The 'debt' is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy

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Perspective

The 'debt' is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy

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Abstract: The temporal imbalance between the release and sequestration of forest carbon has raised a fundamental concern about the climate mitigation potential of forest biomass for energy. The potential carbon debt caused by harvest and the resulting time spans needed to reach pre-harvest carbon levels (payback) or those of a reference case (parity) have become important parameters for climate and bioenergy policy developments. The present range of analyses however varies in assumptions, regional scopes, and conclusions. Comparing these modeling efforts, we reveal that they apply different principle modeling frameworks while results are largely affected by the same parameters. The size of the carbon debt is mostly determined by the type and amount of biomass harvested and whether land-use change emissions need to be accounted for. Payback times are mainly determined by plant growth rates, i.e. the forest biome, tree species, site productivity and management. Parity times are primarily influenced by the choice and construction of the reference scenario and fossil carbon displacement efficiencies. Using small residual biomass (harvesting/processing), deadwood from highly insect-infected sites, or new plantations on highly productive or marginal land offers (almost) immediate net carbon benefits. Their eventual climate mitigation potential however is determined by the effectiveness of the fossil fuel displacement. We deem it therefore unsuitable to define political guidance by feedstock alone. Current global wood pellet production is predominantly residue based. Production increases based on low-grade stemwood are expected in regions with a downturn in the local wood product sector, highlighting the importance of accounting for regional forest carbon trends. © 2013 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: temporal carbon; carbon debt; carbon neutrality; carbon payback; carbon parity; bioenergy; forest biomass

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Introduction

Several years ago, the bioenergy emission accounting rules of prominent renewable energy promotion policies and greenhouse gas (GHG) reporting and trading schemes such as the EU Emission Trading Scheme or the United Nation's Framework Convention on Climate Change (UNFCCC) were identified as misleading.[1–3] The main criticism was that biogenic carbon releases, for example, from forest harvest, were reported as part of the forestry sector while biomass combustion emissions in the energy sector were accounted as zero, thus suggesting the bioenergy system to be carbon neutral. Since then, there has been a flurry of debate on the sustainability of bioenergy, particularly with respect to its carbon footprint.[4–7]

Due to their potential order of magnitude, much of the recent research and debate has focused on the quantification of emissions from direct and indirect land-use change (see Fargione *et al.*,[8] Melillo *et al.*,[9] and a review by Berndes *et al.*[10]). By now, lifecycle analyses (LCA) of biomass to energy value chains[11,12] quantifying additional fossil fuel emissions as well as carbon emissions due to direct land-use change have been incorporated in new policies, such as the European Renewable Energy Directive 2009/28/EC.

While there seems general agreement that carbon emitted from bioenergy combustion was and will again be sequestered from the atmosphere given a sustainable biomass management system, and thus that bioenergy is a form of renewable energy, there is inherent concern that carbon release and sequestration rates may not be in temporal balance with each other.[10] A temporal imbalance challenges whether an increase in bioenergy use may counteract current climate mitigation targets and requires a full accounting of bioenergy systems, incorporating lifecycle with temporal carbon analyses[13] against a reference of reduced bioenergy expansion. This is particularly the case for woody-biomass-based systems that rely on longer rotation cycles. Biomass systems based on short rotation crops generally do not face this issue, and may even accrue initial carbon credits if established on land with low initial carbon stocks.

Forest carbon cycles have been modeled for over 20 years (starting with Harmon *et al.* [14]). Given current climate change mitigation and renewable energy support policies, more recent analyses have focused on the temporal carbon balance of bioenergy systems, and especially on the issue of 'carbon debt'. This term was first used by Fargione *et al.*[8] referring to (above- and below-ground) carbon loss from the conversion of land to liquid biofuel production systems. It was not until 2010, when the terminology appeared in the solid biofuel debate, describing additional emissions from forest biomass as compared to fossil fuels per unit of energy generated.[15] Meanwhile, it has largely been established to describe the loss of sequestered biogenic carbon per land area due to the initial harvest for bioenergy.*

Recent studies evaluating the carbon debt of bioenergy production from forest biomass vary in assumptions and methodologies, regional scopes, and ultimately conclusions. Policy makers are confronted with this portfolio while needing to address the temporal carbon aspect in current regulations. In order to define policies for our carbon constrained world, it is critical to better understand the dimensions and regional differences of these carbon cycles. Only recently, the European Commission launched a tender for an investigation of the carbon impacts of biomass consumed in the EU, specifically dealing with this subject.

This article compares the state-of-the-art temporal forest carbon modeling and highlights the differences in approaches taken and their outcome on the so-called 'carbon debt' of bioenergy. It lists and discusses the uncertainties of current analyses and concludes upon potential policy directions which could be taken based on these findings. However, the article does not discuss all climate change related factors and modeling efforts regarding bioenergy use, in particular geophysical effects such as the albedo.

At the time of writing, no comprehensive review of global temporal carbon research was publicly available. Lippke *et al.*[16] give a general overview of the topic; with a focus on North-American studies. Bowyer *et al.*[17] provide a thorough investigation of the potential role, bioenergy may play regarding the EU's renewable energy and climate targets, in the light of current research. The authors though analyze the topic from a solely European perspective and neglect a wider range of peer-reviewed, international studies,[18–25] which form part of this analysis. We deem these studies indispensable, also within the European context, as the EU's current renewable targets are likely only achieved with international imports of

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*Note that owners of existing intensively managed, even-aged forests (plantations) would consider the plantation establishment as the logical initial reference year, where harvesting redeems a carbon credit rather than creating a new debt. From a policy maker's perspective however, the main question is rather whether he/she should incentivize harvest for bioenergy or not. Most studies analyzed in this article use the moment of harvest as the reference year.

woody biomass.[26–28] In addition, this paper includes new research[29,30] covering woody biomass chains destined to Europe from the South-East USA and British Columbia, Canada, the two most important regions currently exporting wood pellets to the EU.[31] Another reflection of earlier research was done by Holtsmark,[32] where the author compared his own past modeling efforts[21] against work by Cherubini *et al.*[19,20] and McKechnie *et al.*[33] However, he only covered the forest carbon cycling aspect and not post-harvest carbon dynamics in products and landfills; which are part of this analysis.

Results

We find that current temporal carbon modeling studies can be distinguished by their methodological choices, which practically reflect the scoping of the individual analyses, and the scenario assumptions taken within these scopes.

Methodological choices: the modeling framework

Absolute vs. relative carbon balances: payback vs. parity times

As already mentioned, the carbon debt occurs at a reference point in time when forest biomass is harvested or collected for energy purposes. The time span to recover this carbon loss can be indicated to the site itself (absolute) or against a baseline (relative). An absolute carbon balance approach is chosen to define the time until a site reaches its pre-harvest carbon level. This period has been commonly referred to as 'payback'[34] or 'repayment times'[8] in relation to liquid biofuels. Both terms have been applied in the solid biofuel debate,[35] often synonymous with the term 'carbon break-even'.[25,30]

To conclude upon the climate mitigation potential of bioenergy expansion scenarios, they need to be referenced to alternative land or biomass use scenarios, for example, material use of biomass (e.g. pulp and paper), land protection (no harvest) or conversion to agriculture. This provides insight whether it is more beneficial from a net carbon perspective to keep biogenic carbon sequestered in plants (subjected to natural disturbances such as insects or wildfire) or use it for energy purposes. Thus, the relative carbon balance determines the timeframe when a specific site or scenario reaches the same carbon volume as its counterfactual (reference case). This has commonly been referred to as 'carbon (sequestration) parity'.[29,30,35] The selection and construction of the reference scenario is a key influencing factor whether and when a bioenergy scenario becomes carbon beneficial. Obviously, baseline assumptions should be regionally and scenario specific.

Spatial boundaries: stand- *vs.* landscape-level

Spatial boundary choices define whether a single or multiple harvest plots are considered in the carbon analysis. Stand-level carbon analyses look at a single land area, plot or cutblock which is disturbed at once, the disturbance type depending on the scenarios (e.g. whole-tree harvest), and re-grows afterwards. Following harvests are performed after the rotation cycle on the same plot, but are not necessarily part of stand-level analysis. The approach is characterized by its saw tooth carbon cycles, typical for early carbon modeling.[36] The key benefit of stand-level analysis is its simplicity; a primary reason for it still being part of today's carbon analyses.[15,29,30]

While the study of single cutblocks may provide easily comprehendible results, for example, on carbon effects of different harvesting choices, timber/woody biomass supply areas consist of several cutblocks, i.e. contain a time and space dynamic, as introduced via the 'theoretical' or 'fixed' landscape-level approach.[37,38] In a nutshell, it comprehends of an area consisting of *x* (e.g. 80) individual cutblocks following an *x* (i.e. 80) year rotation cycle. The plots are defined to represent the typical forest conditions of the studied region; though may vary in age structure and potentially other characteristics, for example, deadwood volumes. Per year, one of these plots is harvested while the remaining *x–1* (i.e. 79 in our example) keep (re-) growing. While harvesting choices can be randomized within models, they are typically designed to follow an oldest forest stretch first harvesting pattern. This implies that the first cutblock is harvested again only after a re-growth period of *x* (80) years. The landscape carbon balance forms the total sum of all cutblocks (see Eliasson *et al.* [39] for a graphical explanation). Harvesting re-grown forest means that the net forest carbon emissions are zero (if no significant soil disturbance and soil carbon release has taken place). If instead woody biomass were taken from an expansion of harvested forest area, the carbon accounting would need to start again with *x* (80) plots at a mature state and thus net carbon emissions for the first re-growth period. Linked to this, analyses may either include carbon balances for all cutblocks from year one (which would be typical for a situation where bioenergy use is part of a steady-state system), or the analyses may start from the stand-level and then cumulatively increase with one cutblock each year (e.g. reflecting the annual biomass requirements of a new bioenergy plant) until the first cutblock is harvested again, effectively reaching the landscape level. The latter approach has also been called the increasing stand-level approach.[29]

Theoretical vs. empirical data: fixed *vs.* dynamic landscape

Most current forest carbon modeling studies apply a 'fixed' landscape approach, i.e. define a representative yet theoretical forest inventory which is modeled under different scenarios (Table 1). The same carbon models (e.g. LANDCARB or CBM-CFS3) can however also be fed with actual (mostly geospatially explicit) forest inventory data. This 'dynamic' landscape approach possibly represents a more accurate way of modeling forest carbon cycles.

Both modeling efforts however rely on process-based carbon simulations, which, as critics claim[18] and shown in this article, are heavily influenced by parameterization. Also, there seems to be poor agreement among models regarding forest CO_2 exchange rates.[40] An alternative approach would be to use empirical measurements of CO_2 exchanges between the forest ecosystem and the atmosphere taken over time from a tower located above the forest (see Amiro *et al.*[41] for North American studies).[18] Applying temporal plant dynamics (chronosequences), Bernier and Paré[18] were able to study the carbon cycling of a boreal forest under a yearly constant outtake of biomass (stems only, slash is left to decay) for heating, in comparison to fossil oil. When harvested at mature age (120 years), the carbon payback or parity time against fossil oil heating is over 90 years and increases strongly when cut at a younger growth stage.

Extra-ecosystem carbon modeling

In addition to a sophisticated modeling of ecosystem carbon flows, temporal carbon studies typically account for additional fossil fuel, i.e. life-cycle emissions along the respective value chains. Post-harvest carbon modeling becomes a relevant addition when forest products other than bioenergy are generated from biomass harvest. Product and landfill carbon cycles were already part of early bioenergy carbon modeling.[37,38,42,43] Among the recent temporal carbon studies, we found that most account at least for product carbon (though often neglecting landfill carbon storage) and additional fossil fuel value chain emissions (Table 1).

Carbon accumulation vs. impulse response functions

Most temporal carbon analyses use cumulative CO_2 emissions, i.e. account carbon fluxes without considering climate responses. The climate response to a pulse emission, which can be seen as the atmospheric decay of a pulse emission, is described by impulse response functions (IRF). IRF are important to understand the climate response to emissions and can also be formulated to describe the temperature response.[44,45] Climate responses have been shown to differ between fossil fuel CO_2 emissions and those generated by biomass combustion and subsequent tree (re-)growth.[19,46,47] Despite these findings, IRF are typically not part of present temporal carbon studies. It has even been claimed that the application of IRF to scenarios previously derived via carbon accumulation does not change results fundamentally.[32] In our opinion, such drastic conclusions need to be confirmed by additional analysis.

Indirect/market effects

The aim of most studies listed in Table 1 has been a sophisticated modeling of forest carbon cycles for different bioenergy and reference scenarios. With the exception of Böttcher *et al.*,[48] they do not account for wider system effects, i.e. potential indirect effects either scenario may have on, for example, regional, supra-regional, or global level. Connecting forest carbon (ecosystem) with economic models, for example, via land rents and carbon prices, allows the investigation of market dynamics under different bioenergy scenarios. Most prominently discussed in this regard are interactions within the forestry sector and thus the implication of increased demand for wood biomass for energy on fiber markets (e.g. pulp and paper).[49,50] Demand increases for biomass due to energy policies, and thus price increases for woody biomass, could however also lead to the conversion of marginal and fallow land (e.g. in the EU agricultural reserve) or grazing land to tree plantations with cascading effects of expanding grazing and/or cropland into existing forests.[51] Ideally, temporal carbon modeling would integrate region-specific woody biomass demand-supply dynamics, indicating carbon and/or economic implications between different bioenergy scenarios (or policy options). Eventually, such modeling would need to go beyond the forestry sector and cover global macro-economic wood fiber demand-supply and land-use patterns.[49] In this context, it is important to note that the global forest sector experiences long-term autonomous trends, such as the decade long shift of pulp production away from traditional suppliers in the

Table 1. Overview of recent temporal carbon studies and their principle modeling choices.

Study	Methodology	Forest data	Post-harvest carbon cycling	Full LCA	Baseline	Model
Cherubini *et al.*[19]	Fixed landscape	Representative, theoretical plots	N	N	-	Bern 2.5CC
Cherubini *et al.*[20]	Stand-level	Representative, theoretical plots	N	N	No harvest (but no additional tree growth)	Bern 2.5CC
Eliasson *et al.*[39]	Stand- and fixed landscape	Representative, theoretical plots	N	N	-	Q, Coup
Hudiburg *et al.*[22]	Dynamic landscape	Geospatially explicit (California, Oregon, and Washington, USA)	Y	Y	Protection: no harvest	NCAR CESM/ CLM4-CN
BERC[61]	Dynamic landscape	Geospatially explicit (South-East USA)	Y	Y	BAU (timber only harvest) + fossil electricity (several)	Combination (see p. 76)
Galik and Abt[60]	Dynamic landscape	Geospatially explicit (Virginia, USA)	Y	N	-	FORCARB
Jonker *et al.*[29]	Stand- and fixed landscape	Representative, theoretical plots	Y	Y	Protection: no harvest	GORCAM
Lamers *et al.*[30]	Stand- and fixed landscape	Representative, theoretical plots	Y	Y	Slash: roadside burning Protection/no harvest (naturally occuring wildfire) Roundwood: BAU (timber harvest)	CBM-CFS3
MANOMET[15]	Stand-level	Representative, theoretical plots	Y	Y	BAU (timber only harvest) + oil heat BAU (timber only harvest) + coal electricity BAU (timber only harvest) + natural gas heat BAU (timber only harvest) + natural gas electricity	US Forest Service Vegetation Simulator
Zanchi *et al.*[53]	Fixed landscape	Representative, theoretical plots	Y	N	BAU (timber only harvest) + coal/oil/NG electricity	GORCAM
Mitchell *et al.*[35]	Fixed landscape	Representative, theoretical plots	Y	N	Natural disturbances (wildfire, insects)	LANDCARB
Böttcher *et al.*[48]	Dynamic landscape	Forest inventory data of the European Union (except Cyprus, Greece, Malta)	N	N	EU energy demand as under current policies Additional policies from April to December 2009 including an achievement of the targets set by 2009/28/EC and 2009/406/EC	G4M,EFISCEN, GLOBIOM
McKechnie *et al.*[33]	Dynamic landscape	Geospatially explicit (Ontario, Canada)	Y	Y	Decay of harvest residues + coal electricity Decay of harvest residues + mineral oil fuel Protection (natural disturbances) + coal electricity Protection (natural disturbances) + mineral oil fuel	FORCARB-ON
Ter-Mikaelian *et al.*[25]	Dynamic landscape	Geospatially explicit (Ontario, Canada)	Y	Y	Protection (natural disturbances) + coal electricity	FORCARB-ON
Bernier and Paré[18]	Fixed landscape	Empirical carbon flux data	Y	Y	Protection + oil heating	Chronosequence of flux-net data
Holtsmark[21]	Fixed landscape	Representative, theoretical plots	Y	N	BAU (timber only harvest) + coal electricity BAU (timber only harvest) + fossil fuel transport	Statistics Norway internal
Repo *et al.*[23]	Fixed landscape	Representative, theoretical plots	Y	Y	BAU (timber only harvest), decay of residues + fossil fuel based electricity	Yasso07
Repo *et al.*[24]	Fixed landscape	Representative, theoretical plots	Y	Y	BAU (timber only harvest), decay of residues + fossil fuel based electricity	Yasso07

Northern Hemisphere toward countries in Latin America and South-East Asia.[52]

Scenario assumptions and model parameterization

The variations between studies with respect to their assumptions are not shortcomings or methodological differences per se. They are rather a reflection of the large differences in possible scenarios, i.e. feedstock options, plant species, and climatic zones among others.

Life-cycle emissions

A full accounting of additional fossil fuel emissions along the respective value chains appears to be a necessary part of temporal carbon analysis from a methodological viewpoint as they may influence carbon payback and parity times. This was noted, for example, by McKechnie *et al.*[33] regarding the amount and type of energy they assumed for drying feedstock and pelletization. Most current studies account for life-cycle emissions; either via generic, theoretical values[22–24,53] or a more sophisticated life-cycle analysis of individual supply chains.[29,30,33]

Post-harvest carbon flows

Post-harvest carbon scenarios are largely influenced by the assumed conversion efficiencies and the postulated fossil fuel replaced, i.e. the respective fossil fuel baseline. Where no specific value chain is investigated (e.g. hard coal substitution by wood pellets [29,30,33]) temporal carbon studies typically calculate payback and parity times against varying fossil fuel baselines.[23,24,53]

In addition to the conversion efficiency and fossil fuel displacement factors, carbon flows for harvested wood products are also determined by their emission pathway, i.e. the calculated timing of carbon emissions resulting from a temporary storage of carbon in wood products and landfills.[54] The carbon stored in products varies significantly over time. Ingerson[55] argues that sequestration benefits should only apply to shares still stored 100 years after harvesting and processing. Most studies though apply the UNFCCC carbon accounting rule which deducts carbon storage over time depending on the product's expected lifespan. Carbon sequestration rates in landfills vary by world region[54] but are usually multiple times larger than carbon stored in wood products[56]. In the EU though, this sequestration option may become less relevant in the future since landfilling is currently discussed to be phased out completely.

Some carbon studies have provided regionally specific substitution factors and related sensitivity analyses.[30] New research in this area has shown however that displacement factors for carbon stored in wood products may be lower than commonly assumed[57]. Such findings would need to be incorporated in future research.

Baseline construction

Most temporal carbon studies apply two forest baselines. The first is a continued extraction of timber (business-as-usual: BAU) without biomass outtake for energy but fossil fuel energy generation (Table 2). The fossil fuel reference system varies with the fuel bioenergy is assumed to replace. Here, substitution assumptions vary from wood pellets replacing coal based electricity to cellulosic ethanol displacing mineral oil based transport fuel. The choice of the fossil reference system and conversion efficiencies of the selected chains obviously influence the respective payback times dramatically (as sensitivity analyses[30,43,58] show). That is why some studies[23,24,53] construct several fossil reference cases.

The second most common forest baseline is land conservation where harvesting (with a certain share for bioenergy) is compared to forest protection. From a nature conservation and carbon strategy evaluation perspective, this is a valid option. The reference scenario is however less straight forward to define for intensive even-aged forestry,[59] i.e. plantations. Here, protection seems rather unlikely and, in the absence of fiber demand for material (e.g. pulp or timber) or energy purposes, other options such as conversion to agriculture or urban development may be more realistic alternatives with respective consequences for forest carbon stocks. Also, depending on the biome, forest protection implies exposure to natural disturbances, such as wildfires, droughts, or insect infestations. While wildfires have been studied and return rates are often included in the modeling,[30,33,35] droughts, insect outbreaks, and other related climate change impact factors on forest are much harder to predict and model[†]; though may have severe carbon implications. Depending on the production system, forest protection is a valid reference, though many studies still miss a full demand-supply accounting (exceptions include MANOMET[15], Galik and Abt[60] and BERC [61]), and thus neglect potential displacement effects. Not only does this imply a higher usage of fossil fuels but also, where bioenergy

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[†] An in-depth discussion of this issue goes beyond the scope of this paper. The aspect though can be exemplified by the expected but not yet occurred spruce budworm outbreak in Eastern Canada. At the same time, the still prevalent forest damage and carbon release from Mountain Pine Beetle infestation across British Columbia has not been foreseen at this scale but still affects the total forest carbon balance of Canada.

is a co-product of timber harvesting, the compensation of lumber volumes from other world regions, or the use of other materials such as steel or concrete instead of wood, including respective carbon implications. At the same time, forest protection assumptions postulate that the carbon and thus the land will not be used for human economic activities for centuries; an assumption generally questionable in our land-constrained world.

Biomass type and forest biome

Current temporal carbon analyses within the carbon debt discussion have largely focused on forest biomass, in particular residues (from harvesting and/or processing) and roundwood. The forest biomes covered in contemporary carbon analysis are primarily (sub-) boreal. Due to the impact either choice has on the modeling outcome, we evaluate these items in detail in the following section.

The range of carbon parity times

Study selection

Due to the aforementioned modeling choices and scenario assumptions, the study range found in literature is not directly comparable without prior grouping. Here, we first limited the selection to studies on (fixed and dynamic) landscape level, as we believe this is more representative of real-life harvesting practices. Following, we distinguish by woody biomass type harvested/collected to generate energy. Here, we separate between roundwood/stemwood (or whole-trees) and residues, due to the respective carbon (outtake) volumes associated with either feedstock. It is important to stress that apart from the large difference in carbon volume, the two segments, in particular whole-tree and residue removal, may have different other environmental impacts, for example, onsite productivity due to nutrient removal (more prevalent in foliage). The third cut is made by forest biome and reference scenario. Apart from Cherubini *et al.*,[19] who also modeled fast growing, tropical species (though did not cover post-harvest carbon cycling), the literature range can be separated into temperate southern, sub-boreal/temperate northern, and boreal forests. Within these, attention needs to be paid to the assumed initial forest age, land-use or management regime change, and rotation cycle as all factors strongly influence the initial carbon stock prior to harvest, eventually defining the carbon debt.

Residues/Slash

Parity times for residues (Table 2) mostly vary depending on the respective fossil fuel used in the reference scenario, as the biogenic reference is always carbon release back into the atmosphere, either via decay or burning. The second most important influencing factor for natural decay scenarios is the size/diameter of the residue and the forest biome, i.e. conditions affecting the decay rate. The range of parity times within the two sub-boreal studies[30,53] falls within those for small diameter residues in boreal forests.[23,24] The shortest times were found for processing and harvesting residues which would otherwise be burnt at the factory or roadside respectively. Here, the direct carbon release in the reference case causes an immediate carbon benefit and a net zero parity time.[30] The longest parity times were for stump harvest in boreal forests (of northern Finland) when compared to natural decay and natural gas based electricity generation.[23]

(low-grade) Stem-/roundwood

Roundwood related parity times (Table 2) vary to some degree by forest biome with significantly shorter periods for highly productive regions, such as the temperate moist forests of the South-Eastern USA. Parity times against site protection or continued timber harvest with fossil fuel reference (BAU) are at maximum 50 years for these conditions.[29,61] In the (sub-) boreal region, parity times against forest protection (and fossil fuel energy generation) are about twice as large but variations between studies,[18,25,30,33] mostly linked to forest management and reference case assumptions, exist. Under specific conditions, as for example, those in British Columbia where insect infestation has killed a large amount of merchantable timber stock, bioenergy harvest can reach parity times as low a zero.[30] Here, a high share of naturally decaying tree biomass in the protection reference shortens parity times, unless the disturbed forest regenerates quickly. Parity times against regular timber harvest (BAU) vary greatly with the fossil fuel reference, the shortest being coal and oil compared to natural gas. The forest management regime influences parity times in the sense that the harvest intensity (or outtake level) needs to be adapted to the respective biome and site productivity in order not to exceed sustainable yield levels. Shortening rotation times or increasing the amount of fellings in less productive regions, for example, the boreal forest biome, increases parity times to several centuries.[21,53] Afforestation on the other hand has a parity time of zero years given that the land would not be sequestering large amounts of carbon otherwise.

Discussion and conclusion

Key influencing factors

Differences in the modeling framework and parameterization are the main distinctions between current temporal

Table 2. Carbon parity times for different biomass types by biome and reference case.

Biomass type	Biome: reference case	Min	Max	Studies: forest management regime
Residues/ Slash[a]	(Sub-) Boreal: BAU + coal based electricity	0	16	[23,24,30,33,53]: collection instead of slash-burn or decay
	(Sub-) Boreal: BAU + oil based electricity	3	24	[23,24,53]: collection instead of decay
	(Sub-) Boreal: BAU + natural gas based electricity	4	44	[23,24,53]: collection instead of decay
(low-grade) Roundwood[b]	Temperate southern: Protection[c] + coal electricity	12	46	[29]: thinnings and additional fellings on existing plantations (20-25 year rotation)
	Temperate southern: BAU + fossil electricity mix	35	50	[61]: thinnings and additional fellings on existing plantations (35 year rotation)
	(Sub-) Boreal: Protection + coal electricity	0	105	[25,30,33]: additional fellings in previously unmanaged forest
	(Sub-) Boreal: Protection + oil heating	90		[18]: additional fellings in previously unmanaged forest
	(Sub-) Boreal: BAU + coal electricity	53	230	[21,30,53]: additional fellings in previously un-/managed forest
	(Sub-) Boreal: BAU + coal electricity	17	114	[53]: clear-cut replaced with SRC[d] (10-20 year rotation)
	(Sub-) Boreal: BAU + oil electricity	20	145	[53]: clear-cut replaced with SRC[d] (10-20 year rotation)
	(Sub-) Boreal: BAU + natural gas electricity	25	197	[53]: clear-cut replaced with SRC[d] (10-20 year rotation)
	(Sub-) Boreal: BAU + natural gas electricity	300	400	[53]: additional fellings in managed forests
	(Sub-) Boreal: BAU + fossil electricity	0	0	[53]: afforestation

Applied definitions:

[a] Slash: residues from timber harvesting including tops and branches (possibly also stumps in the case of Finland and parts of Sweden) of harvested/merchantable trees, whole non-merchantable trees (e.g. standing, cracked deadwood).

[b] Dedicated removal/harvest of round-/stemwood for energy will foremost target low-grade timber fractions (e.g. pulpwood). It is highly unlikely that sawlog quality stemwood systematically ends up as bioenergy feedstock. Low-grade timber harvest typically includes operations such as:

Thinnings: pre-/commercial cutting of selected rows/individual trees to allow a stronger growth of remaining trees.

Additional fellings: increased harvesting intensity in a defined region i.e. higher biomass outtake than under a BAU scenario (i.e. timber harvest).

[c] 'Protection' equals no harvest.

[d] SRC: Short rotation coppice (dedicated energy plantation) with a high (10 year) and low (20 year) productivity .

forest carbon analyses. Across these studies however, there is a set of key factors that influence carbon payback and parity times (Table 3).

Pre-harvest

First and foremost, we need to consider the carbon volume sequestered in the living plant stock prior to harvest. This is directly connected to prior land-use and forest management regimes in the specific case of woody biomass. If land-use change is assumed to occur or can be linked to the bioenergy system, respective carbon emissions, for example, from peatland drainage for plantation set-up, can jeopardize any temporal carbon savings.[8,9,62] Land-use change however can also have positive effects in the case of afforestation.[10] The most important pre-harvest, general condition influencing the carbon payback/parity times is the plant growth rate, which in turn is determined by the biome, site productivity, tree species, and management regime. Carbon payback/parity times tend to be shorter for intense (e.g. plantations) compared to extensive silvicultural regimes (e.g. natural regeneration).[25] At the same time, a change in forest management regime, for example, the shortening of rotation cycles can possibly alter age structures in a forest landscape which eventually reduces the temporal carbon storage and may lead to longer payback/parity periods for bioenergy scenarios.[14,18,32,35] The management regime should thus be adapted to the respective site conditions.

Harvest

Second, the type of harvested woody biomass used has a dramatic effect on the payback and parity times. This is foremost linked to the size and sequestered carbon volume in the biomass[23,24] and the respective counterfactual, i.e. what happens without biomass for energy harvest. Thus, the collection of residues from existing timber operations provides material which would have released its carbon (via decay or burning) back to the atmosphere anyway (over time spans defined by the biome's decay rate) while green

Table 3. Key influencing factors on carbon payback/parity times.

Key influencing factor	Increasing carbon payback/parity time (from left to right)		
Land-use/ -management	Change involving carbon uptake (e.g. afforestation)		Change involving carbon release (e.g. peatland drainage)
Silvicultural regime[59]	Intensive even-aged forestry (e.g. dedicated replanting with highly productive seeds, fertilization, etc.)		Extensive, close-to-nature forestry (e.g. natural regeneration)
Plant growth rate	High (e.g. tropical)	Medium (e.g. temperate)	Low (e.g. boreal)
Carbon content of harvested biomass	Low (e.g. branches)	Medium (e.g. stumps)	High (e.g. stems)
Harvest share of living biomass	Low (e.g. higher deadwood share)	Medium	High (e.g. green tree harvest)
Harvesting intensity	Low (e.g. residues only)	Medium	High (e.g. whole-trees)
Fossil fuel conversion efficiency reference	Low (e.g. old coal power plant)	Medium	High (e.g. new gas CHP plant)
Biomass to energy conversion efficiency	High	Medium	Low
Carbon intensity of substituted fossil fuel	High (e.g. coal)	Medium (e.g. oil)	Low (e.g. natural gas)
Share of otherwise decaying biomass	High	Medium	Low

tree harvest reduces the pool of living and thus future carbon stocks. In this regard, the volume of deadwood assumed to be present in the baseline can have a dramatic effect on payback/parity times. Simulations for varying degrees of insect infested forests[30] revealed that sites with a higher kill rate (of previously living forests) have a much slower regeneration back to previous carbon levels, and thereby may become a net source of carbon over several decades.[63,64]

Post-harvest

The third group of assumptions concerns post-harvest carbon cycling. In line with early sensitivity analyses,[42,58] we find that influencing factors largely include the efficiency of the biomass to energy conversion chain, the amount of additional fossil fuel emissions, and whether or not carbon storage in landfills (with or without methane capture/flaring) is accounted for. Regarding the baseline construction, carbon emission rates and the efficiency of the respective products and fossil energy replaced are the most important variables.

Current range of main uncertainties and requirements for future research

Soil carbon dynamics

Soil carbon dynamics are complex and little empirical data is available from long-term field-tests regarding woody biomass for energy harvest in forests.[65,66] Of major relevance is the amount of biogenic carbon from residue material (harvest residues) sequestered within the soil over time (from instable above- and belowground to stable belowground carbon pools) and whether stable carbon pools (mineral soil carbon) are potentially disturbed and reduced due to harvest. On the latter point, some studies suggest,[39] that soil carbon stocks decline but stabilize over longer time due to intensified harvest. Error margins though could dramatically affect payback/parity times due to the sheer size of soil carbon stocks in boreal forests. Further research is needed to reduce such uncertainties.

Reference fossil fuel

A coherent approach should be followed for the choice of the reference (fossil) fuel. Three basic options exist:

(1) Substitution (de facto fuel substitution, e.g. co-firing wood pellets in coal power plants).
(2) Replacement of the average energy mix (as proposed e.g. by the European Commission).
(3) Replacement of the marginal energy production technology (along the merit-order) that would have been used/built had biomass not been used for energy (e.g. a modern natural-gas-fueled combined-cycle plant).

So far, all studies also assume constant conversion efficiencies of the fossil reference system. Given the often long payback times of the bioenergy systems investigated, this causes additional uncertainty. It is widely believed that, for example, fossil fuel electricity generation will become more efficient and the penetration of other renewable energy sources will continue lowering the average GHG emission per kWh. On the other hand, the conversion of biomass to electricity is also likely to become more efficient, and could potentially even be connected to carbon capture and storage (Bio-CCS). Biomass is expected to be used in various conversion processes than solely electricity and heat generation in the future. While first analysis on the temporal carbon balance of, for example, lignocellulosic ethanol exist[33] more research will be needed in this area.

Counterfactual definition and market dynamics

Thorough analysis has to be spent on defining the most likely, i.e. realistic counterfactual to (no) bioenergy harvest including an accounting for potential displacement effects. Bioenergy systems are typically connected to existing forestry industries (whether previously unmanaged or managed forest is used).[28] Thus bioenergy extraction takes place within existing demand-supply patterns for other woody biomass products (primarily timber and cellulose). Forest protection is – for example, from a nature conservancy viewpoint – a valid baseline case. It would have to be evaluated holistically however, i.e. include carbon emissions from displacement effects (e.g. land-use change in other world regions) and socio-economic consequences. Required research to establish most realistic baseline scenarios include for example an analysis of macro-economic drivers for additional land-use, possibly linked to spatially-explicit analysis where this is most likely to occur (e.g. based on limitations such as required logistic infrastructure, price and suitability of land, etc., as done by Verstegen *et al.*[67]).

Along these lines, as a first step, we recommend linking temporal carbon research with fiber market data and thus to current sourcing practices and economic bioenergy potentials. The vast majority of wood pellets imported to Europe for co-firing are based on processing and harvesting residues with an increasing though still minor share from low-grade roundwood.[27,28] Generally, the higher economic value for timber and cellulose products makes large-scale use of whole-trees for energy purposes highly unlikely wherever there is regional competition for the fiber.[68] At the same time, the technical potential of harvesting residues is high in many of the world's 'fiber-baskets', and is thus more likely to be used as feedstock when process-based wood waste streams become scarce.

Lessons for policymakers

The debate of the carbon consequences of bioenergy has highlighted the importance of considering time scales when comparing alternative energy supply and GHG mitigation options. Forest bioenergy is a case in point as short-term renewable energy consumption targets, for example, by the European Union (EU) for 2020,[69] may have climate effects beyond these timescales. Integrating forest biomass into these seemingly conflicting targets is not straight forward. A first step for policymakers could be to decide whether bioenergy should contribute to short- or long-term emission savings. As the reviewed studies show, the majority of options investigated indicate a possibility to achieve emission reductions in the long-term. While these strategies would involve a short-term biogenic carbon pulse, the emitted carbon would be (re-) sequestered via plant growth within a tree life-span. 2050 and 2100 are often used as carbon level reference points; also in relation to bioenergy.[70,71] Since energy systems, fossil and bioenergy, have lifetimes of typically 20 to 30 years, we deem 2050 as the better alternative for policy choices regarding bioenergy.

There are also a number of feedstock options which offer (almost) immediate net carbon benefits, provided they substitute GHG intensive fossil fuels. These include the use of (i) harvesting or processing residues,[23,24,30,33,53,72] (ii) standing deadwood from highly insect-infected sites,[30] and (iii) new plantations on highly productive or marginal/previously unused (and carbon poor) land.[29,53] Previously, such options were coined 'additional carbon',[3] i.e. biomass which either grows in excess to current volumes (e.g. yield increases on existing plantations) or whose carbon would have been released back into the atmosphere relatively rapidly anyway (e.g. via decay). None of these options however can be seen as a silver bullet as their overall climate mitigation potential is determined by the effectiveness of their fossil fuel displacement. We deem it therefore unsuitable to define political guidance (e.g. support measures or exclusions) by feedstock alone. There always needs to be an accounting of the fossil fuel and regional forest carbon reference.

The continued import dependency of the EU regarding woody biomass for energy, in particular wood pellets for large-scale co- and mono-firing, makes the current debate on the temporal carbon balance of bioenergy particularly relevant for European policy makers. We think the discussion so far suppresses that current wood pellet import streams are predominantly residue based while (low-grade) roundwood still plays a marginal role.[27,28,73] Yet many temporal carbon analyses focused on whole-tree harvesting in (sub-) boreal regions. Future EU import streams will likely continue to be dominated by North America,[74] especially from the South-East USA where an increasing share is based on pulp-grade plantation roundwood from the temperate southern forest biome. The wood fiber demand increase for pellet production in this region however coincides with a steady downturn of the US forest products sector (since 2006)[75] and a regional oversupply of pulp-grade roundwood. This highlights the importance of putting temporal carbon balances into regional market perspectives when defining future policy measures.

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