Focus Article

# The climate effect of increased forest bioenergy use in Sweden: evaluation at different spatial and temporal scales

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Bioenergy from boreal forests managed for productive purposes (e.g., pulp, timber) is commonly held to offer attractive options for climate change mitigation. However, this view has been challenged in recent years. Carbon balances, cumulative radiative forcing, and average global temperature change have been calculated for a variety of bioenergy management regimes in Swedish forests, and the results support the view that an increased use of forest biomass for energy in Sweden can contribute to climate change mitigation, although methodological (e.g., spatial scales) and parameter value choices influence the results significantly. We show that the climate effect of forest-based bioenergy depends on the forest ecosystems and management, including biomass extraction for bioenergy and other products, and how this management changes in response to anticipated market demands; and on the energy system effects, which determine the fossil carbon displacement and other greenhouse gas (GHG) mitigation effects of using forest biomass for bioenergy and other purposes. The public and private sectors are advised to consider information from comprehensive analyses that provide insights about energy and forest systems in the context of evolving forest product markets, alternative policy options, and energy technology pathways in their decision-making processes.


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## INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) reports that the anthropogenic increase in greenhouse gas (GHG) concentrations in the atmosphere is very likely the cause of more than half of the increase in global average surface temperature. For a likely chance of keeping the temperature increase over the preindustrial to below 2°C, the IPCC finds that global GHG emissions should be reduced by 40–70% by mid-century compared with 2010, and to near-zero by the end of the century.[1] Strategies to abate GHG emissions include shifts away from fossil fuels, forest protection, and promotion of carbon (C) sinks, e.g., sequestration and storage of atmospheric C in the biosphere, i.e., vegetation and soils.

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It has long been recognized that biomass removal—to provide bioenergy, or for any other purpose—influences biospheric C stocks on the land from which the biomass is removed.[2] The size and temporal dynamics of such C stock changes [i.e., the biosphere–atmosphere carbon dioxide ($CO_2$) flows] have been researched since the 90s[3,4] to clarify the implications of bioenergy (and terrestrial carbon sinks) with respect to climate change mitigation[5–7] and to explore options for crediting/taxing land users for increasing/reducing C stocks.[8,9] Biospheric C stock changes were considered in some early life cycle analyses,[10,11] but many of them have relied on the assumption that bioenergy systems can be considered 'C neutral' and have therefore ignored the biosphere–atmosphere $CO_2$ flows. Based on this assumption, forest bioenergy systems have commonly been recognized as effective options for replacing fossil fuels and reducing GHG emissions in the energy sector.

However, in recent years the assumption about C neutrality has been questioned, and different approaches for considering biosphere–atmosphere $CO_2$ flows have been put forward (see, e.g., Ref 12). The concept 'C debt' was originally introduced by Ref 13 to illustrate $CO_2$ emissions associated with land-use change for the cultivation of biofuel feedstock. But the concept has also been applied in studies of long-rotation forestry systems, where the temporal pattern of C fluxes differs substantially for bioenergy/regrowth compared with decomposition/regrowth (for an overview, see Ref 14). Several of these studies adopt a single-stand perspective[15] and commonly also start the accounting from when biomass is removed from the stand and used for energy.[16–19] Other studies question the validity of this approach, arguing that the whole forest production landscape has to be considered and finding that GHG benefits can be immediate or delayed, depending on, for example, the structure of the forest (e.g., age structure and tree species), interaction with other forest product industries, and the changes in forest management that may be implemented in response to increased bioenergy demand.[20] Estimates of the climate impact of bioenergy are highly sensitive to the assumed counterfactual (reference) scenario without bioenergy,[21] and using several counterfactual scenarios is therefore recommended.[22] All in all, evaluations of the climate effect of forest bioenergy diverge on methodological approach, including spatial system boundaries and chosen reference scenario(s).

In addition to quantifying C balances, studies have used a variety of metrics to analyze the climate effects of forest bioenergy systems. For example, Refs 23 and 24 use cumulative radiative forcing (CRF) to quantify the warming effect of using slash (tops and branches) and stumps for energy purposes, and Ref 25 also uses global average surface temperature for the same purpose. Ref 26 discusses the use of different metrics based on radiative forcing (RF) and the absolute global temperature change potential (AGTP) for pulse emissions and sustained emissions for a variety of biofuels. All these studies are at the level of the forest stand, and only Ref 24 evaluates the climate response to changes in forest management.

This paper aims to: (1) describe common methodological choices and assumptions in assessments of GHG balances for bioenergy systems that use biomass from long-rotation forestry as feedstock; (2) clarify how these choices and assumptions influence assessment outcomes; and (3) discuss the GHG and associated climate effects of increasing forest harvest for energy use. To support this, Swedish forest-based bioenergy systems under different management regimes were modeled to quantify and compare climate effects. The results are presented in terms of C balances, CRF, and global mean temperature change ($\Delta T$) (see Box 1). Carbon storage and GHG emissions, i.e., $CO_2$, $N_2O$, and $CH_4$, associated with wood products, bioenergy, and alternative fossil fuel supply chains are considered when calculating CRF and $\Delta T$, but other climate forcers, such as albedo, black and organic carbon aerosols, and ozone precursors, are outside the scope of this paper. These climate forcers can influence the climate effect of bioenergy systems significantly, but they have seldom been considered in scientific publications that concern the climate effect of bioenergy systems that use biomass from long-rotation forestry as feedstock. Significant albedo changes can occur when bioenergy systems are associated with distinct land cover change, such as deforestation to establish energy crop cultivation or afforestation of agriculture land. The bioenergy systems considered in this paper are not associated with such land cover changes but rather with changes in the utilization of biomass flows within existing forest ecosystems.

## ASSESSMENTS AND MODELS

A framework (Figure 1) is used to assess and describe the C balance and the GHG-mediated climate effect of using biomass from long-rotation forestry for energy in Sweden. The core of the framework consists of two linked assessments, i.e., a forest and a forest product assessment (see sections below) that are used to quantify the biospheric and fossil C balances associated with forest management and forest product flows (including bioenergy products) up to (and including)

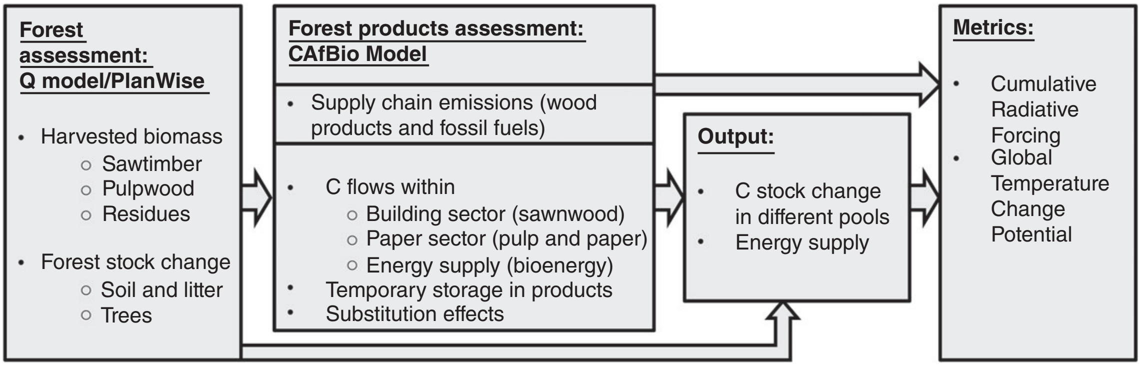


**FIGURE 1** | Model description.

the point when the C in the products is oxidized and released as $CO_2$ into the atmosphere.

The model output is used to quantify, on an annual basis, (1) the C stored in the forest (trees and soil), forest products, and atmosphere pools; (2) the C emissions associated with changes in these C pools; and (3) the avoided emissions of fossil C. In addition, the supply chain emissions for wood products and fossil fuels are added so that GHG emissions can be obtained. Results are presented as C stock changes in the different pools, i.e., in forest products, soil, trees, and in fossil fuels displaced due to the biomass use. Based on the annual volumes of $CO_2$ emitted to the atmosphere and other non-$CO_2$ GHG emissions, CRF and AGTP are calculated following recommendations in Supplementary Material Section 8.SM.11 in the IPCC Fifth Assessment Report.[27] The climate metrics are presented in Box 1.

## Forests and Their Management

Assessments of forest ecosystem C dynamics are done at two different spatial scales: the stand level and the landscape level. The forest stand level represents the scale at which forest operations are conducted, and the forest landscape level is the scale at which forest management across a mosaic of forest stands is coordinated to supply a continuous flow of forest products. For the latter, we make a distinction between a theoretical landscape, which is constructed by combining identical stands of different ages, and a real landscape. We use the Q model[28] for assessments of forest stands and theoretical landscapes, and the model PlanWise[29] for assessments of real forest landscapes. The outputs from these models (i.e., the C in harvested biomass and interannual changes in C stock in soil, litter, and tree biomass) are accounted for, and the C in harvested biomass is used as input data for the CAfBio model, see *the CAfBio model* section.

### *Stand Approach (the Q Model)*

The version of the Q model[28] used in this paper consists of a stand-level basal area growth model that responds to climate conditions and specified management practices. The predicted basal area is converted into tree biomass fractions (needles, branches, stems, and stump-coarse root system) by using the Marklund allometric functions.[30] Litter is continuously formed from needles and branches as well as from stems and stumps generated at forest thinning and final harvest. A decomposition model based on the continuous-quality concept[31] is used to calculate the C in litter, which is allocated to a subsystem of the soil organic matter pool.[32]

The forest stand is modeled as an even-aged stand established by planting seedlings: the model accounts for all C flows on an annual basis, starting with regeneration and including three thinning events before final harvest, when the stand is clear-cut and regenerated. The C flow evaluation is initiated at the time trees are established after a final harvest event, in order to capture the effect of management on forest growth. The C stock in soil and litter at time zero is determined by the prior forest management. If a new forest management practice is introduced, the final harvest and the C stock in soil and litter at the end of the rotation period are the result of the new management. The time scale used in these assessments is 300 years, which corresponds to three rotation periods for the forest stand.

### *Theoretical Landscape Approach (the Q Model)*

The stand-level results from the Q model are used to build a theoretical forest landscape by combining time-shifted single stands to obtain a uniform age distribution at the landscape level. The landscape is assumed to have a homogeneous site quality, i.e., stands that are subject to the same management have identical growth development. The number of stands is equal to the length of the rotation period, i.e., 100

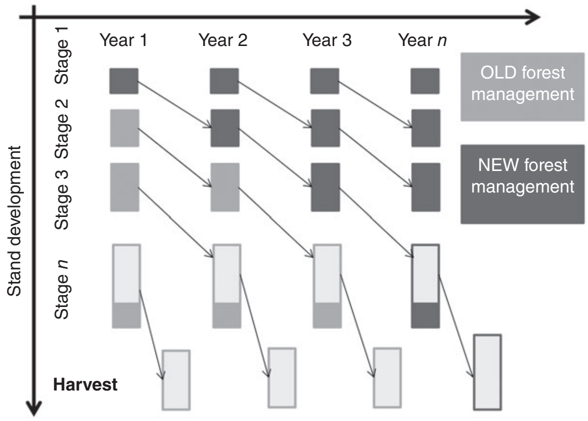


**FIGURE 2 |** Conversion from one forest management regime to a new one in the forest landscape.

years, and each year the oldest stand is harvested and becomes a newly planted re-growing stand in the subsequent year. The annual harvest is equal to the annual growth, i.e., the managed forest is harvested on a sustained-yield basis, and the C stock in the forest landscape is stable.[32]

The introduction of a new management practice that affects forest growth is modeled by assigning a different growth profile to a forest stand in the year it is replanted. During a time period corresponding to the rotation period of a stand, the forest landscape goes through a transition toward a new state characterized by the new forest management. This is illustrated in Figure 2; each year one new stand is regenerated and becomes subject to the new forest management, until the last stand has been felled and replanted under the new forest management regime. After the full rotation period, the forest landscape reaches a new equilibrium and the annual removal is equal to the annual growth again.

### *Real Landscapes (PlanWise and the Heureka Suite)*

PlanWise is an optimizing application in the Heureka suite, a forest analysis and planning system that is used both for university research and for long-term forest management planning in the forest industry (e.g., evaluation of management systems and strategies, scenario analysis, and inventory).[29] Heureka provides multi-objective analyses supporting the planning of forest management over large areas with heterogeneous stands and differing management objectives. It can be used to make short- and long-term projections relating to timber production, economics, environmental conservation, recreation, and carbon sequestration. The basis of Heureka is tree growth under different forest management systems, ranging from no management to intensive even-aged forestry, in different forests types and structures. Several submodels are used to estimate growth projections, management responses, recreational values, C sequestration, and habitat suitability. Heureka simulates forest management practices (e.g., thinning, harvesting, fertilization, genetically improved regeneration stock) as determined by, e.g., the interest rate, the specified goal function, and even feedstock flow constraints.

PlanWise has a core of empirical growth and yield models (stand and individual tree growth), which are based on Swedish National Forest Inventory data and validation in long-term experimental plots.[33] It includes in-growth, i.e., seedling establishment under the canopy[34] and natural mortality, the latter providing a flow of biomass to the dead wood pool where decay functions transfer the dead wood between decay classes.[35] The mortality level depends on stand age, tree species, number of stems and site index.

For this study, PlanWise is used to illustrate how forest conditions and management can influence the outcome in three real forest landscapes. Management alternatives consisting of a sequence of silvicultural and harvest activities are generated to mimic forest management across landscapes by profit-driven forest companies in the region. The assessments made in this paper cover 100 years, with rotation periods of varying length depending on stand and site conditions.

## Forest Products

### *The CAfBio Model*

The CAfBio model is used to model the flows of biomass C within the forest industry and society where the forest products are used. CAfBio accounts for the C in harvested biomass obtained as output from the Q model or PlanWise. The harvested biomass in CAfBio is allocated to the production of sawnwood, wood-based panels, and paper (designated harvested wood products, HWP), and bioenergy products. CAfBio takes into account the losses in the production processes so the amount of C that ends up in HWP and bioenergy products can be quantified correctly. The model considers the climate mitigation benefit of C sequestration and temporary storage in HWP. The residence time for C in the HWP pool is modeled using the gamma decay function described in Ref 36. Once a product in the HWP pool has lasted the specified service lifetime, it can be incinerated, recycled, or landfilled. If recycled or placed in landfill, the C in a product will remain outside the atmosphere, whereas the C is transferred directly to the atmosphere as $CO_2$ in case of incineration (see next section). The CAfBio model also considers the supply chain GHG emissions for wood products and fossil fuels, as well as the fossil C displacement effects of wood product use, taking into account incineration of wood products at the end of the service lifetime.

### *Characteristics of Forest Sectors*

Harvest biomass flows are accounted for in terms of volume and C, using the conversion factor 206 kg C $m^{-3}$ wood.[37] Carbon and volume flows are estimated for the different forest products. Stemwood consists of two different wood qualities: sawtimber and pulpwood. Data related to sawnwood, pulp and paper, and bioenergy are presented below. Most of the Swedish sawnwood and paper production is consumed abroad and C displacement effects associated with HWP vary from country to country. However, as the reference and almost all bioenergy-adapted scenarios (exception are BIO2+s and BIO_City) were defined to be identical concerning HWP, i.e., the associated C flows cancel out when the net effects are calculated, the HWP systems could be characterized based on data for Sweden only. The effects of not considering HWP exports when the BIO2+s and BIO_City scenarios are analyzed are discussed in the *Results and Discussion* section.

All harvested sawtimber is processed in Swedish sawmills. Sawmill flows are set based on data from Swedish Statistical Yearbook of Forestry 2011.[37] Both sawnwood products (representing 44% of the total C input) and by-products are considered: chips (25.5%) are used in the pulp and paper industry, sawdust (1.5%) is used in the production of board and bioenergy products. Some of the bark (6%)—assumed to be 10% of the volume of the tree—is used for internal energy purposes[38] and the rest (23%) is used in a biomass district heating plant—a combined heat and power plant (CHP) with an overall efficiency of 85% (calculated on lower calorific value for dry matter ($LHV_{DM}$) based on Ref 39) and a power-to-heat ratio of 0.37.[39] Supply chain emissions are based on Ecoinvent 2.0[40] and calculated with the GABI software.[41]

All harvested pulpwood is processed in Swedish pulp and paper mills, which also use by-products from saw mills (10.4% of the total biomass inflow to pulp and paper mills).[37] The biomass flows in the pulp and paper industry are set based on data from the Swedish Forest Agency,[37] assuming 70% and 30% shares for chemical and mechanical pulp, respectively. All C in the wood entering the mechanical pulp process ends up in the paper. All bark and all process by-products generated in the chemical pulp process (black liquor and lignin) are used for internal process energy purposes.[38] As a result of these assumptions, 68% of the C in pulpwood ends up in paper products and the remaining 32% is immediately released to the atmosphere associated with the internal use for process energy.

As mentioned earlier, the forest product flows are defined based on data for Sweden, which means that almost all products are incinerated to produce energy after their end of life. Only 1% of the sawnwood products and 0.5% of the paper products are assumed to be placed in landfill[42] [methane correction factor (MCF) of 0.95 and degradable organic carbon (DOC) of 0.5].[36] Sawtimber mass and heating values are calculated using conversion factors from the Swedish Forest Agency.[37]Wood products and residues from production are incinerated in a biomass CHP district heating plant similar to as described above. The C stored in paper products is assigned a storage time profile according to a gamma decay function.[36] For paper incineration, an average heating value of 16 MJ $kg^{-1}$ dry basis is assumed.[43] Paper is incinerated in a waste CHP plant with an overall efficiency of 85% (calculated on $LHV_{DM}$ based on Ref 39), and the power-to-heat ratio is 0.23.[39]

Slash, stumps, and the extra stemwood harvested in the ‘intensification’ and the ‘bioenergy-adapted forestry’ scenarios (see next section) are used for bioenergy. Note that ‘bioenergy’ here does not include the above-described energy use of the wood products at end of service life or the industrial residues associated with their production. Consequently, the emissions associated with the production, use, and end-of-life management of these wood products are included in the respective product category. Average $LHV_{DM}$ for wood fuels is 19 MJ $kg^{-1}$ (the density is 0.42 Mg DM $m^{-3}$).[37] GHG emissions related to extraction, production, and transportation for wood chips from slash and stumps are based on Ref 44. The biomass for energy is assumed to be used in a biomass CHP district heating plant similar to as described above.

## Scenarios

The forest scenarios generated with the Q model (Table 1, see Ref 32) are representative for Norway spruce (*Picea abies* (L.) Karst) stands in Southern Sweden (Växjö; 56.87°N, 14.81°E), managed with a rotation period of 100 years and with an average forest production around 7 $m^3$ $ha^{-1}$ $year^{-1}$. The REF, BIO1, and BIO2 scenarios replicate Ref 32, while the forest productivity data in two intensification scenarios, BIO1+ and BIO2+, are modified to represent a situation where measures to promote growth result in 20% more biomass volume (stemwood and slash pools combined) at the end of the rotation period

**TABLE 1** | Forest Scenarios Generated with the Q Model

| Scenario | Harvest Level (Forest Products) |
|---|---|
| REF | Stemwood (sawtimber and pulpwood) |
| BIO1 | REF + 80% tops and branches (slash) in all thinnings and final harvest (bioenergy) |
| BIO2 | REF + BIO1 + 50% stumps in final harvest (bioenergy) |
| BIO1+ | As BIO1 but with enhanced growth: the difference in tree volume compared to BIO1 increases linearly over the rotation period to reach 20% in final felling (20% additional stemwood and slash are used for bioenergy) |
| BIO2+ | As BIO2 but with enhanced growth as in BIO1+ (bioenergy) |
| BIO2+s | As BIO2+ but with extra sawtimber production (20% additional stemwood is used in the sawmills and the rest for bioenergy) |

**TABLE 2** | Forest Scenarios Generated with PlanWise

| Scenario | Harvest Level (Forest Products) |
|---|---|
| REF_City[1] | Stemwood (sawtimber and pulpwood) and tops and branches (slash) in approximately 40% of the final harvest, in the respective City forest holding (bioenergy) |
| BIO_City[1] | As REF but with intensified extraction of slash: stemwood (sawtimber and pulpwood) and slash in approximately 45% of the thinnings and 60% of final harvest, in the respective city forest holding (bioenergy) |

[1] City: Skea, Skellefteå forest; Osund, Östersund forest; Gbg, Göteborg forest.

(Table 1). Neither data nor new runs with the Q model were available to support quantification of the soil C pool in BIO1+ and BIO2+. Soil C was therefore set to be the same as in BIO1 and BIO2. In reality, the soil C pool in BIO1+ and BIO2+ can be expected to be larger than in BIO1 and BIO2 due to more litter production in BIO1+ and BIO2+. Note that slash harvest is assumed not to affect forest growth patterns.

Forest scenarios generated with PlanWise are shown in Table 2 and described in Ref 45. Three authentic forest holdings were analyzed: 'Skea', in the Skellefteå area [64.5°N; 9,171 ha with an average of 121 $m^3$ $ha^{-1}$ dominated by Scots pine (*Pinus sylvestris* L.) and an average timber productivity potential of 3.7 $m^3$ $ha^{-1}$ $year^{-1}$], 'Osund', in the Östersund area (63.5°N; 1,712 ha with an average of 95 $m^3$ $ha^{-1}$ dominated by Norway spruce and an average timber productivity of 3.4 $m^3$ $ha^{-1}$ $year^{-1}$), and 'Gbg', in the Göteborg area [56°N; 4,216 ha with an average of 134 $m^3$ $ha^{-1}$ dominated by broadleaves (mainly birch, *Betula* ssp.) and an average forest production of 8.7 $m^3$ $ha^{-1}$ $year^{-1}$]. The reference scenarios (REF_City) simulate a 'business as usual' forestry where forest management is planned for sawtimber and pulpwood production and forest fuels are considered a by-flow associated with this production, which might be extracted if economic conditions allow, but not a relevant factor in management planning. The corresponding bioenergy-adapted forestry scenarios (BIO_City) simulate situations where the forest companies adapt their forest management to three assortments: sawtimber, pulpwood, and forest fuel, and consider these three are equally important. BIO_City scenarios include simulation of forest management activities that potentially enable intensified extraction of slash in all harvest activities (thinnings as well as final harvest).

Changes in forest management to produce more forest fuels are based on an integrated view of all forest products, aiming at the financially most beneficial outcome for the forest owner. The production of HWP in all BIO scenarios except BIO2+s and BIO_City is set equal to the HWP production level in the REF scenario. Thus, stemwood output in excess of that in REF in BIO1+ and BIO2+ is assumed to be used for bioenergy. In the BIO2+s and BIO_City scenarios, stemwood output in excess of that in REF is instead assumed to be used for production of sawtimber products. Obviously, stemwood used for bioenergy would not correspond to the burning of high-quality sawtimber, but it could for instance be realized by increasing the minimum top diameter for pulpwood to increase the output share going to bioenergy. The additional sawtimber products that are produced in BIO2+s and BIO_City are assumed to have the same fossil C displacement factor as other sawtimber products (see below).

The biomass that is used for energy is assumed to displace either a combination of coal-based heat boilers (efficiency 0.89[46]) and condensing power plants (efficiency 0.38[47]) or natural gas (NG)-based CHP plants [overall efficiency of 85% (LHV basis) and power-to-heat ratio of 0.67[39]]. The former can be said to represent a situation where existing nonintegrated coal-based heat and power generation is shut down and replaced with new biomass-based CHP, and the latter represents a situation where new biomass-based CHP is built instead of new gas-based CHP, either to replace old generation or to meet increasing energy demand. In the former case, 1.27 Mg of fossil C is displaced per Mg of C in biomass used and in the latter case, 0.55 Mg of fossil C is displaced per Mg of C in biomass used (obtained from conversion efficiencies and C density of the fuels, energy basis). Supply chain GHG emission factors of coal and NG are taken from Ref 48. The fossil C displacement factor associated with sawnwood use (displacing manufacture and use of GHG-intensive products) was set to 2.74 or 2.31 Mg C per Mg C in sawnwood, which corresponds to displacement of concrete where either coal or NG was used in the manufacturing process of the displaced concrete.[49] Obviously, also other structural products and materials can be displaced, such as steel or some other materials used in flooring, windows, and doors. A review of 21 international studies produced an average displacement factor for wood products at 2.1 Mg C per Mg C in sawnwood.[50] Assuming this lower displacement factor would improve the situation for bioenergy relative to sawnwood products, but results presented below would only be marginally affected.

## RESULTS AND DISCUSSION

The consequences of a change in harvest intensity are evaluated by comparing the bioenergy scenarios with several reference scenarios. The results are first presented as net C stock change, and then climate effects are presented in terms of CRF and $\Delta T$, which in addition include the effects related to supply chain emissions of $N_2O$ and $CH_4$ from woodchips, sawnwood, and fossil fuel.

### C Balances at the Stand Level

Figure 3 shows the C stored in different pools (soil and litter, trees, HWP, landfilled wood) as well as in displaced fossil fuels in the BIO1 and REF scenarios. The black line in Figure 3(c) shows the net C stock, which is obtained by subtracting the values in REF from those in BIO1 pertaining to C stored in the pools and in displaced fossil fuels. Thus, in this particular case, the line shows the net C effect of changing the harvest intensity to provide biomass that is used to displace NG; less C is stored in the soil and litter pool, and less fossil C is emitted. This net C stock curve is used as a basis for comparing scenarios in Figures 4 and 5 as well. HWP production is the same in BIO1 and REF, meaning that the net C effect of shifting from REF to BIO1 is zero with respect to HWP.

Figure 4 shows how the net effect of forest slash removal on C storage varies in the scenarios at the stand level. The net C stock effect for BIO1 and BIO2 is shown as sudden C losses from the soil and litter pool at thinning and final harvest, followed by a gradual gain as slash left in the forest in the REF scenario decay. As can be seen, the use of slash for bioenergy (BIO1) results in relatively small C losses during the initial thinning events and a larger loss at final harvest. In the longer term, the cumulative effect of avoiding fossil C emissions dominates, and the fluctuating net C stock line will stay on the positive side, i.e., reduced net C emissions to the atmosphere. Extraction of stumps together with slash (BIO2) results in larger net C losses and it takes longer to reduce net C emissions when NG is displaced (Figure 4). This is due to the lower decomposition rate for stumps. If forest slash extraction for energy coincides with measures to promote forest growth (BIO+ scenarios represented with dotted lines in Figure 4), net C savings are obtained sooner as more C is stored in the growing trees.

The reason NG was chosen as reference fuel in Figures 3 and 4 is not that NG is considered the most likely fuel to become displaced by biomass, but these scenarios clearly illustrate how stand-level accounting can come to the conclusion that forest bioenergy systems are associated with net C emissions during an initial time period due to low fossil C displacement. As is shown in Figure 5 below, when biomass is extracted from the forest landscape to displace coal, the C emissions reduction can be immediate. As explained in section *scenarios*, coal was assumed to be used in a heat boiler and a condensing power plant, which together had a lower combined efficiency than the corresponding biomass CHP plant. In contrast, the fossil C displacement factor was much lower in the NG case as this fuel is less C intensive than coal and the associated technologies were assumed to have higher conversion efficiencies.

### C Balances at the Theoretical Landscape Level

Figure 5 shows how the net C stock changes at the landscape level for all the forest scenarios, and for both the NG and Coal scenarios. The drastic shifts between net C stock increases and decreases that are

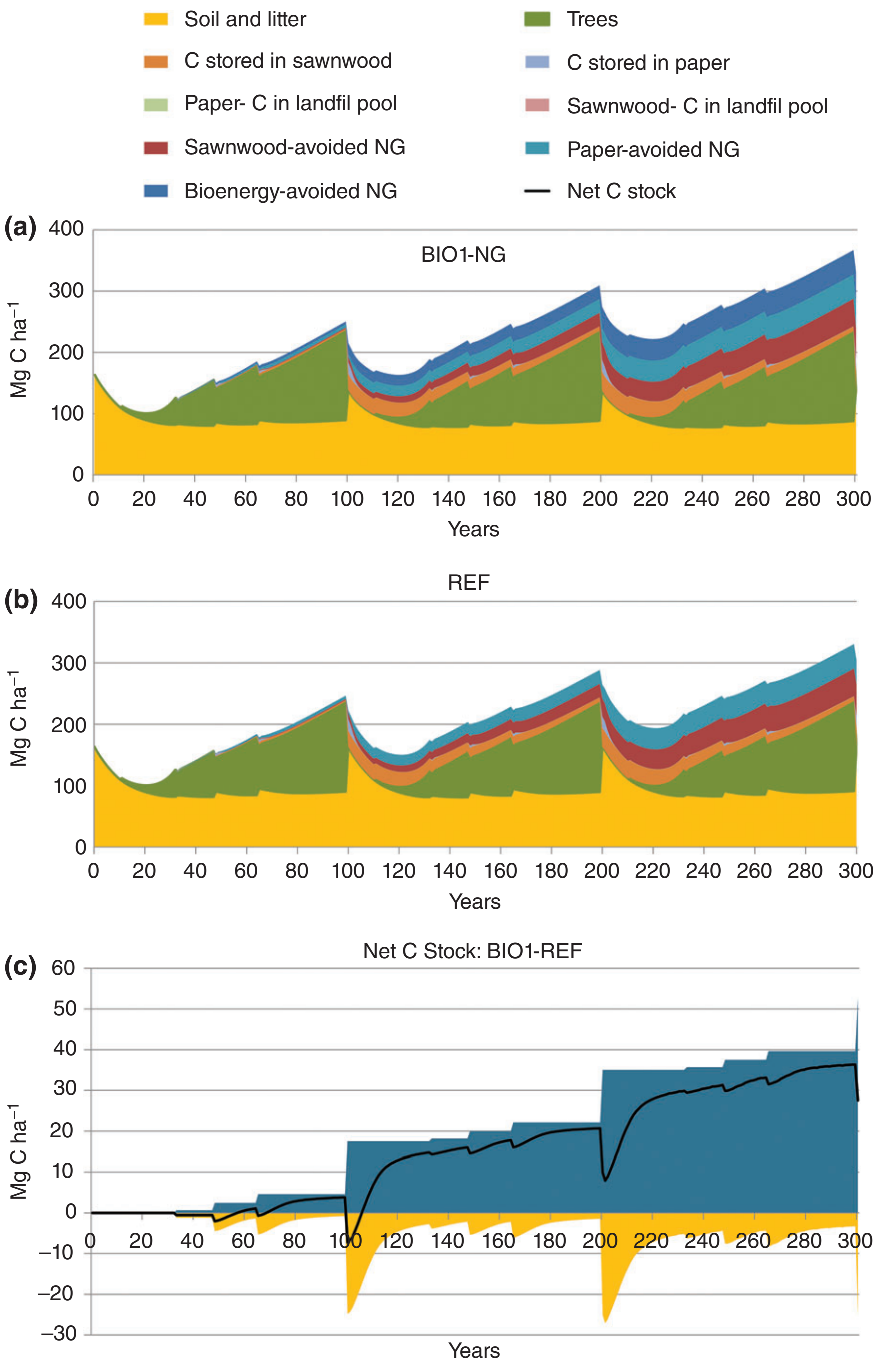


**FIGURE 3** | C stock in the different pools at the stand level for (a) BIO1 (stemwood and 80% slash removal) with bioenergy displacing NG and (b) REF (stemwood removal). (c) Net C stock effect of shifting from REF to BIO1.

shown in Figure 4 do not appear at the landscape level where C growth in some stands balances C losses in other stands. The assessment at the landscape level also captures the effects of changes in forest management (harvest intensity and growth-enhancing measures) differently. By including both the NG and Coal scenarios, Figure 5 further demonstrates the importance of reference scenarios, i.e., fossil C displacement factors, in assessments of forest bioenergy systems.

When coal is displaced, the net C savings are practically instantaneous for all scenarios, while they appear later when NG is displaced. NG displacement with slash (BIO1) results in net C savings earlier

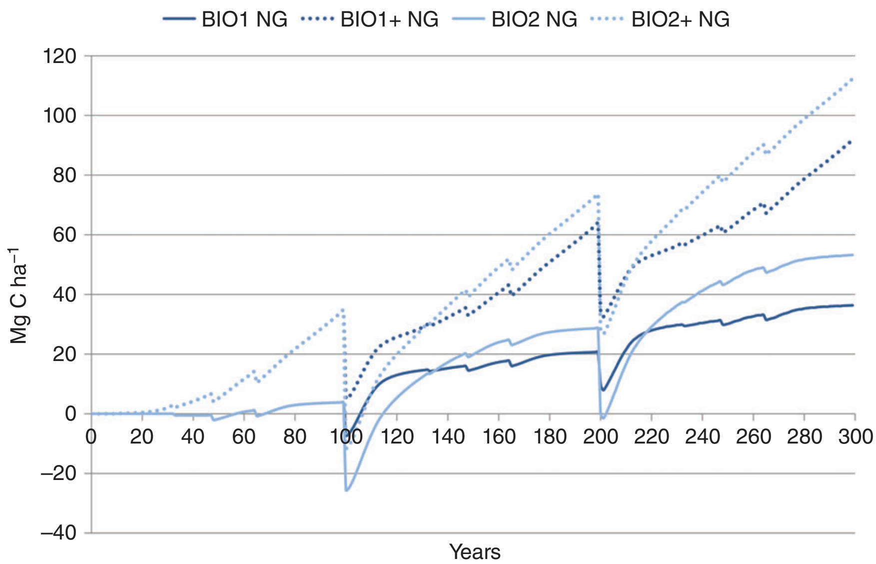


**FIGURE 4** | Net C stock comparison between the forest scenarios, for NG scenario at the stand level. The BIO1 (80% slash removal) and BIO2 (80% slash and 50% stumps removal) curves are identical until the first final felling when the first stump extraction event takes place in BIO2.

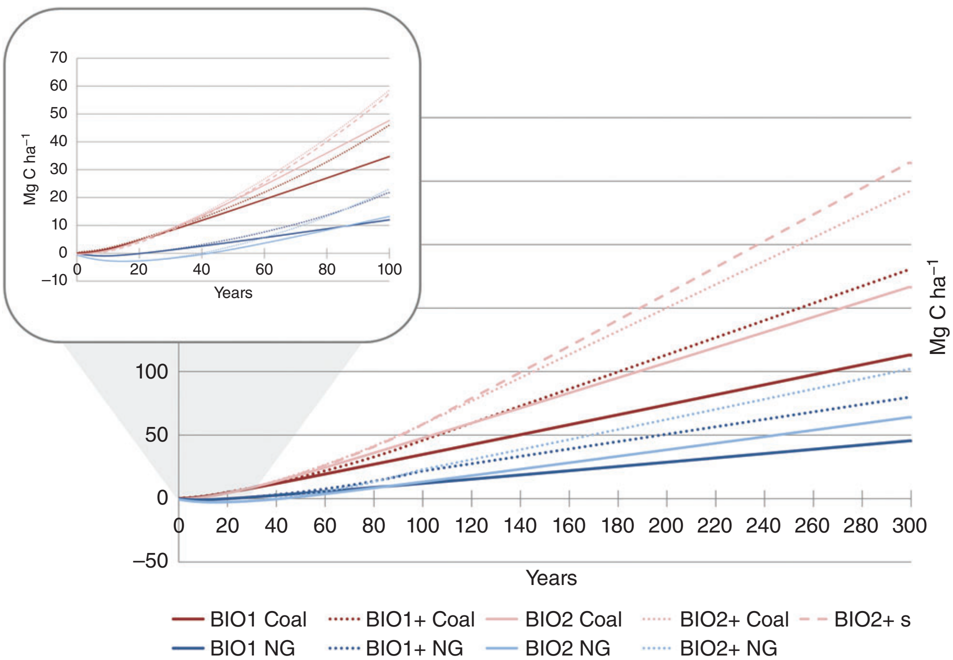


**FIGURE 5** | Net C stock comparison between the forest scenarios, for NG and Coal scenarios at the landscape level. Each line represents the net difference between the bioenergy-adapted scenarios and the reference scenario, i.e., BIO1: 80% slash removal; BIO2: 80% slash + 50% stumps removal; BIO1+: as BIO1 but with enhanced growth and additional stemwood used for bioenergy; BIO2+: as BIO2 but with enhanced growth and additional stemwood used for bioenergy; BIO2+s: as BIO2 but with enhanced growth and additional sawtimber used for sawnwood and the rest for bioenergy.

than when stumps (BIO2) are also used, but in the longer term harvesting stumps in addition to slash brings larger C savings thanks to the larger total biomass output for fossil fuel displacement. If forest owners, in addition to extracting slash for energy, invest in measures to enhance forest growth (BIO+ scenarios), the net C savings are obtained slightly earlier and increase faster. The outcome depends on how the additional forest growth is used. The BIO+ scenarios show the outcome when the additional growth is used for energy displacing coal and NG, and the BIO+s scenario show the outcome when

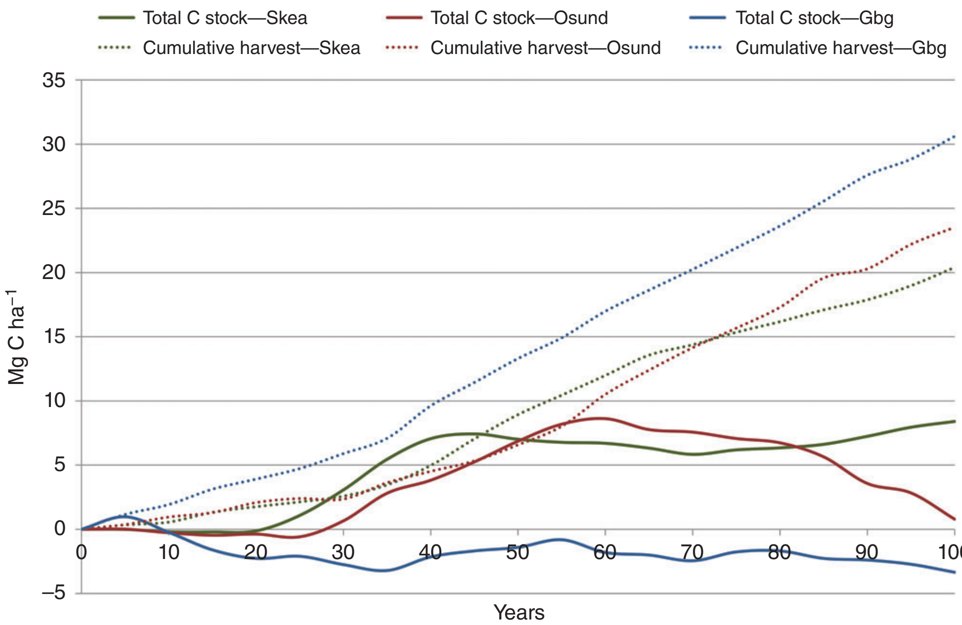


**FIGURE 6** | Net C stock (BIO-REF) in forest pools and in the harvested biomass in Skellefteå (Skea), Östersund (Osund), and Göteborg (Gbg).

the additional stemwood growth is instead used to produce HWP. In the latter case, the net C gain is higher in both the medium and long term (once the enhancing measures are implemented in the whole landscape) thanks to the additional stemwood use to produce HWP that contribute to additional C storage in HWP, displace more structural materials and in addition are used for energy displacing fossil fuels at the end of HWP lifetime. Notice that if exports of sawnwood were included, it would imply additional emissions from transport and lower fossil C displacement at the end of the products life, but the observations above would hold unless very pessimistic assumptions are made concerning exported wood products.

It should be noted that very slow implementation of growth-enhancing measures was modeled. The measures are implemented on one new stand each year and the increased C sequestration associated with the resulting higher biomass growth rates across the landscape does not outweigh the C losses associated with increased biomass extraction for energy to displace NG in the short term, contrary to the earlier C saving shown at the stand level (Figure 4). Lower slash extraction rates or stronger landscape-wide implementation of growth-enhancing measures would result in net C savings being obtained sooner. As has been shown in other studies for Sweden, management changes to enhance growth can increase forest production and annual harvest rates while simultaneously increasing the forest C stocks.[51–53] In addition to forest management, forest structure (e.g., age class and species distribution) and natural conditions influence the net C effect of forest bioenergy. As is shown below, this influence can be larger than the influence of bioenergy use patterns, e.g., whether coal or NG is displaced.

## C Balances in Real Forest Landscapes

Figures 6 and 7 show the results of the PlanWise simulations for three real landscapes, comparing (1) a REF scenario with forest management planning for sawtimber and pulpwood production not considering forest fuels as a factor in management planning; with (2) three BIO scenarios where the forest companies adapt the forest management planning to obtain an economically optimal output of forest products, placing equal weight on sawtimber, pulpwood, and forest fuels. Figure 6 shows the net C in forest pools (i.e., C in trees, soil, and litter) and in cumulative biomass harvest for the bioenergy-adapted scenarios compared with the reference scenario.

The differences illustrate how forest product markets, forest structure, and natural conditions can influence the outcome. Forest management optimization in the BIO scenarios resulted in longer average rotation periods, reduced sawtimber output, and increased pulpwood and forest fuel output due to increased thinning frequency providing both pulpwood and forest fuels. These changes caused net gains in forest C storage in the BIO_Skea and BIO_Osund scenarios and a net loss in the BIO_Gbg scenario over the 100 years. As a consequence of reduced sawtimber

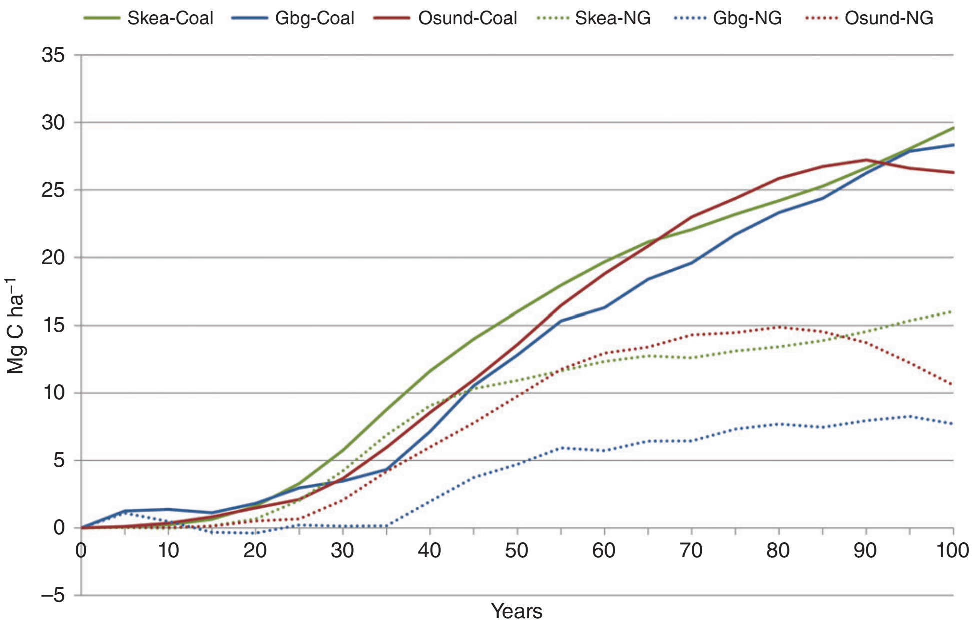


**FIGURE 7** | Net C stock (BIO-REF) in Skellefteå (Skea), Östersund (Osund), and Göteborg (Gbg) with bioenergy displacing NG or coal.

output, less C was stored in HWP, and there were also increased GHG emissions associated with the additional production of structural products such as concrete needed to balance the lower HWP production. However, as shown in Figure 7, in five out of six scenarios the negative effects of increased GHG emissions and reduced C storage in forests and/or HWP are outweighed by the increased fossil C displacement associated with bioenergy use, and net C savings are obtained already in the first year. If HWP export patterns had been considered in the calculations, and if the lower sawnwood output had resulted in lower HWP export, the net C balances would be slightly better for the bioenergy-adapted scenario. Figure 7 is also illustrative of the influence of forest structure and natural conditions when a new management practice is implemented, the use of biomass to displace NG in the Skea-NG scenario temporarily results in higher net C savings than when coal is displaced in the two other scenarios. However, in the longer term, the higher fossil C displacement effect of coal displacement dominates.

The results presented above should be considered context specific and should not be understood as representative for varying conditions across the world. Rather, the varied outcome in the three BIO scenarios underlines the need for empirical data and knowledge, supporting a valid representation of forest ecosystems and management systems in the specific locations investigated. The dynamics resulting from the interaction of short-term demand changes, market expectations, and long-term supply responses will vary depending on the character of demand, forest structure, forest industry profile, and forest owners' views about emerging bioenergy markets.[54–57] For instance, the increased pulpwood output in the BIO scenarios presented above contrasts with findings in some other studies[58–62] indicating that rising demand for fuel wood causes competition for low-quality sawtimber and pulpwood.

Beyond effects of policies and strategies directly targeting the bioenergy sector, studies have shown that forest product markets are also affected by other policies and underlying energy market trends and drivers. For instance, Ref 63 found that oil price increases caused significant changes in timber supply and grading ratios in Bavaria in Germany, tending toward an increase in wood graded for energy use with rising oil and timber prices. Ref 64 showed that increased energy prices in Norway could result in increased output of some forest products and decreased output of others, depending on forest industry structure and raw material use. Ref 65 analyzed the effects of prices for fossil fuel $CO_2$ emissions on wood use in Europe and showed how the competition for different timber quality grades depends on these C prices. At C prices below 50 €Mg$^{-1}$ $CO_2$, mainly forest chips, recycled wood, bark, and black liquor were used for energy, while at a C price of 110 €Mg$^{-1}$ $CO_2$, roughly one third of wood used for large-scale heat and power production would also be suitable for material use. It is well established that if C sequestration in forests was credited at the same C price levels as fossil $CO_2$ emissions, forest management and policy would likely change drastically at the C prices needed to stabilize fossil $CO_2$ emissions (see, e.g., Ref 66).

Many of the above-cited studies illustrate how biomass demand for energy, compared to possible forest supply sources, can have a critical influence on the character of the forest sector response, which in turn influences the forest C effects of providing forest biomass for energy. This is largely a matter of pace of demand growth versus pace of mobilizing different types of biomass supplies. Illustrative of this, Ref 67 found that demand growth above the possible mobilization level for forest residue supply in southeastern United States can drive up roundwood prices considerably, with implications for both forest landowners and users of forest resources. However, longer-term bioenergy demand also matters. For instance, Ref 68 analyzed the marginal cost of forest supplies for bioenergy and quantified the level of bioenergy demand, given that cheaper residue resources have become depleted and it becomes more profitable to use roundwood for energy purposes than to continue extracting additional harvest residues. The possible supply and cost of agriculture-based bioenergy will here have an important indirect influence on forest C balances over time, by influencing the demand growth for forest-based bioenergy.[69]

As discussed in this section and also shown in other studies,[70–72] landscape-level forest C stocks need not go down due to biomass (residues or roundwood) use for energy. Again, the outcome for forest C balances depends on demand and local/regional circumstances. Using the case of forest bioenergy in southeastern United States as an example, Ref 73 reported that the amount of softwood harvested from private pine forests almost doubled between the early 1950s and the late 1990s, whereas carbon stocks in these forests remained essentially constant due to investments to increase forest productivity and expand the area with planted pine, mostly on nonplanted pine land. The net C savings of bioenergy also depend on how the forest sink develops and risks of future forest C losses, and how these are influenced by natural drivers and evolving forest management regimes, including forest protection.[74–79]

## Climate Effects of Forest Bioenergy

Using CRF and $\Delta T$, we consider the climate effects of the bioenergy systems, focusing on the C balances derived for the theoretical landscape. The metrics include the effects of both net $CO_2$ emissions—obtained by calculating the net C stock changes in bioenergy scenarios (Figure 5) and converting them into $CO_2$—and the $N_2O$ and $CH_4$ emissions associated with the respective scenarios.

Figures 8 and 9 show the climate effects of the fossil and biomass-based systems, expressed in terms of CRF (8a and 9a) and $\Delta T$ (8b and 9b). The net CRF and net $\Delta T$ (Figure 8) are obtained by subtracting the effect of the fossil system from the effect of the bioenergy system. Note that a different amount of energy is produced in each scenario in these diagrams. Figure 9 shows the CRF and $\Delta T$ effects of supplying 1MJ of heat with coal, NG, or biomass. The absolute cooling effect of 1MJ of some bioenergy systems with enhancing measures, i.e., BIO1+ and BIO2+s, shown in Figure 9(b) when the values become negative, is entirely caused by forest management (plus, for BIO2+s, increased HWP production). The former scenario presents a temporary cooling effect, and the latter shows a cooling effect that persists as long as the forest management remains unchanged. All the diagrams illustrate the climate benefits of the bioenergy scenarios compared to the REF scenario, either as negative net CRF/$\Delta T$ (Figure 8) or as lower CRF/$\Delta T$ when 1 MJ of heat is produced using biomass compared to fossil fuels (Figure 9). As can be seen, when NG is chosen as reference fuel, these specific forest bioenergy cases are associated with a small initial warming before the effect of avoided fossil C emissions starts to dominate (note the differences in scales in the magnified diagrams). When coal is chosen as the reference fuel instead, these forest bioenergy scenarios are associated with a net cooling from the start.

Figures 8 and 9 also illustrate the inertia in the system. The CRF (Figure 9(a)) continues to increase after the end of the third rotation period, i.e., 300 years, although the slope of the line decreases slightly when emissions cease. The $\Delta T$ (Figure 9(b)) also captures this temperature impact after the third rotation period, although this effect decreases, which means that part of the climate impact can be reversed.

The C Stock, CRF, and $\Delta T$ figures show similar trends. The climate benefits of some bioenergy systems are delayed compared with others; however, in all cases, if climate warming effects are present, they can be reversed, and, in most of the cases, still provide great climate mitigation benefits in the medium term. The CRF and $\Delta T$ figures indicate earlier benefits of bioenergy use than the C stock figures as the upfront emissions are associated with fossil fuels and other GHG gases are not included in the C stock graph. However, in the modeled cases, the effect of these emissions is relatively small compared with biogenic C fluxes. CRF indicates later climate benefits than $\Delta T$ as it reflects cumulative effects, where the inertia of

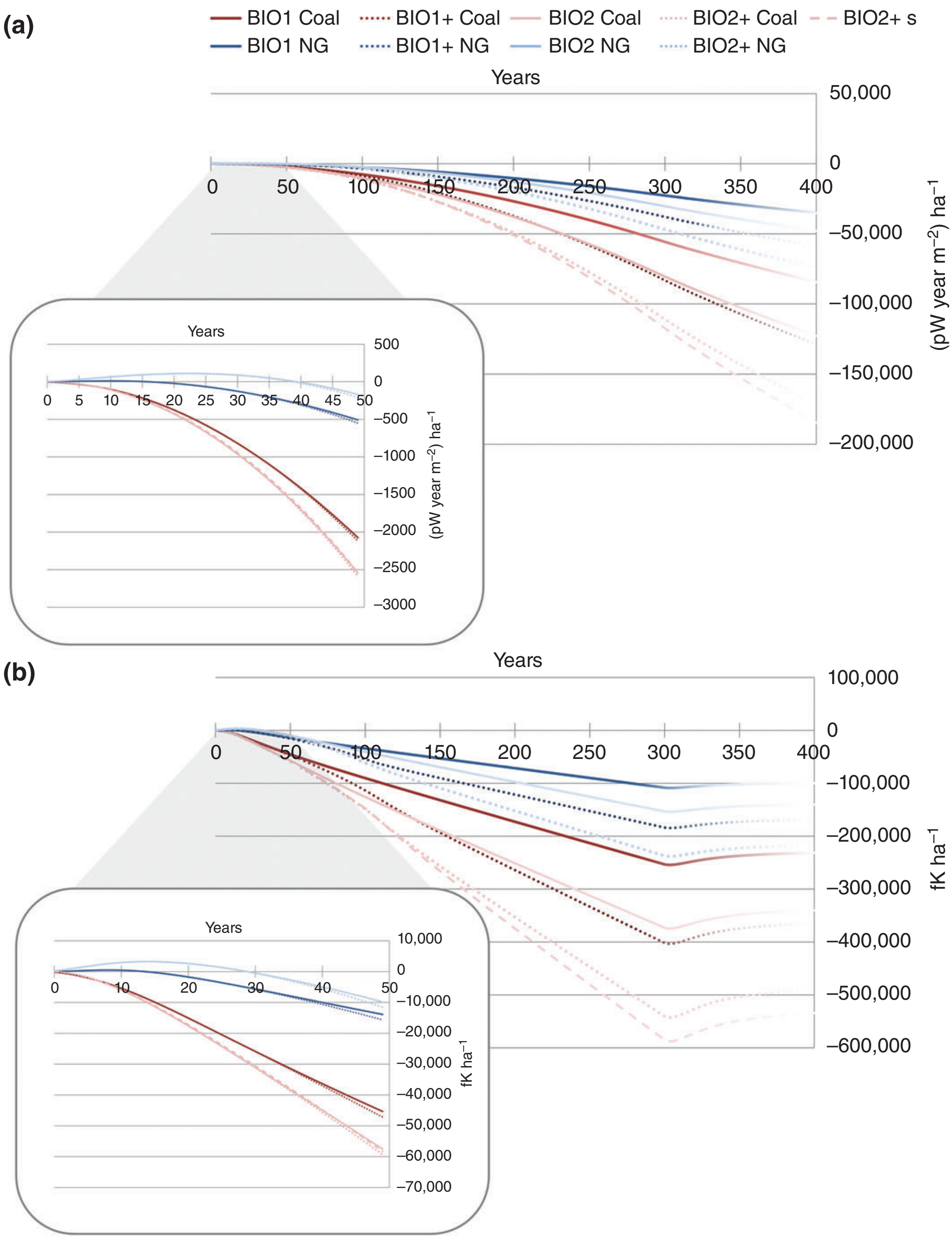


**FIGURE 8** | Climate effects of the fossil and biomass-based systems at the landscape level. (a) Net CRF; (b) Net $\Delta T$. Negative values correspond to cooling. Each line represents the net difference between the bioenergy-adapted scenarios and the reference scenario, i.e., BIO1: 80% slash removal; BIO2: 80% slash + 50% stumps removals; BIO1+: as BIO1 but with enhanced growth and additional stemwood used for bioenergy; BIO2+: as BIO2 but with enhanced growth and additional stemwood used for bioenergy; BIO2+s: as BIO2 but with enhanced growth and additional sawtimber used for sawnwood and the rest for bioenergy.

the climate system comes into play and the dynamics become less important.

The results shown are consistent with those in other studies. For example, Ref 23 found that the use of slash and stumps to displace NG will result in reduced CRF after 15–25 years, while CRF was reduced almost immediately when coal was displaced. Ref 25 concluded that during the first 20 years the climate impacts of using slash are slightly lower than fossil fuel use, NG, and coal, while the use of stumps causes higher climate impacts during the first 30 years. Both these studies use approaches similar to the BIO1

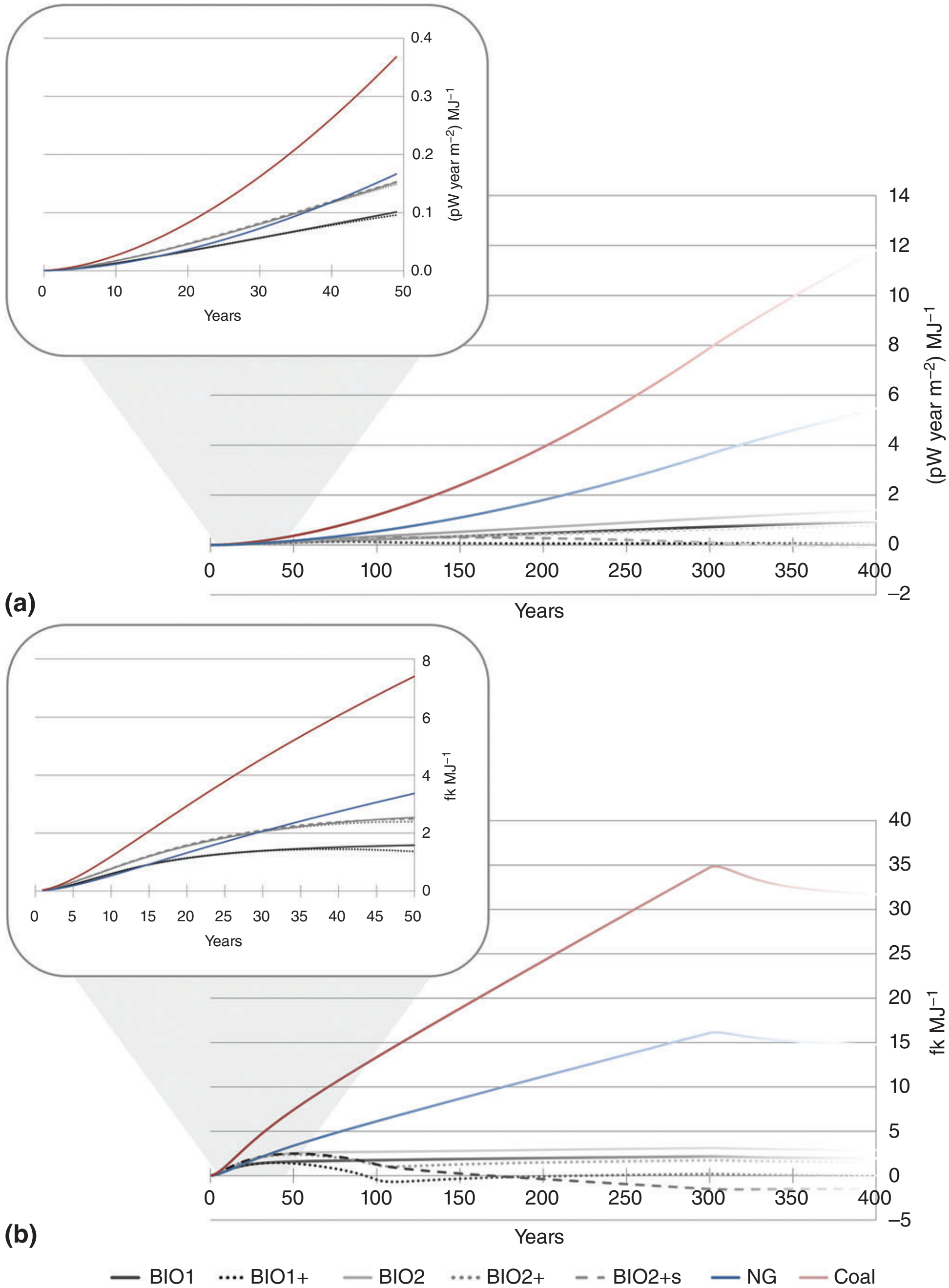


**FIGURE 9** | Climate effects of the fossil and biomass-based systems at the landscape level. (a) CRF for the fossil and biomass-based systems; (b) $\Delta T$ for the fossil and biomass-based systems. Negative values correspond to cooling. Each line represents the net difference between the bioenergy-adapted scenarios and the reference scenario, i.e., BIO1: 80% slash removal; BIO2: 80% slash + 50% stumps removals; BIO1+: as BIO1 but with enhanced growth and additional stemwood used for bioenergy; BIO2+: as BIO2 but with enhanced growth and additional stemwood used for bioenergy; BIO2+s: as BIO2 but with enhanced growth and additional sawtimber used for sawnwood and the rest for bioenergy.

and BIO2 stand-level modeling with accounting set to start at the point in time when additional biomass is extracted and used to produce forest fuel. In this paper, the climate benefits of bioenergy arise later at the landscape level, but the warming effect of the bioenergy system during the initial time period was at the same time significantly lower as the C stock change is smoother at the landscape level than the stand level. The results reported in this paper are also in line with Ref 24 who in addition pointed to the greater climate mitigation potential for forest bioenergy systems when more intensive forest management is applied. Ref 26

BOX 1

### CLIMATE METRICS

In addition to C balances, several metrics are used in this paper to describe the effects of forest bioenergy systems, following Ref 27.

- The RF[80] describes the net change in the energy balance of the Earth system induced by some imposed perturbation, in this case the change in GHG concentration, given that other processes within the troposphere remains unchanged. The RF time profile associated with a unit pulse emission is calculated for each gas,[27] and the total RF impact is calculated for an emissions scenario spanning over several years by using convolution of the emissions and the RF for a pulse emission of the gases in question[80,81]. In other words, the RF in a particular year is obtained by adding the RF due to that year's emissions to the amount of RF from previous years' emissions remaining in the atmosphere.
- RF is integrated over time to obtain the cumulative RF (CRF). Positive values reflect warming and negative values reflect cooling.
- The AGTP is defined as the change in global mean surface temperature at a chosen point in time in response to an emission pulse.[80,82] The AGTP is calculated for each gas,[27] and the global surface temperature change ($\Delta T$) profile for a given bioenergy scenario is calculated by using convolution of the GHG emissions and the AGTP.[80,81] In other words, the $\Delta T$ in each particular year is obtained by adding the AGTP due to that year's emissions to the amount of AGTP from previous years' emissions remaining in the atmosphere.

evaluated climate effects of a single pulse emission and sustained emissions, while this work evaluates a time profile of emissions that to a higher degree represents a forest bioenergy system. They found higher emissions for a Nordic spruce stand than reported here, but their AGTP results are lower for the bioenergy system than for the fossil fuel reference as they also include albedo effects, which in their cases benefit the bioenergy systems.

## CONCLUSION

As shown above, methodological choices and assumptions about parameter values can have large influence on the outcome of assessments of the climate effect of forest bioenergy systems. Comparison of assessments at the stand and landscape levels further revealed that analyses of the same bioenergy system can result in different conclusions depending on the definition of system boundaries and how temporal aspects are captured. Also, definitions of counterfactual 'no bioenergy' reference scenarios are crucial for the outcome.

The effectiveness with which fossil C is displaced is a major influence on the net GHG balances. In this paper, reference scenarios included coal or NG, with faster climate benefits when bioenergy displaced coal. Obviously, if bioenergy competes with other renewable technologies, the fossil C displacement effects would be much lower and could even be negative. Adaptation of forest management to bioenergy demand can also affect HWP production and associated GHG balances, as illustrated in the case of construction wood displacing other products such as concrete. Again, other displacement patterns than the one used in this paper would yield different outcomes.

Assessment frameworks (including choice of metrics) are shaped by questions asked and by the scope of those addressing the questions. Consequently, the outcome of assessments and conclusions about the climate effects of bioenergy implementation can differ. For instance, aspirations to link products with the emissions arising on the exact locations of production and consumption may favor GHG accounting on smaller scales such as the forest-stand level, with accounting commenced at the point in time when biomass is removed from the stand and used in the production process. As shown above, this approach would result in assigning all bioenergy products upfront C emissions corresponding to the amount of C in the biomass removed from the forest stand. Depending on how sustainability requirements are defined concerning GHG balances, the outcome might then be that forest fuels can only be certified as sustainable if produced from certain feedstocks, such as quickly degrading forest slash—and possibly only if they are destined to displace C-intensive products like coal.

However, forest management planning is not done at the stand level but at the landscapes level considering the total forest product portfolio. Managed forests are viewed as large biomass production systems and management activities are coordinated across the whole landscape to deliver a steady stream of biomass for multiple products. Compared with forest stands, C stocks in managed forest landscapes are relatively stable (unless affected by events such as storms, fires, and insect outbreaks). As illustrated in the modeling of C balances in three real landscapes, biomass harvest for energy is one of many interacting factors influencing the development of forest C stocks, including forest product markets, forest ecosystem structure and management, and natural conditions. Thus, GHG balances associated with forest fuels are context-specific rather than feedstock-specific and, given the interconnectedness of forestry and forest product markets, it is appropriate to evaluate the climate effect of forest management and the total forest product output instead of looking at one forest product at a time. The attention should shift from stand-level C accounting to landscape-level assessment and planning and promotion of forest management that secures forest vitality and sustained (or enhanced) $CO_2$ sequestration.

Important issues have received less attention in recent years during which the timing of forest C sequestration and emissions has been in focus. These issues include (1) bioenergy's contribution to reducing fossil fuel use; (2) the magnitude of GHG emissions other than those associated with short-term forest C stock fluctuations; and (3) broader issues of sustainable forest management, considering other ecosystem services of the forest such as air quality improvement, water purification, soil stabilization and biodiversity conservation, and social services such as employment and recreation.

We recommend that climate change mitigation strategies in the forest sector recognize the possible C sink/source function of growing forests, the full range of forest products, and other values provided by forests, which are determined by conditions that vary considerably around the world. Analyses should therefore capture the specific context with respect to forest structure, natural abiotic/biotic forces, and character of the associated forest industry, considering prospective forest product markets as well as alternative policy options and energy technology pathways.

## ACKNOWLEDGMENTS

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