Yes, since it is similar to considering just the emissions and sinks of one rotation period.
Nature as a reference	Yes	Yes, but continuous forest growth not considered
Implications	Forests as carbon sinks and disturbances lead to significant impacts	In-between

Currently there exists no consensus on what reference system to use, which will be an important discussion in the future. For the calculator, we use the net zero reference system by default since only actual emissions and uptake of carbon is considered. This is most aligned with currently used GHG accounting standards.

4.1.3. Calculating the CO_2 budget in the atmosphere over time

4.1.3.1. Net effect on atmospheric CO_2 A(t)

Three CO_2 sources and sinks are considered when calculating net CO_2 emissions to the atmosphere:

- **CO_2 decay in the atmosphere**: when a CO_2 molecule is released to the atmosphere, it can be removed by both the ocean and terrestrial biospheres (As considered in the carbon cycle models, see chapter 4.1.3.2).
- **Assimilation of CO_2 from onsite biomass growth and decomposition**: considers the CO_2 uptake due to forest regrowth and emissions due to nDOM and harvest residue decomposition (see 4.1.3.3)
- **Net CO_2 emissions in the reference system:** zero, for the net zero reference; considers carbon debt due to avoided continuous growth, as in the non-harvest scenario (foregone sequestration)

The net effect of harvesting on atmospheric carbon compared to a scenario without harvesting is calculated as follows:

Equation 11

$$A(t) = C_a(t) + A_H(t) - A_0(t)$$

Where,

$C_a(t)$: Carbon budget in the atmosphere at year t following the initial emission of 45tC, corresponding to the total harvested carbon over a hectare of Norway Spruce (Equation 14)

$A_H(t)$: Carbon budget in the atmosphere due to biomass regrowth and decomposition over time (Equation 15)

$A_o(t)$ Carbon budget in the atmosphere of the reference scenario (Equation 16)

In Figure 3, the black curve is calculated with Equation 14, representing the remaining share of the C pulse emission from harvested biomass. The green curve represents the accumulated effect of atmospheric carbon on the continued growth and carbon capture in the forest in the no-harvest scenario (FS scenario). The blue curve is calculated with Equation 15; this curve represents the accumulated net effect of the atmospheric carbon on decomposition of the harvest residue, the release of soil carbon, and the effect of the stand's regrowth (carbon capture).

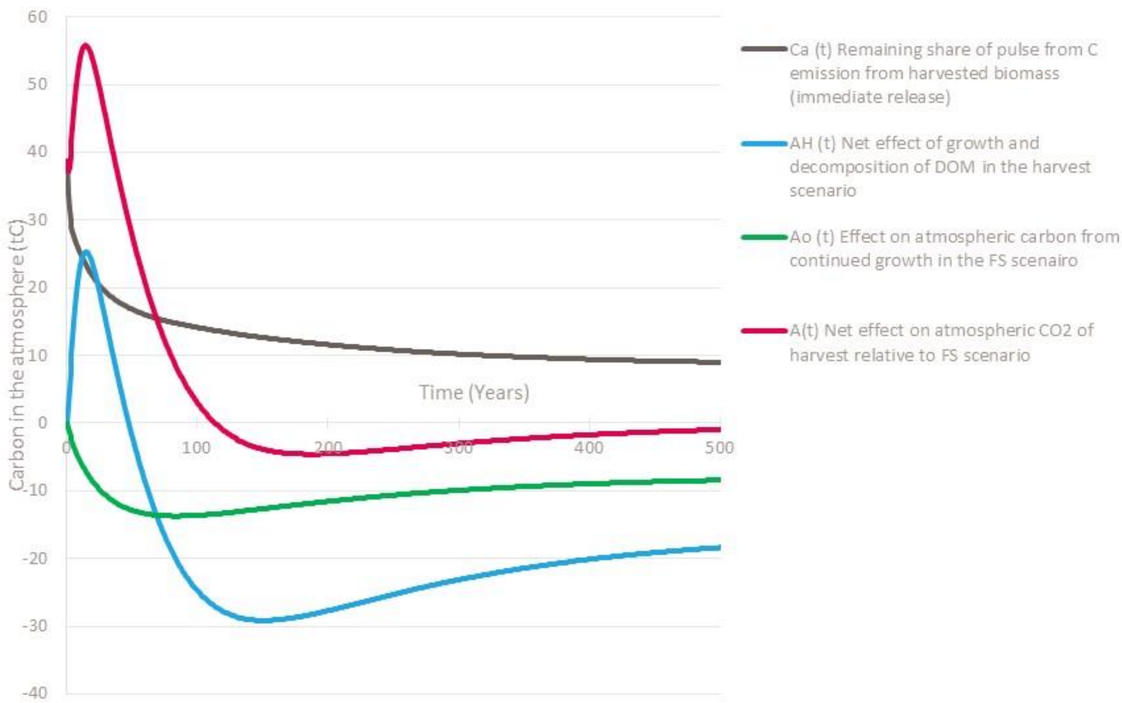


Figure 3: Net effect on atmospheric carbon of Norway spruce biomass harvesting over a hectare and use relative to the foregone sequestration non-harvest scenario (in tC). Black curve represents Ca (t), blue curve is $A_H(t)$, green curve is $A_o(t)$ the pink curve is A(t).

The figure above is based on the assumption that the carbon stored in harvested biomass is released in the year of the harvest. For an accounting of temporal carbon storage (delayed emissions), see the following chapters.

Besides the release of the carbon stored in harvested biomass (green curve), the decomposition of harvest residues, nDOM, and BGB during post-harvest years leads to a temporal increase in carbon released to the atmosphere. In the case above, only after 100 years is the released carbon fully assimilated.

The presence of negative values in the atmospheric decay profiles (after 100 years) appear as a contradiction because the amount of CO_2 in the atmosphere is lower than the level before the emission. The reason for this is that atmospheric CO_2 is taken up in different biogeochemical sinks at different time constants. The same time constants are also applied to CO_2 uptake in biomass regrowth.

4.1.3.2. CO_2 decay in the atmosphere

The residence time of carbon dioxide in the atmosphere is typically calculated based on the Bern carbon cycle model. The model considers carbon uptake in the biosphere and oceans, and assumes that a fraction of emitted CO_2 is permanently retained in the atmosphere.

The fraction of the initial pulse of CO_2 at time t is labeled as y(t) and calculated as follows:

$$y(t) = y_0 + \sum_{i=1}^{3} y_i e^{-t/\alpha_i}$$ *Equation 12*

This model is based on the Bern2.5CC carbon cycle model using a CO_2 concentration of 378 ppm in the atmosphere (Joos et al. 2013). The parameters are average values of a set of climate models and set as y_0 = 0.217, y_1 = 0.259, y_2 = 0.338, y_3 = 0.186, α_1 = 172.9, α_2=18.51, α_3 = 1.186 (Joos et al. 2001, 1996; Holtsmark 2015a; Joos et al. 2013)

In the following, we assume that all carbon stored in the harvested stem and residues (total of 45.4 tC in the case of the Norway spruce) is released in the atmosphere the same year as the harvest. The amount of carbon in the atmosphere Ca(t) over time can be determined by the following:

$$C_a(t) = E(t, \sigma).y(t)$$ *Equation 13*

where,

E(t, σ) is the total harvest (tC) at year t of the carbon stored in the harvested stem and residues.

y(t) fraction of the initial pulse of CO_2. Calculated with Equation 13

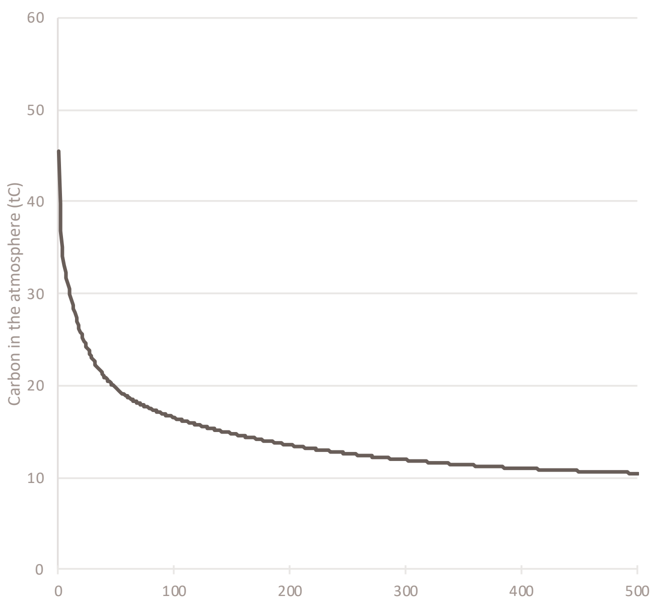


Figure 4: Carbon in the atmosphere after an Initial emission of 45.4 tC, corresponding to the total harvested carbon over a hectare of Norway Spruce at t_0, $C_a(t)$ based on Equation 14

Besides harvested biomass, the Bern 2.5CC model is also applied to fluxes of CO_2 generated by the stand's growth, as well as the release of CO_2 due to decomposition of nDOM and harvest residues left on the forest floor.

4.1.3.3. Emission and sink of biogenic carbon from the forest stand A_H (t)

The concentration in the atmosphere of bio CO_2 over time can be described through a combination of the net carbon stock changes of the forest $\varphi'_H(t)$ and the removal of CO_2 by the ocean and terrestrial biosphere sinks y(t). The atmospheric C concentration due to biomass regrowth and decomposition over time A_H (t) is calculated as a convolution between two functions, and the pulse emission can be represented as the sum of earlier emissions $\phi'_H(t)$ at time k multiplied by the fraction still remaining in the atmosphere after time t-k. H represents the calculations when harvest occurs.

$$A_H(t) = -\int_0^t \varphi'_H(k)\, y(t-k)\, dk$$ *Equation 14*

Where,

$\varphi'_H(t)$ represents the time derivative of $\varphi_H(t)$, which is net carbon flux from the atmosphere to the stand due to stand growth, as well as the release of soil carbon and CO_2 from the decomposition of harvest residues and NDOM.

y(t) fraction of the initial pulse of CO_2. Calculated with Equation 13

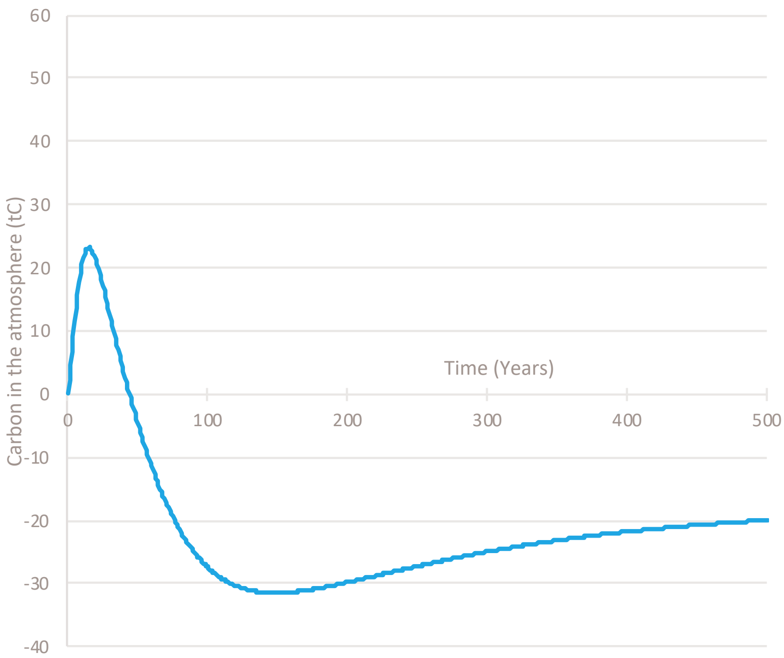


Figure 5: Net effect on the atmospheric carbon of biomass regrowth and decomposition (in tC).

Carbon emissions from decomposition of harvest residues, BGB, and nDOM dominate the net carbon balance during the first 50 years, while in the following years, biomass regrowth continues to accumulate carbon (negative carbon emissions values).

4.1.3.4. Reference system A_o (t)

The carbon budget of the reference scenario without harvesting $A_0(t)$ is calculated as:

$$A_O(t) = -\int_0^t \varphi'_0(k)y(t-k)dk$$

Equation 15

Where,

$\varphi'_0(t)$ represents the time derivative of the total forest carbon stock $\varphi_0(t)$. It is the net carbon flux from the atmosphere to the stand in the reference system.

y(t) fraction of the initial pulse of CO_2. Calculated with Equation 13

The carbon stock model of the two reference scenarios and the related carbon emitted to the atmosphere is illustrated in Figure 6. For the steady-state reference (a, SS), no changes in carbon stocks are assumed. In the foregone sequestration scenario (b, FS), emissions and uptake of carbon are considered relative to the baseline (indicated by the gray dotted line), and the Bern 2.5CC model is also applied to the carbon fluxes.

a) Net zero b) Foregone sequestration

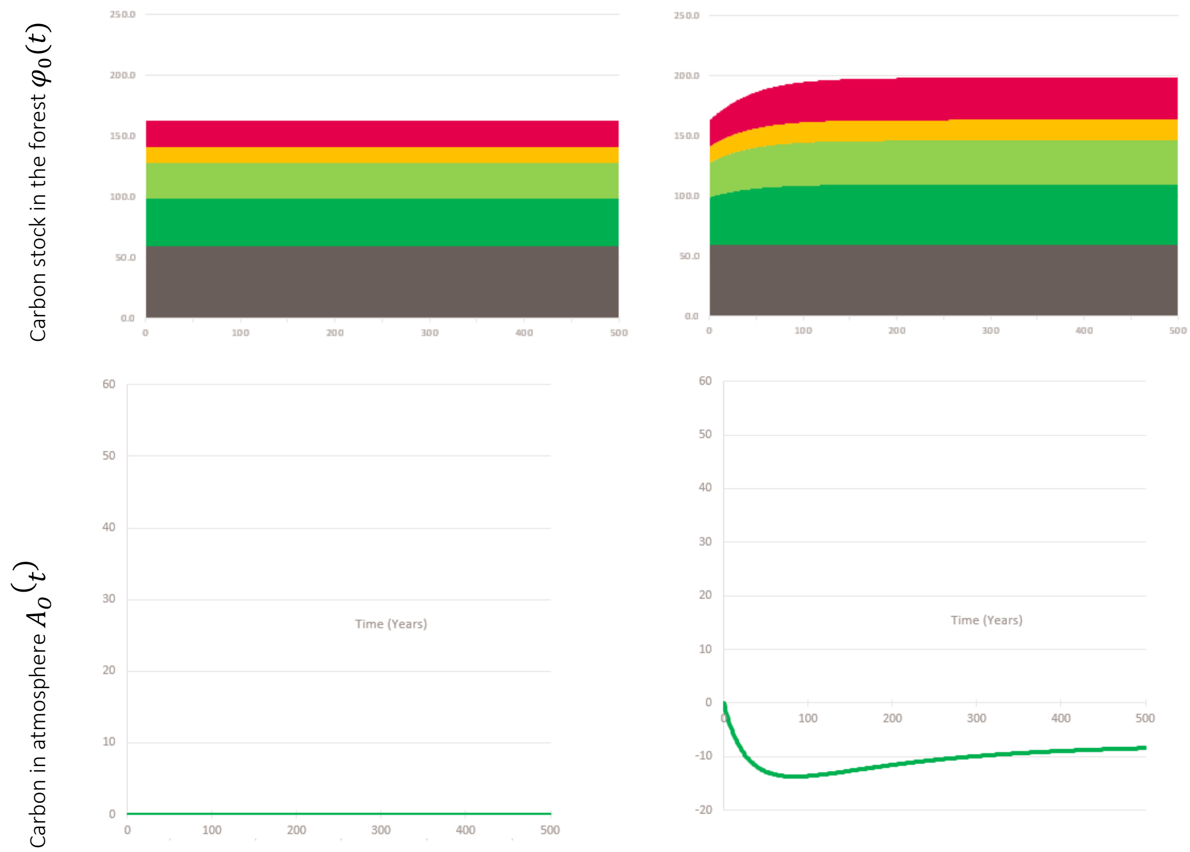


Figure 6: Carbon stock in the forest (tC) and the carbon in the atmosphere (tC) of the two reference systems (net zero and FS) over time. Equation 16

4.1.4. $GWP_{bio,\ forest}$ calculation

Absolute global warming potential, $AGWP_{CO2}$ of a CO_2 pulse emission E, from time zero to T (time horizon) is usually calculated as follows (Holtsmark 2015a):

$$AGWP_{CO2}(T) = \alpha CO_2 \int_0^T y(t)\, E(\tau_{h,}\sigma)\, dt \qquad \text{Equation 16}$$

where α_{CO2} is the radiative forcing effect of CO_2, T is the applied time horizon (20, 100 or 500 years), whereas y(t) is the fraction of the pulse emission remaining in the atmosphere at time t (see Equation 13) and E($\tau_{h,}\sigma$) is the total CO_2 emitted at the year of harvest h (h=0), calculated.

More recently, Cherubini et al. (2011a) introduced the concept $AGWP_{bioCO2}$, which is intended to measure the absolute warming potential of a pulse of CO_2 caused by the combustion of biomass when it is taken into account that harvesting is followed by regrowth of trees in a forest stand and other dynamic processes triggered by harvesting. Using the model of a forest stand described above, the appropriate definition of $AGWP_{bioCO2}$ is then:

$$AGWP_{bio\ forest\ CO2}(T) = \alpha CO_2 \int_0^T A(t)\, dt \qquad \text{Equation 17}$$

where A(t) represents the net effect of harvesting on the atmospheric carbon stock, compared with the baseline scenario without harvesting (see section 4.1.3.4). To measure the relative global warming effect of biomass combustion, Cherubini et al. (2011a) next defined the GWP_{bio} factor for a time horizon T as:

$$GWP_{bio}(T) = \frac{AGWP_{bio\ forest\ CO2}(T)}{AGWP_{CO2}(T)} \qquad \text{Equation 18}$$

The radiative forcing effect of CO_2, α_{CO2} expected to decrease over time as the concentration of CO_2 increases. For simplicity's sake, we make the approximation that α_{CO2} is constant over time (Holtsmark 2015a)

$$GWP_{bio\ forest}(T) = \frac{\int_0^T A(t)dt}{\int_0^T y(t)E(\tau_h,\sigma)dt} \qquad \text{Equation 19}$$

Basically, the $GWP_{bio,\ forest}$ factor is calculated as the area below the curve from the pink line divided by the area below the curve from the gray line in Figure 3

The integral is estimated by numerical approximation.

5. Wood processing and allocation

This section considers how much wood needs to be extracted from a forest (in kg C) to produce the amount of input materials (in kg C) and the wood extraction factor, which mainly depends on two parameters:

- **Wood processing:** amount of wood that needs to be extracted from a forest (in kg C) to produce the amount of input materials (in kg C). Some of the wood biomass extracted from a forest might be used for other products (e.g. 20% as in the fictive mass balance below) or as waste (10%).
- **Allocation:** considers that different forest fractions are used for different products. Harvested stem wood with a larger diameter is typically used for furniture or construction, while other biomass is typically used for pulp production and fuelwood (Smith et al. 2006). In the calculator, economic allocation as implemented in ecoinvent is available. Results of the $GWP_{bio,\ forest}$ after economic allocation would eventually encourage the use of wood fractions with the highest economic values for long-lived products.

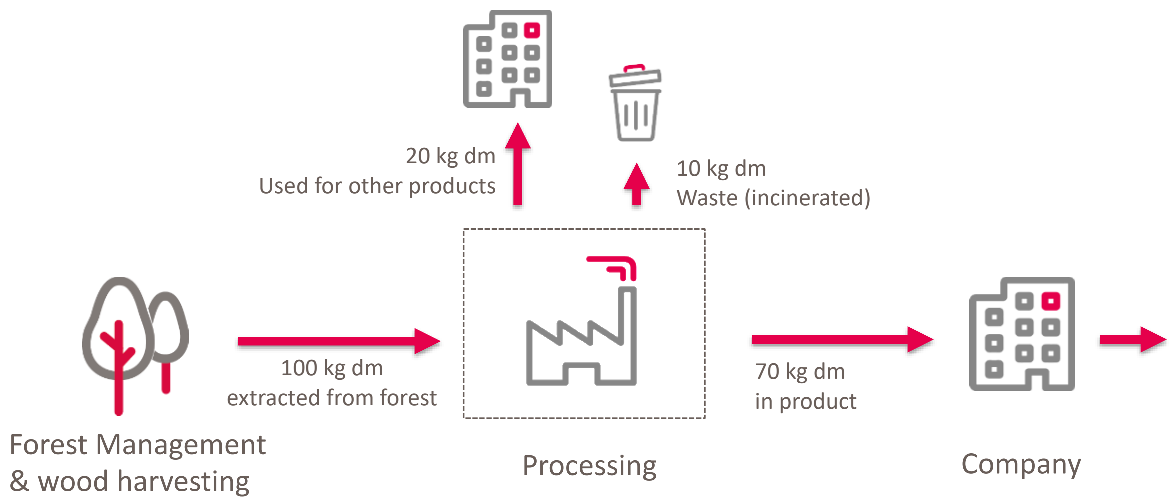


Figure 7: Fictive mass balance of wood processing.

Different approaches are available in the calculator:

Category	Wood extraction factor	Description
Mass balance (default)	1	Amount of carbon contained in material = amount of carbon extracted from forest (default)
Economic allocation (ei 3.5)	≥0	The amount of standing wood (kg C) of each input material is based on ecoinvent v3.5, cut-off version and is expressed as carbon extracted from forest (kg C) per carbon contained in material (kg C). Values greater than one indicate that either a high value biomass is used, or that processing losses occur. Values

		lower than one indicate that low value biomass is used, and that more burden is assigned to the high value product (e.g., timber vs. sawdust)
Recycled (cut-off)	0	The source of the forest biomass is from recycled wood. A cut-off approach is used here, which means that no burden from wood extraction is assigned if recycled material is used.
Waste biomass (zero burden)	0	Waste biomass is used, which means that no burden from wood extraction is assigned if "waste" material is used.
Specific value	≥0	Specify your own value.

A wood extraction factor of one means that the exactly the same amount of carbon is extracted from a forest as it is contained in a product. A factor of zero means that no burden caused by the forest carbon gap is assigned to the product analyzed.

Equation 20

$$C_{extracted} = C_{extracted} * FE$$

Where,

$C_{extraction}$ Carbon extracted from forest (kg C)

$C_{product}$ Carbon contained in the product (kg C)

FE Forest extraction factor – considering conversion efficiencies and allocation (dimensionless).

6. Carbon storage in products — $GWP_{bio,\ product}$

A proportion of the harvested biomass is stored in the anthroposphere as a wood product (i.e., construction material, furniture). These products do not emit CO_2 to the atmosphere immediately, but at the end of their lifespan instead.

The lifespan of the wooden product is the time that CO_2 emissions are delayed. In this time, the forest stand is being regrown, sequestering carbon and creating a net reduction in atmospheric CO_2 concentration. The $GWP_{bio,\ product}$ calculates the effect of storing harvested biomass as a wood product. Moreover, if carbon storage in a product is longer than the assessment time horizon it is assumed as permanent capture. The $GWP_{bio,\ product}$ is calculated as follows (Helin, 2016):

$$GWP_{bio\ product}(T) = \frac{AGWP_{bio,product}\,(T)}{AGWP_{CO2}(T)} = \frac{\int_0^T \alpha CO_2(t)\, S_{seq}(t)}{AGWP_{CO2}(T)} \quad \text{Equation 21}$$

where $S_{seq}(t)$ is the reduced CO_2 concentration due to delayed release (or permanent storage) of carbon in the biomass products. $S_{seq}(t)$ is given a value -1 over the product lifetime Ʈ and instant release to the atmosphere is assumed at the end of a product's lifetime, for simplicity. For forest biomass use with instant release to the atmosphere in t = 0, such as bioenergy, S_{seq} equals 0, thus $GWP_{bio,\ product} = 0$.

6.1.1. Product carbon stock model

Carbon storage time depends on the type of product and practices where the biomass is being used. For example, biofuels and some paper classes are considered a short-term use product, produced and used in the same year (Pingoud et al. 2003). Timber structures such as wood frames for building houses are considered "long-term use" commodities.

In cases where no specific values are available, select "use default" and choose the most appropriate category. Here is an overview of the categories and the corresponding lifetimes (in years):

Product category	Lifetime (in years)
Energy - combustion/incineration	0
Building materials: products made of sawn timber, plywood/veneer, or particleboard used for construction work in buildings, civil engineering	50
Other building material: products made of sawn timber, plywood/veneer, or particleboard used for maintenance in houses or civil engineering. Includes commodities as fences, windows, frames, panels, wooden floors, and doors	16

Structural support materials: products made of sawn timber, plywood/veneer, or particleboard used for form works, scaffolds, and other wood-based products needed on building sites	1
Furnishing: products made of sawn timber, plywood/veneer, or particleboard used for furnishing houses and offices	16
Packing materials: products made of sawn timber, plywood/veneer, or particleboard; or paper and paperboard-products used for packing other commodities: shipping boxes, wrapping, and boxing	1
Long-life paper products: products made of pulp used for longer periods such as books, maps, and posters	4
Short-life paper products: products made of pulp used for short periods such as newsprint and sanitary papers	1
Others	

In addition to carbon stored during use phase, effects also depend on end-of-life treatment. In the following table, the implications of each end-of-life treatment scenario are described.

End-of-life treatment system	Assumption/effect
Incineration/combustion	For incineration and combustion, no storage is assumed (immediate release)
Recycling	For recycling, no benefits beyond the product lifespan are assumed either (benefits are instead assigned to the product using the recycled material again).
Landfill — wood	Decay of wood biomass over time (extended storage time). The fraction going to landfills is further divided into non-degradable and degradable pools for paper and wood products. The nondegradable pool is permanently sequestered. The fraction of the degradable pool remaining in subsequent years is determined by first-order decay, that is, fraction remaining=exp(-years×ln(2)/half-life).
Landfill — paper	Same as wood, but with a different ratio of degradable and non-degradable.
Unknown (default)	Immediate release (no additional storage) — conservative assumption

The fraction of the degradable pool is considered as 10% for wood and 50% for paper. A half-life of 23.1 years for wood and 11.6 years for paper is assumed (IPCC 2019).

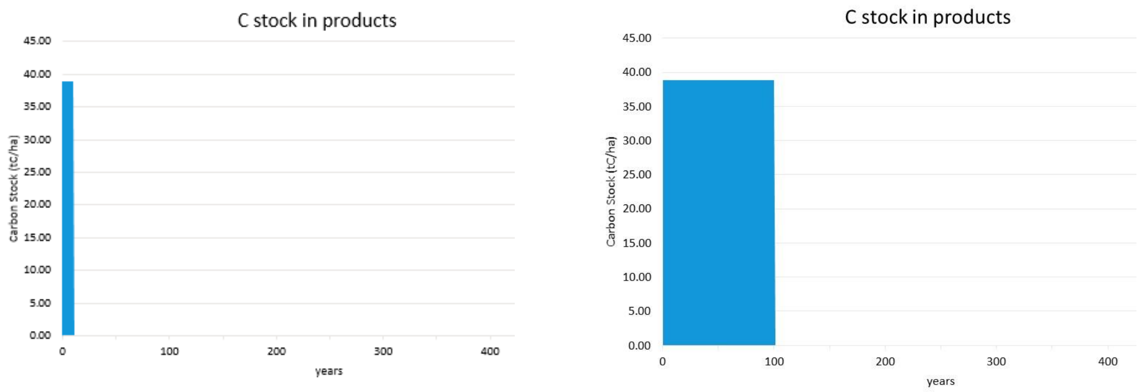


Figure 8: 20 and 100-year storage of carbon in the products (followed by direct release, e.g., incineration)

6.1.2. CO_2 emissions in the atmosphere

The curves presented in Figure 9 describe atmospheric decay of CO_2 pulses from a biomass product at the end of its life cycle. Biomass is harvested from a forest stand with a rotation period of 100 years. The curve on the left represents a storage period of 20 years, and the one on the right represents a storage period of 100 years.

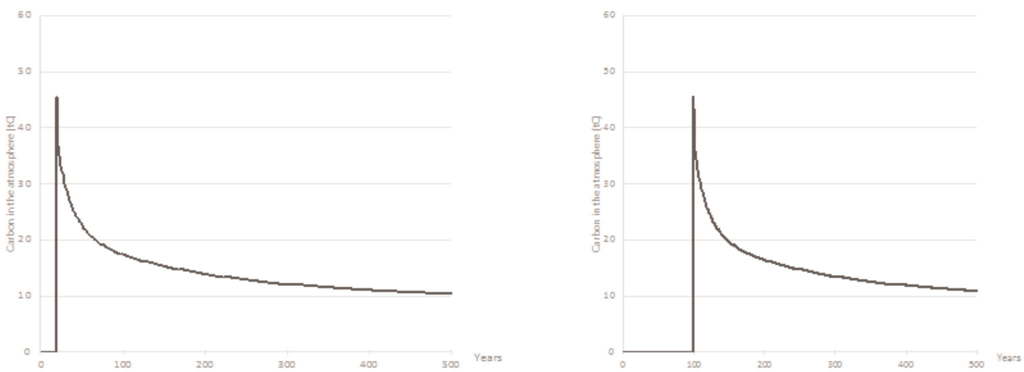


Figure 9: Carbon emissions from wood products emitted after 20 years and 100 years (in tC)

The GWP impact of temporarily storing carbon depends on the time horizon of the study. For instance, if carbon is stored over 20 years, the GWP_{20} is minus one (permanent storage) and the GWP_{100} and GWP_{500} give is closer to a factor of zero (no storage benefits) since the time horizon of the study is significantly higher than the temporal storage time (see Figure 10).

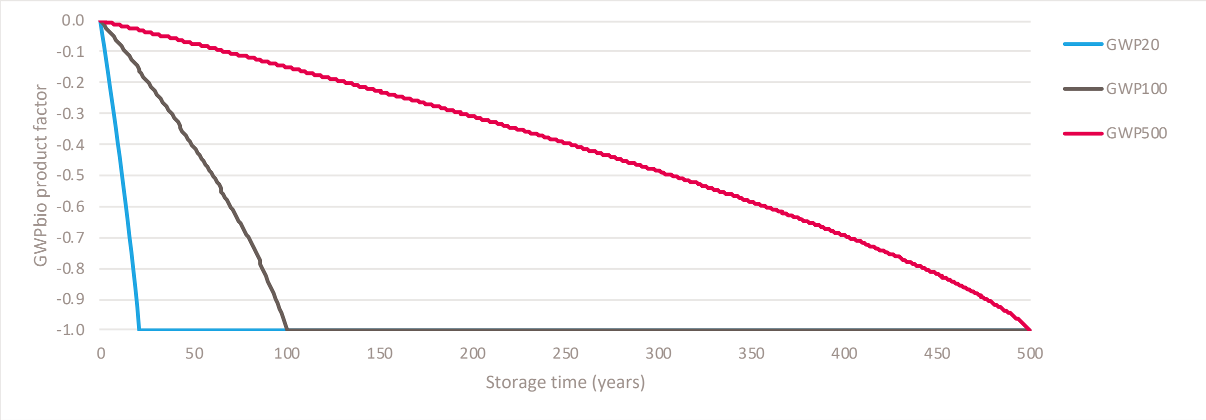


Figure 10: GWP $_{bio\ product}$ curve for different storage time (in years).

The GWP$_{bio,\ product}$ for different time horizons and storage times are provided in Table 7.

Table 7: GWP$_{bio,\ product}$ values for different time horizons.

Time horizon	0-year storage	20-year storage	100-year storage
GWP 20	0	-1.00	-1.00
GWP 100	0	-0.16	-1.00
GWP 500	0	-0.03	-0.15

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