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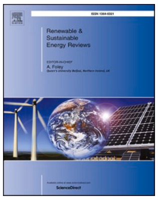

Climate effects of forestry and substitution of concrete buildings and fossil energy

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ABSTRACT

Forests can help mitigate climate change in different ways, such as by storing carbon in forest ecosystems, and by producing a renewable supply of material and energy products. We analyse the climate implications of different scenarios for forestry, bioenergy and wood construction. We consider three main forestry scenarios for Kronoberg County in Sweden, over a 201-year period. The Business-as-usual scenario mirrors today's forestry while in the Production scenario the forest productivity is increased by 40% through more intensive forestry. In the Set-aside scenario 50% of forest land is set-aside for conservation. The Production scenario results in less net carbon dioxide emissions and cumulative radiative forcing compared to the other scenarios, after an initial period of 30–35 years during which the Set-aside scenario has less emissions. In the end of the analysed period, the Production scenario yields strong emission reductions, about ten times greater than the initial reduction in the Set-aside scenario. Also, the Set-aside scenario has higher emissions than Business-as-usual after about 80 years. Increasing the harvest level of slash and stumps results in climate benefits, due to replacement of more fossil fuel. Greatest emission reduction is achieved when biomass replaces coal, and when modular timber buildings are used. In the long run, active forestry with high harvest and efficient utilisation of biomass for replacement of carbon-intensive non-wood products and fuels provides significant climate mitigation, in contrast to setting aside forest land to store more carbon in the forest and reduce the harvest of biomass.

1. Introduction

The question of how forests could best be managed to mitigate climate change is discussed more intensively as society grows more concerned with anthropogenic climate disruption. Forest ecosystems store vast amounts of biogenic carbon, and management activities could focus on preserving and enhancing this reservoir to prevent the stored carbon from entering the atmosphere. On the other hand, forests can produce a renewable supply of material and energy products, which could be sustainably used in place of carbon-intensive materials and fossil fuels. Researchers have developed integrated analysis techniques to clarify connections and potential trade-offs between different forestry strategies, where both biogenic carbon storage in forests and the outcomes of using wood to substitute carbon intensive products in technological systems within society are included.

Early efforts to understand the carbon dynamics of managed forest systems include Dewar's 1991 exploratory accounting of trees, soil and wood products [1], and Nabuurs & Mohren's 1993 comparison of carbon flows in different forest types [2]. Schlamadinger & Marland provided a strong theoretical foundation for integrated analyses in 1996, with system modelling that considered carbon changes in forest ecosystems, wood products and fossil fuels [3]. Their focus was to understand the dynamic relationships of the various carbon stocks and flows, while using best generic estimates of system parameter values. Börjesson & Gustavsson advanced the state-of-the-art in 2000 with specific estimates of wood product substitution benefits from a Swedish case study [4].

A growing number of concrete analyses were conducted in the early 21st century, based on forestry and substitution data specific to United States in 2004 [5], Sweden in 2007 [6] and Switzerland in 2010 [7]. More recently, improvements in data availability and modelling sophistication have enabled robust and comprehensive analyses of the climate mitigation effectiveness of different large-scale forestry strategies in Sweden in 2017 [8] and Canada in 2018 [9]. Generally, such analyses have consistently found that the greatest climate benefits come from strategies aiming at high forest productivity and harvest level, as well as efficient utilisation of harvested woody biomass to substitute carbon intensive energy and materials.

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The potential for wood substitution of fossil energy is large, because more than 80% of global primary energy is from fossil fuels, with the largest dominance in the transportation sector where about 92% of all energy supply was from fossil fuels in 2018 [10]. Building systems also represent large wood substitution potentials, as building construction activities largely use non-renewable materials and about 60% of global raw material use is connected to such activities [11].

Bioenergy and wood construction systems can be designed in many different ways to substitute many types of non-wood construction and energy systems [12]. Such opportunities give a large range of climate change mitigation effects that may vary for different forest management systems [8]. Hence, the substitution effects vary broadly with how we use the harvested woody biomass, what non-wood systems we replace, and the type of forest management that is used [13].

Here, we estimate the climate effects of different silvicultural scenarios for Kronoberg County in Sweden, combined with different substitution scenarios. We analyse the climate effects over 201 years of directing forest management towards enlargement of the set-aside area in forests, or towards increased forest production, relative to the current forest management. We quantify the substitution effects of replacing concrete buildings with wood buildings and fossil energy with bioenergy in a lifecycle perspective. We estimate the net CO_2 emission of the forest and technological systems over a 201-year period, and the resulting climate effects in terms of radiative forcing. Our objective is to understand the short- and long-term climate implications of alternate pathways for forest management and the built environment. The novelty of the study is the linking of different system models, and applying them to enrich knowledge about different long-term management and substitution possibilities for the forest-rich geographic area of Kronoberg County in Sweden.

2. Methods, scenarios and data

We developed a computer model integrating forestry, energy, building and climate components, and driven by a range of scenarios (Fig. 1). The forestry scenarios include the Business-as-usual (BAU) scenario that mostly reflects today's forestry practices, the Production scenario with 40% higher productivity achieved through more intensive forest management, and the Set-aside scenario with half of all productive forest land set-aside for conservation. Each scenario and assumed harvest level provides a supply of forest biomass to be used for buildings and energy. The building construction scenarios include modern prefabricated concrete, modular timber, and cross-laminated timber building systems. The energy scenarios include modern large-scale high-efficiency energy and transportation systems based on biomass, fossil coal, gas or oil.

For each scenario combination, we estimate the annual fossil CO_2 emissions from forest operations, biomass harvest and transport, the avoided CO_2 emissions from using biomass to substitute fossil fuels and materials, and the carbon stock changes in living trees, wood products and soil. We then use a simple climate system model to estimate the annual decay of atmospheric CO_2 concentration, the resulting annual changes in instantaneous radiative forcing, and the build-up of cumulative radiative forcing that drives global climate change.

The same forest land area is included in all scenarios, and the same amount of pulp wood, energy and housing services are delivered to society. The scenario with least pulpwood (Set-aside) steers the amount of pulpwood in other scenarios, and surplus of pulpwood in other scenarios (BAU and Production scenarios) is used for energy. The maximum harvest of timber steers the potential for wood buildings, and in scenarios with less timber, more concrete buildings are constructed to give the same amount of housing service. Hence, in the Production scenario, more biomass is harvested compared to the BAU, increasing the potential production of timber buildings and use of bioenergy. In the Set-aside scenario, the harvest is lower compared to BAU, decreasing the potential production of timber buildings and use of bioenergy. With fewer timber buildings and less bioenergy, the construction of concrete buildings and the use of fossil fuels both increase to deliver the same amount of service to society.

In fields such as forestry with century-long growth cycles, it is necessary to conduct modelling over time scales sufficient to capture these long-term patterns. In addition, the climate dynamics of cumulative radiative forcing take a long time to distinguish. Still, short- and medium-term climate implications are of great interest to society, including policy makers. Hence, it is useful to consider climate change over many different time horizons. This work builds on previous research using dynamic [14] system [15] modelling [5], to understand the climate effects associated with different scenarios over 201 years

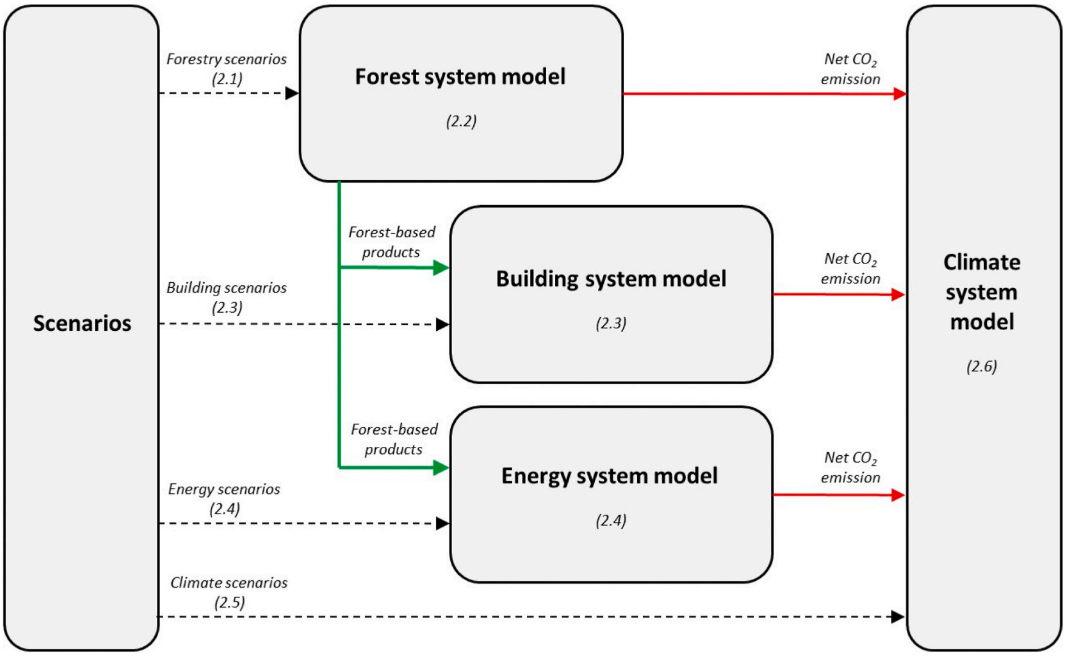

Fig. 1. Flowchart diagram of modelling methodology. Numbers in parentheses indicate the article section describing the component.

within the spatial area of Kronoberg County. A life cycle system analysis approach is used and the long time horizon of our analysis enables us to show the short-, medium- and long-term climate implications of the various options, even though the uncertainties increase strongly in the long run. Hence, within this long 201-year period, short- and medium-term events and patterns are also evident.

2.1. Forest area and forest management scenarios

This study focuses on Kronoberg County in southern Sweden, based on initial forest conditions in 2016. Kronoberg County has a total area of 8466 km^2 and a total population of about 200,000 people. The county is abundantly forested, with 6500 km^2 of productive forest land area. There is another 290 km^2 of set aside forest, including forest protected in the European Union's Natura 2000 land protection network. About 75% of the trees are Norway spruce and 25% are Scots pine. The production forests of Kronoberg County have a standing volume of about 91 million m^3 of timber, and a mean annual volume increment of 5.9 m^3 (over bark) per hectare per year. The forest in Kronoberg County was heavily affected by the severe storm Gudrun in January 2005 [14], damaging about 70 million m^3 of the Swedish forests, mostly spruce trees [15]. The storm had a significant impact on the age structure of the forest in Kronoberg County.

The Swedish Forest Agency performs forest impact studies on a regularly basis of the Swedish forest, considering different ways to manage the forest over 100 years. The studies are used to strategically analyse the consequences of different forest management approaches, including the potential trade-offs between diverse societal goals. Analyses of the current and expected future timber balances and their drivers should enable deeper understanding of the economic, ecological and social consequences of management decisions. Data from the latest forest impact study (SKA 15) [16] are used for our forest scenarios, which are summarized in Table 1.

The BAU scenario reflects today's Swedish forestry, with the stem harvest in final fellings almost equal to forest growth in production forests excluding set aside land. Annual felling volumes from Swedish forests have steadily increased during the past 45 years [17], and the current felling level is close to the forest growth level but also depends on the age structure of the forest. The Production scenario uses higher management intensity such as species selection and fertilization to increase forest growth level by 40% after 100 years. In all scenarios, the forest productivity remains constant after 100 years until the end of the 201-year study period. The Set-aside scenario is somewhat extreme where 50% of the productive forest land area is set aside at the starting point of the forest modelling. In the BAU and Production scenarios, 11.3% of forest land is set aside.

In all scenarios almost all annual stem wood growth in non-set-aside production forest area is harvested. We also estimate the climate implications of harvesting forest residues, corresponding to 80% of slash (branches and treetops) and 40% of stumps from final fellings. In a sensitivity analysis we consider the forest management scenarios Production20 (80/40) with an increased production of 20% instead of 40%, the Set-aside32 (80/40) scenario with 31.8% of forest land set aside instead of 50%, and a Set-aside + Production (80/40) with 50% of forest land set aside and increased forest productivity of the non-set aside area as in the Production scenario. The set-aside area of 31.8% is equal to the relative set-aside area in the environmental scenario in SKA 15 [16]. All forest management scenarios are based on future climate change corresponding to the Representative Concentration Pathway (RCP) 4.5 [18].

2.2. Forestry modelling

The Heureka Regwise simulator [19] is used to model forest development and harvest. The tool contains simulation models for growth, mortality and ingrowth of the tree layer. Height growth is modelled of individual trees in young stands with a mean height less than 7 m, and basal area is modelled of individual trees in established stands with a mean height greater than 7 m. The tool also models the management, harvest, climate change effect, storm fellings, and carbon storage in soil and dead wood. Soil carbon stock estimates are based on the Q model [20]. Measured data from the Swedish national forest inventory (NFI) [21] were used as input data for the forest simulations. NFI plots are divided into various categories including protected forests like nature reserves, retention patches and voluntarily set-aside forests, as well as productive forests in non-protected areas. Forestry simulations for each scenario were conducted with five-year time steps starting in year 2016 and ending in 2216 and translated to annual values by linear interpolation and used as input for further analysis.

The specific fossil emissions from different activities of forest management are summarized in Table 2. Estimates of fossil CO_2 emissions from forest establishment include the activities of seed production, soil scarification, regeneration and cleaning [22,23]. Emissions from fertilizer production and application activities include CO_2, CH_4 and N_2O converted to CO_2e using GWP over a 100-year time horizon [24,25]. Emissions from forest thinning activities are based on a two-machine system using diesel fuel [26]. Emissions from final harvesting activities are based on data specific to the southern region of Sweden [22,23].

Table 1
Forest management scenarios.

Name	Descriptions
Reference	
BAU	Set-aside forest area is 11.3%. In non-set-aside forest areas, management is similar to current Swedish forestry practices, with annual stem wood harvest nearly equal to annual stem wood growth but without harvest of slash or stumps.
Main analysis	
BAU (80)	BAU plus 80% slash harvested from final fellings.
BAU (80/40)	BAU plus 80% slash and 40% stumps harvested from final fellings.
Production	Set-aside forest area is 11.3%. In non-set-aside forest areas, production increases to 40% higher volume production during the first 100 years compared to BAU and then the productivity remains constant, the annual stem wood harvest is nearly equal to annual stem wood growth, and no slash or stumps are harvested.
Production (80)	Production plus 80% slash harvested from final fellings.
Production (80/40)	Production plus 80% slash and 40% stumps harvested from final fellings.
Set-aside	Set-aside forest area increases so 50% of forest land area is not harvested. In non-set-aside forest areas, the forest productivity is the same as BAU scenario, the stem wood harvest is nearly equal to annual stem wood growth, and no slash or stumps are harvested.
Set-aside (80)	Set-aside plus 80% slash harvested from final fellings.
Set-aside (80/40)	Set-aside plus 80% slash and 40% stumps harvested from final fellings.
Sensitivity analysis	
Production20 (80/40)	Set-aside forest area is 11.3%. In non-set-aside forest areas, production increases to 20% higher volume production during first 100 years compared to BAU and then productivity remains constant, the stem wood harvest is nearly equal to annual stem wood growth and 80% slash and 40% stumps are harvested from final fellings.
Set-aside32 (80/40)	Set-aside forest area increases so 31.8% of forest land area is not harvested. In non-set-aside forest areas, the forest productivity is the same as BAU scenario, the stem wood harvest is nearly equal to annual stem wood growth, and 80% slash and 40% stumps are harvested from final fellings.
Set-aside + Production (80/40)	Set-aside forest area increases to 50% (as in the Set-aside scenario). In non-set-aside forest areas, forest productivity increases by 40% (as in the Production scenario), the annual stem wood harvest is nearly equal to the annual stem wood growth, and 80% slash and 40% stumps are harvested from final fellings.

Table 2
Specific fossil CO_2 emissions from forest management.

Activity	Specific emissions (tC ha^{-1})	Reference
Establishment	0.0465	[22,23]
Fertilizer production	0.0357	[23]
Fertilizer application	0.0009	[24]
Thinning	0.6327	[26]
Harvesting	0.7836	[22,23]

Modeling calculations are made per hectare of operation of each activity in each year of the forest rotation.

2.3. Uses of forest products – building systems

The building systems analysis is based on a prefabricated concrete building constructed in Växjö city in Kronoberg county in Sweden, remodelled to the energy-efficiency level of the Swedish passive house criteria. The building is further redesigned in detail with prefabricated modular timber and cross-laminated timber (CLT) frame systems. Each of the analysed building versions contains 24 apartments in six storeys, with a heated building floor area of 1686 m^2. Fig. 2 shows the floor plan and section of the building. The building designs are according to regulations of the Swedish and European construction standards [27], and designs of the timber building systems were carried out in cooperation with the relevant Swedish companies.

The external wall framing of the concrete building consists of two layers of concrete panel elements with expanded polystyrene (EPS) insulation in between. The load-bearing internal walls of concrete and the external walls support the intermediate concrete floor slabs with laminated wood flooring. The roof has a concrete slab, stone wool insulation, wooden trusses and aluminium roofing sheets over asphalt layers.

The framing of the modular building system consists of separate light-frame timber volume elements, manufactured in a factory and delivered for assembly on site. The external walls have ventilated façade plaster, glass wool insulation between timber studs, and gypsum boards as internal finishes. The internal walls have timber stud elements clad with gypsum panels while the intermediate floors have laminated wood flooring over particleboards supported by glulam beam elements, with glass wool insulation and plywood below. The roof has stone wool insulation, wooden trusses and aluminium roofing sheets over asphalt layers.

The structural framing of the CLT building system consists of CLT panel elements. The external walls have ventilated façade plaster, stone wool insulation between timber studs, and CLT panels with gypsum boards as internal finishes. The inner CLT load-bearing walls are clad with gypsum. The intermediate floors have laminated wood flooring over CLT panels and glulam beams with stone wool insulation and finished with gypsum boards below. The upper floor consists of stone wool insulation with wooden trusses and aluminium roofing sheets over asphalt layers.

For all the analysed building systems, the partition walls comprise 95 or 145 mm timber studs with 600 mm gaps, finished with gypsum boards. The ground floors are made up of layers of drained gravel, EPS insulation and concrete slabs with laminated wood flooring. The ground floors of the timber building systems have been adjusted considering their lighter weight compared to the prefabricated concrete system. The windows and external doors for all three building alternatives consist of three panes of clear glass and wood frames with external protective aluminium profiles and have an overall U-value of 0.8 W m^{-2} K^{-1}. The U-values of the other envelope elements for the building systems are 0.11 W m^{-2} K^{-1} for the ground floors, 0.11 for the external walls and 0.05 for the roofs. For more information about the analysed building systems see Ref. [28].

The full lifecycle impacts of the building systems are considered excluding the operation phase, as all the building versions are modelled to have the same operation energy use, thus impacts from the operation phase will be the same for all three buildings. We consider full material chains, covering extraction, processing, and transport of the materials needed for the construction of the buildings, including material losses. We also consider calcination and carbonation carbon flows related to cement materials. The energy chains include the efficiencies of fuel cycles, conversion and distribution systems.

The service life of each building system is assumed to be 80 years. At the end-of-life of the buildings, steel is expected to be recovered and recycled for the manufacture of new steel products. The demolished concrete is crushed into aggregate and exposed over four months to increase carbonation and subsequently used as below-ground filling material, while the demolished wood is recovered and used for energy. Cement calcination emissions and carbonation uptake analyses are based on [29]. Fig. 3 shows the emissions from calcination during

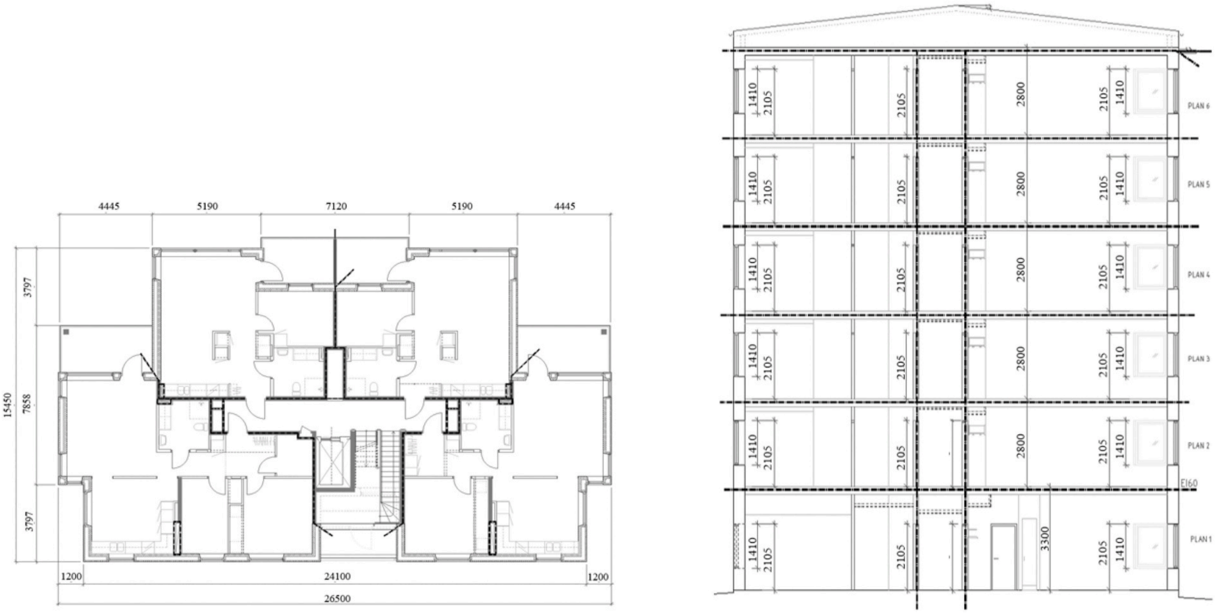

Fig. 2. Floor plan (left) and section (right) of the reference prefabricated concrete building.

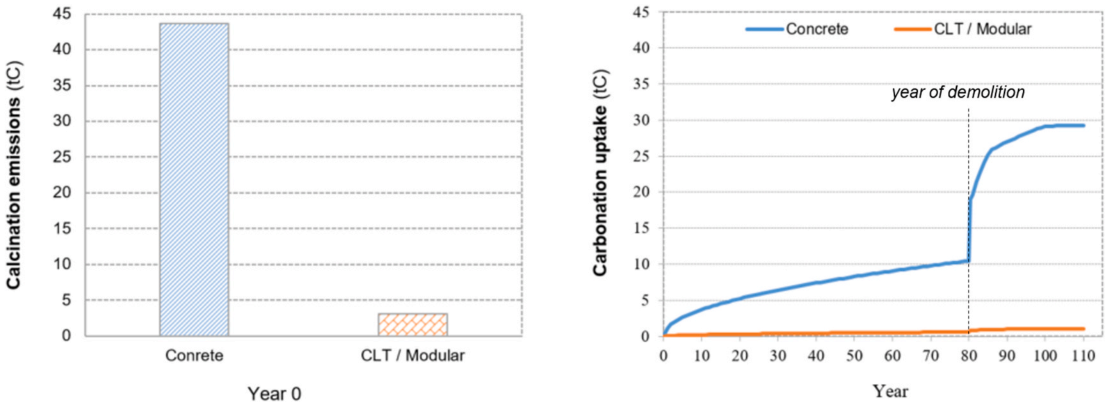

Fig. 3. Calcination emissions (left) and carbonation uptake (right) of cement-based materials in the analysed building systems.

cement manufacture, as well as cumulative carbon uptake due to carbonation of the cement-based materials in the analysed concrete and timber building systems.

Table 3 summarizes the resources used for different building systems based on [30] and data from Refs. [31,32]. The differences between wood-based and concrete-based building systems are used to evaluate the climate effects of different scenarios. In the main analysis, modular wood buildings replace concrete buildings, and in a sensitivity analysis CLT buildings replace concrete buildings, to show the effects of different timber building systems.

Production systems for building materials and construction change over time, giving variations in energy demands between processing materials using state-of-the-art facilities and those processed in older industries [33]. Hence, a spatial variation exists, as technological changes diffuse across countries. When comparing different materials, we consider the relative differences between producing them. If the processes for different materials have the same speed of development, the relative differences between them will remain about the same.

2.4. *Uses of forest products – energy systems*

Despite significant efforts to reduce GHG emissions in Europe, coal, fossil gas and oil provided respectively 14%, 24% and 33% of the EU primary energy supply in 2018 [10], and fossil fuels are likely to remain a dominant energy source for a long time. The share of renewables was 15.6%, comprised of 10.3% bioenergy, 1.8% hydro and 3.5% others. In comparison, of the total global primary energy use in 2018, fossil fuels, biomass and nuclear constituted about 81%, 9.5% and 5.0%, respectively, giving a fuel dependence of 95.5% [10]. Increased use of bioenergy could reduce the dependence on fossil fuels and facilitate the integration of intermittent wind and solar in renewable energy systems.

Table 3
Resources used for constructing one building and available wood residues with the different building systems.

Parameter (per building)	Concrete	CLT	Modular
Year of construction			
Stem wood (*dry tons*)	103	750	331
Fossil fuels used for building material production *(MWh)*	1136	517	556
Bioenergy used for building material production *(MWh)*	86	401	220
Electricity used for building material production *(MWh)*	242	214	238
Fossil fuels used for logistics *(MWh)*	9.32	76.8	32.0
Wood residues available for fuel substitution *(MWh)*	164	2103	736
Year of demolition			
Fossil fuels used for logistics *(MWh)*	2.85	13.5	7.52
Wood residues available for fuel substitution *(MWh)*	288	1359	761

Today, average conversion efficiency of standalone power plants in the EU is relative low [10,34] and use of combined heat and power (CHP) technologies are being promoted due to their better overall conversion efficiency and the simultaneous demand of heat and electricity in existing energy system. Beside the existing energy conversion technologies, emerging bio-based technologies based on gasification are of interest since a wide range of primary fuels can be used. Also, the produced syngas can be used directly for heat and electricity production as well as to upgrade to different types of motor fuels [35–40].

Residues from harvested forests, wood processing and end-of-life wood construction materials are here assumed to be used for energy purposes. The energy from such residues is used to replace that from fossil-based energy systems to provide the same energy service. Hence, each scenario of using bioenergy has a corresponding scenario of using fossil energy. Biomass is assumed to be mobilized and used in places where they can give greater benefits, because costs and emissions for the transportation of biomass for long distance are relative low [41]. In all the scenarios in this study, we include an international transport distance of 1000 km for forest biomass to be used for energy purposes.

In this analysis, we consider the use of biomass in large-scale CHP conversion facilities, including CHP plants using steam-turbine technology (CHP-BST), CHP plants using emerging gasification technology with combined cycle (CHP-BIGCC) and stand-alone production of methanol biomotor fuel (MF-MeOH). We consider three energy scenarios: (i) CHP-BST replaces efficient conventional coal-based CHP plants (CHP-CST), (ii) CHP-BIGCC replaces high-efficiency fossil gas-based CHP plants using combined cycle technology (CHP-FGCC) and (iii) MF-MeOH replaces gasoline in transportation. Conversion efficiency details of these considered technologies are given in Table 4.

2.5. *Climate scenarios*

Atmospheric CO_2 concentration has increased by 40% since pre-

Table 4
Conversion efficiencies of energy systems.

Conversion technology	Main product		Coproduct		Reference
	Type	Efficiency	Type	Efficiency	
Combined heat and power system					
CHP-BST	Heat	57%	Electricity	31%	[42]
CHP-BIGCC	Heat	47%	Electricity	43%	[42]
CHP-CST	Heat	57%	Electricity	31%	[43,44]
CHP-FGCC	Heat	47%	Electricity	50%	[43,44]
Motor fuel system					
MF-MeOH	MeOH	41%	Electricity	6%	[45]
Stand-alone electricity system					
BST	Electricity	45%	–	–	[44]
BIGCC	Electricity	50%	–	–	[46,47]

industrial times, primarily due to fossil fuel emissions, which has led to climate change [18]. Global mean surface temperature has increased by 0.85 °C between 1880 and 2012, and depending on future emission levels is expected to further increase by 0.3 °C–4.8 °C by 2100 [18].

During the decade 2002–2011, the average land temperature in Europe was 1.3 °C warmer than that during the period 1850–1899 [48]. The annual average temperature in Sweden is projected to increase between 2 °C and 6 °C by 2100, relative to the period 1961–1990. The greatest change is expected to occur in winter, though all seasons are likely to be affected [49]. In addition to temperature, solar radiation, precipitation, humidity and wind are expected to change.

Many factors will determine future climate conditions, such as population change, economic and social activities, governance policies, energy use, land use and technological changes. A number of different plausible emissions scenarios are used to model global climate systems, representing varying levels of GHG concentration in the atmosphere. The IPCC AR5 assessment report details four representative concentration pathway (RCP) scenarios that are named after their radiative forcing expected in 2100 relative to preindustrial levels. The RCP2.6 scenario has 2.6 W m^{-2} of forcing in 2100, while RCP4.5 has 4.5 W m^{-2}, RCP6.0 has 6.0 W m^{-2}, and RCP8.5 has 8.5 W m^{-2} [18]. These four RCPs represent atmospheric concentrations of 450, 650, 850, and 1370 ppm CO_2 equivalent by 2100, respectively [18,50].

In this study, all estimates of climate change effects on forest growth are based on the RCP4.5 scenario, which characterises climate change mitigation efforts that are currently feasible and that stabilise radiative forcing without overshoot after 2100 [51].

2.6. Changes in atmospheric CO_2 concentration and radiative forcing

The analysis of climate effects of forestry and forest products is complex, due to multiple stocks and flows of carbon that change over different time periods. Hence, the time horizon that is considered has a strong impact on the calculated climate benefits of biomass substitution [52]. The most common approach to analysing the climatic aspects of forestry is the carbon balance method, where net carbon emissions are summed up without regard to when they occur during the analysed period. In such an approach, systems with lower net emissions at the conclusion of the analysed period are suggested to have smaller climate implications, compared to systems with greater net emissions. However, such a method does not consider the atmospheric dynamics of GHG emissions and their effects on climate change.

A more suitable indicator is cumulative radiative forcing (CRF), which considers the energy added to or reduced from the earth system, and is a proxy measurement for surface temperature change. By using CRF instead of the carbon balance method, the effects of temporal dynamics of GHG emissions and uptakes on climate change can be considered. Other factors that give climate effects such as albedo changes, can also be expressed in terms of cumulative radiative forcing, enabling a comparison between different mechanisms that result in climate effects.

In our modelling, changes of atmospheric CO_2 concentration are calculated annually for 201 years, considering: (1) The net ecosystem exchange (NEE) of CO_2 between the forest system and the atmosphere based on changes in carbon stored in living trees, dead wood, soil as well as their natural growth and decay processes, and (2) material and fuel substitution effects of forest product and biomass use in the energy and building sectors. The NEE (in units of tons of C) during year t is calculated by using Equation (1):

$$NEE_t = (LTB_{t-1} - LTB_t) + (SC_{t-1} - SC_t) - HB_t \tag{1}$$

where LTB is the living tree biomass (tons of C), SC is the soil carbon (tons of C), and HB is the harvested biomass (tons of C).

The emission effects compared to the reference case of material and fuel substitution by forest product use is calculated by using Equation (2):

$$\Delta Emissions = \Delta NEE + \Delta Building + \Delta Bioenergy + \Delta Fossil + \Delta Operations \tag{2}$$

where *ΔNEE* is the NEE of the selected scenario minus that of the reference scenario, *ΔBuilding* is the building-related emissions of the selected scenario minus that of the reference scenario, *ΔBioenergy* is the emissions from bioenergy of the selected scenario minus that of the reference scenario, *ΔFossil* is the emissions from fossil energy of the selected scenario minus that of the reference scenario, and *ΔOperations* is the emissions from forest operations of the selected scenario minus that of the reference scenario.

Natural removal of CO_2 from the atmosphere is estimated by using Equation (3) [53,54],

$$(CO_2)_t = (CO_2)_0 \times \left[0.217 + 0.224e^{\frac{-t}{394.4}} + 0.282e^{\frac{-t}{36.54}} + 0.276e^{\frac{-t}{4.304}}\right] \tag{3}$$

where t is the number of years since the emission occurred, $(CO_2)_0$ is the mass of CO_2 that is initially emitted, and $(CO_2)_t$ is the mass of CO_2 that remains in the atmosphere at year t.

We then convert the time profile of mass of CO_2 in the atmosphere to atmospheric concentration of CO_2, based on the mass of the atmosphere as well as the molecular masses of CO_2 and air. Based on the resulting changes in CO_2 concentration in the atmosphere, we calculate the marginal changes in instantaneous radiative forcing using Equation (4) [54–56],

$$F_{CO_2} = 5.35 \times \ln\left\{1 + \frac{\Delta CO_2}{CO_{2ref}}\right\} \tag{4}$$

where F_{CO2} is the instantaneous radiative forcing in units of W m^{-2}, ΔCO_2 is the change in atmospheric concentration of CO_2 (ppmv), and CO_{2ref} is the reference atmospheric concentration of CO_2 based on the RCP4.5 scenario. The resulting values of instantaneous radiative forcing are annual and global averages, which we then integrate across time and area to determine aggregated impacts. For each year through 2216, we estimate the CRF in units of MJ of heat accumulated within the Earth system, per m^2 of surface area of the troposphere (MJ m^{-2}).

3. Results

3.1. Forest growth, harvest and carbon balance

Fig. 4 presents the mass of carbon in living tree biomass, in forest soil and dead wood, and in total for the three scenarios over the 201-year modelling period. All the 3 scenarios show increasing trends in forest carbon storage. The Production and BAU scenarios somewhat continue to increase the living tree biomass during the full 201-year period and by the final year the difference in standing biomass between the Set-aside and Production scenarios is rather small. Total carbon storage is highest in the Set-aside scenario during much of the time, while the Production and Set-aside scenarios each have roughly the same total amount of carbon storage by the end of modelling period, while the BAU scenario has significantly less carbon stored.

Fig. 5 shows the cumulative harvested saw logs and pulp logs of the 3 main scenarios. Saw logs are predefined in the Heureka modelling software based on the diameters of the stem wood and are used to produce lumber and other mechanical wood products, while pulp logs have smaller diameters and used to produce lower value pulp and paper products. The Production scenario has the greatest harvest of both saw and pulp logs, together more than twice as much as the Set-aside scenario after 201 years. In the Production scenario more saw logs are harvested than pulp logs, while in the other 2 scenarios more pulp logs are harvested than saw logs. This is likely due to the differences in management regime and species selection that result in a higher proportion of large-diameter saw logs in the Production scenario.

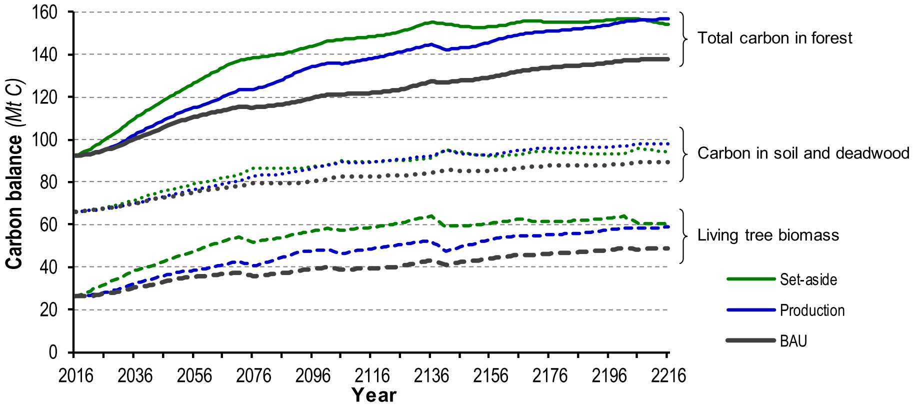

Fig. 4. Carbon storage in living tree biomass (above and below ground), in soil and dead wood, and in total, for the three forest scenarios.

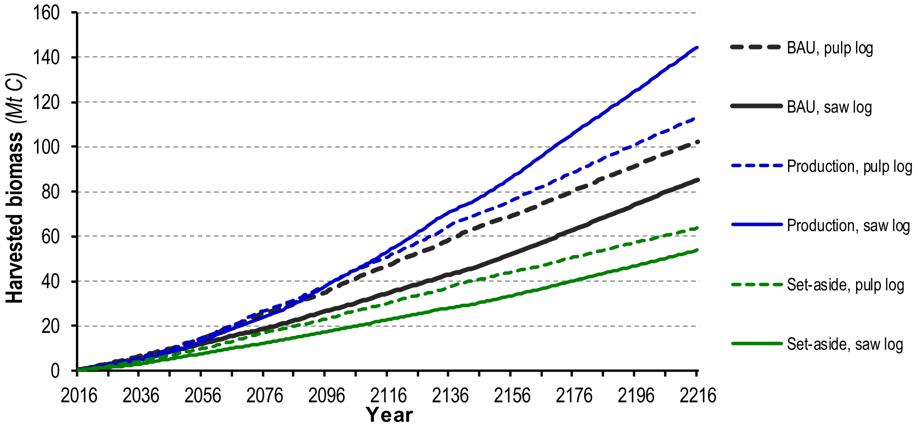

Fig. 5. Cumulative harvested biomass divided in saw logs and pulp logs for the three forest scenarios.

Fig. 6 shows the cumulative harvest in the three Production sub-scenarios, differentiating between stem wood (including saw logs and pulp logs), slash, and stumps. The difference in cumulative harvest of stem wood is very small between the Production sub-scenarios, and is a result of the slightly reduced forest growth due to the nutrient loss from harvesting slash and stumps. The harvest of stem wood is about ten times higher than that of slash. When slash and stumps are both harvested (Production (80/40), roughly the same amount of biomass in slash and stumps are harvested. The harvest of forest residues is based on practical potential based on current technologies and not on theoretical potentials, and 80% slash and 40% stumps are assumed to be harvested from final fellings.

Fig. 7 shows the cumulative harvest of the 3 main scenarios including slash and stumps, distinguishing between the harvest of logs (both pulp and saw logs) and residues (both slash and stumps). The Production scenario has substantially greater harvest of both logs and residues, compared to the other two forest scenarios. Biomass harvest in the Production scenario is more than double that of the Set-aside scenario. In all scenarios, the amount of harvested logs is about 5 times greater than the harvested residues.

3.2. Climate effects

To estimate the climate effects of changes in forestry practices, the

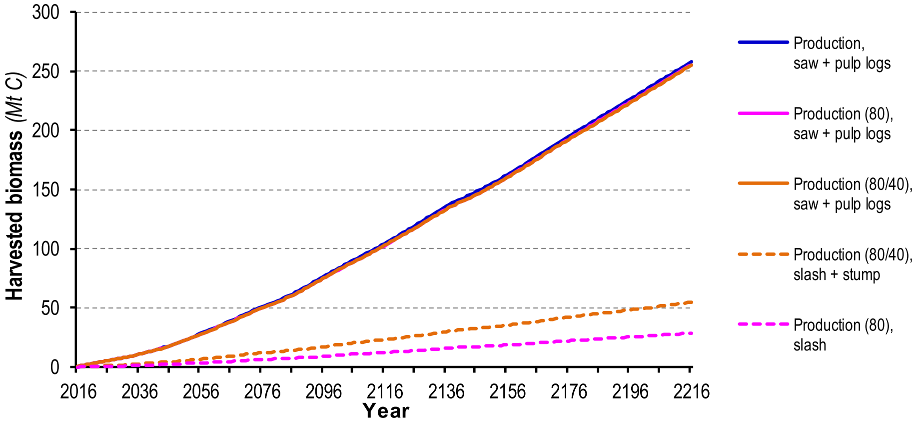

Fig. 6. Cumulative harvest divided in stem wood (including saw and pulp logs), slash and stumps for the three Production sub-scenarios.

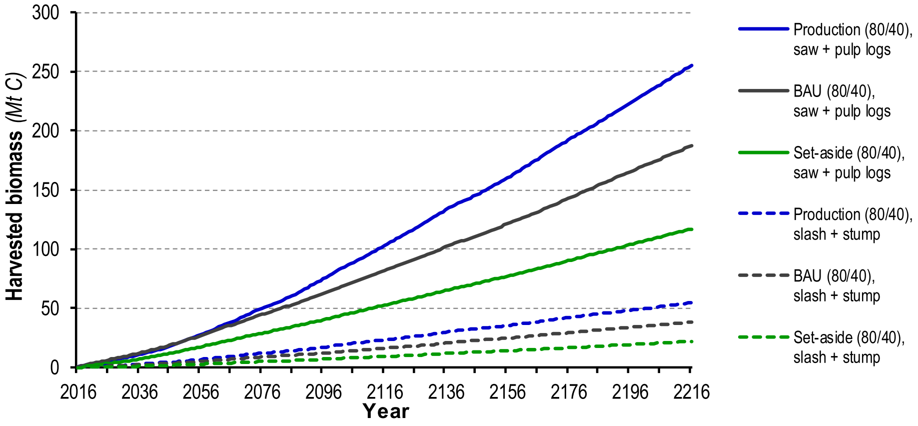

Fig. 7. Cumulative harvest divided in stem wood (including saw and pulp logs) and residues (including slash and stumps) for the BAU (80/40), Production (80/40) and Set-aside (80/40) scenarios.

carbon flows of the Production and Set-aside scenarios are compared to the flows of the BAU scenario. Fig. 8 shows the cumulative CO_2 emissions for the different scenarios, relative to the BAU scenario which is the zero line. The collected forest residuals, by-products from wood processing and construction, and incremental pulp wood are used for heat and electricity production using CHP-BST technology to replace heat and electricity from CHP-CST technology. Saw logs are used to make buildings with modular timber frames, which replace concrete frame buildings. For the first 30–35 years the cumulative emission is lowest for the Set-aside scenarios (top figure). Over the full 201-year period (bottom figure), the Production scenarios yield strong emission reductions and the Set-aside scenarios result in increased emissions. This is because the Production scenario continues to produce large biomass harvests that substitute for carbon intensive fuels and materials, while the carbon storage in the Set-aside scenario gradually stabilizes as the set-aside forest stands mature. The Production scenarios have less cumulative emissions than BAU after about 20 years while the Set-aside scenarios have greater emissions than BAU after about 80 years.

Fig. 9 shows the CRF for the same scenarios as in Fig. 8. The long-term pattern of CRF is about equal to the cumulative emissions, with the Production scenarios having strong reductions in climate forcing, while the Set-aside scenarios have greater forcing than BAU. However,

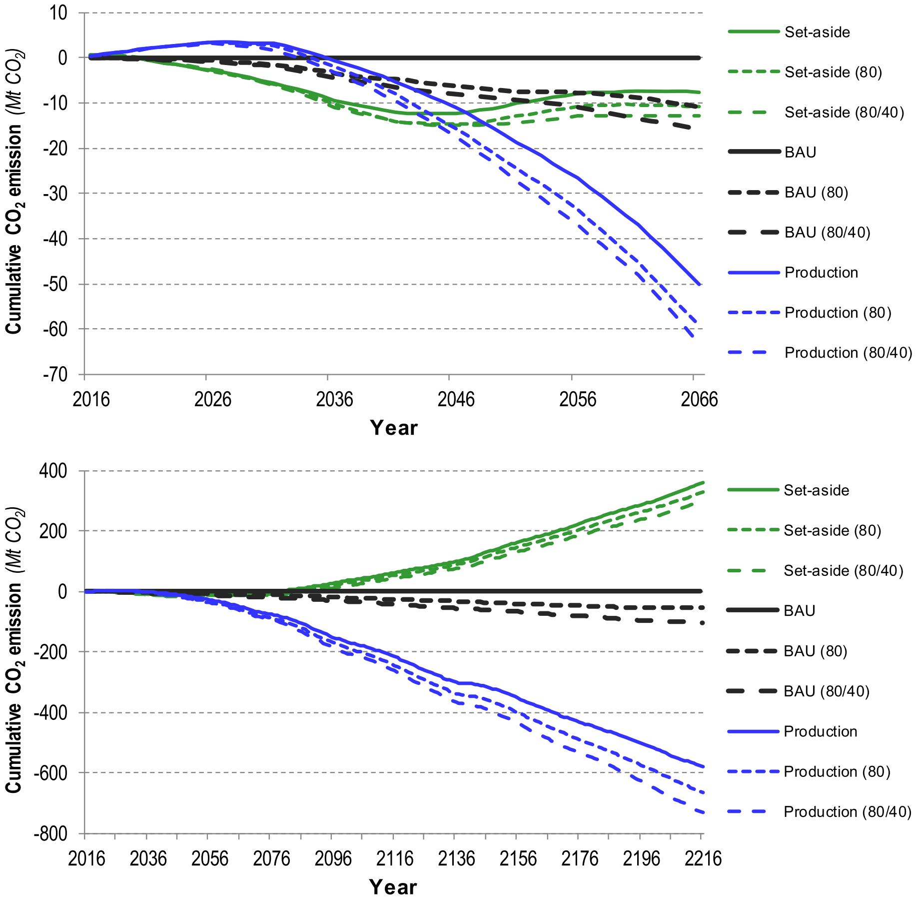

Fig. 8. Differences in cumulative CO_2 emissions for different forest management scenarios compared to BAU (zero line) when CHP-BST plants and modular timber frame buildings replace CHP-CST plants and concrete frame buildings, respectively, during first 50 years (top) and full 201-year period (bottom).

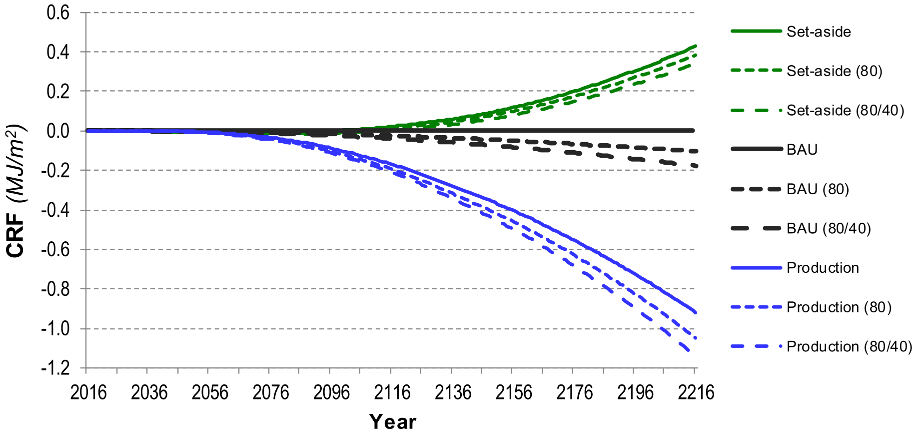

Fig. 9. Differences in cumulative radiative forcing from different forest management scenarios, compared to BAU (zero line) when CHP-BST plants and modular timber frame buildings replace CHP-CST plants and concrete frame buildings, respectively.

the difference between the scenarios is very small during the first 50 years.

Fig. 10 and Fig. 11 show the cumulative total CO_2 emissions and the CRF, respectively, for the different forest scenarios relative to the BAU scenario, when the collected forest residuals, by-products from wood processing and construction, and incremental pulp wood are used for heat and electricity production using CHP-BIGCC technology to replace that from CHP-FGCC technology, and saw logs are used to make buildings with modular timber frames that replace concrete frame buildings. The figures show patterns that are similar to Figs. 8 and 9, but the magnitude of the differences between scenarios is smaller because the carbon intensity of the replaced fossil fuel system is lower.

Figs. 12 and 13 show the cumulative total CO_2 emissions and CRF, respectively, for the different forest scenarios relative to the BAU scenario, when the collected forest residuals, by-products from wood processing and construction, and the extra pulp wood are used for motor fuel production replacing gasoline, while buildings with modular timber frame replace concrete frame buildings. The figure shows similar patterns as the previous figures, but the magnitude of the differences between scenarios is much smaller, and the effects of harvesting slash and stumps is much smaller. This is because the conversion efficiency of biomotor fuel production is quite low (see Table 4) so less fossil fuel is

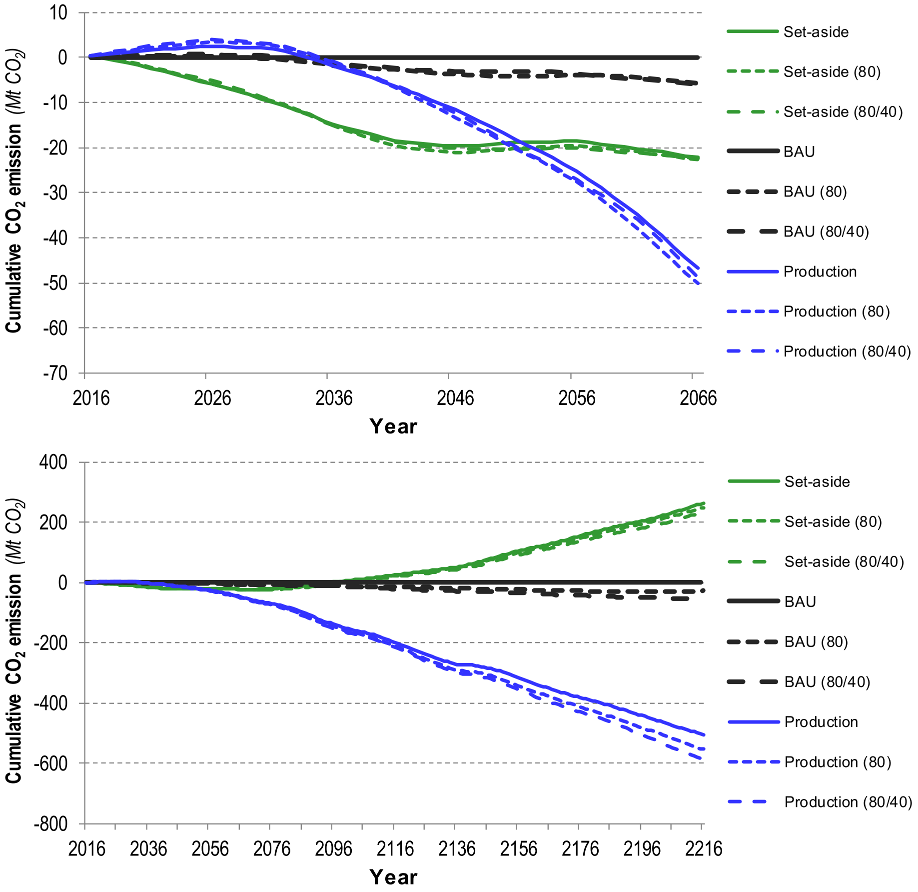

Fig. 10. Differences of cumulative CO_2 emissions for different forest management scenarios compared to BAU (zero line) when CHP-BIGCC plants and modular timber frame buildings replace CHP-FGCC plants and concrete frame buildings, respectively, during first 50 years (top) and full 201-year period (bottom).

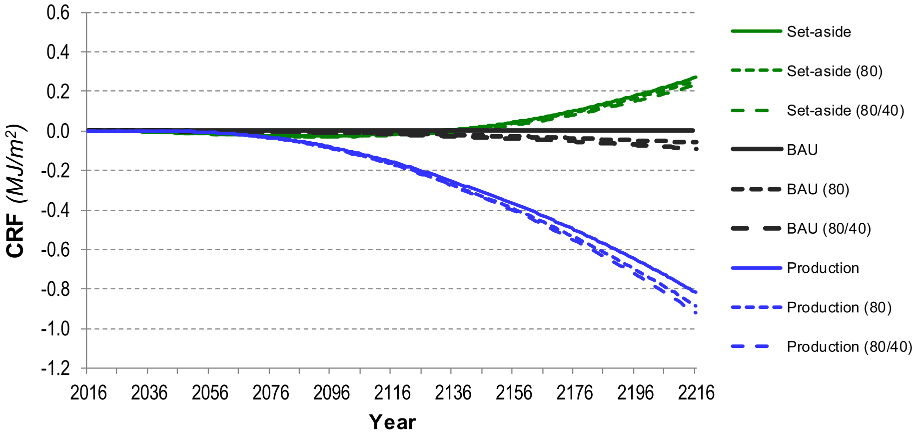

Fig. 11. Differences of cumulative radiative forcing from different forest management scenarios compared to BAU (zero line) when CHP-BIGCC plants and modular timber frame buildings replace CHP-FGCC plants and concrete frame buildings, respectively.

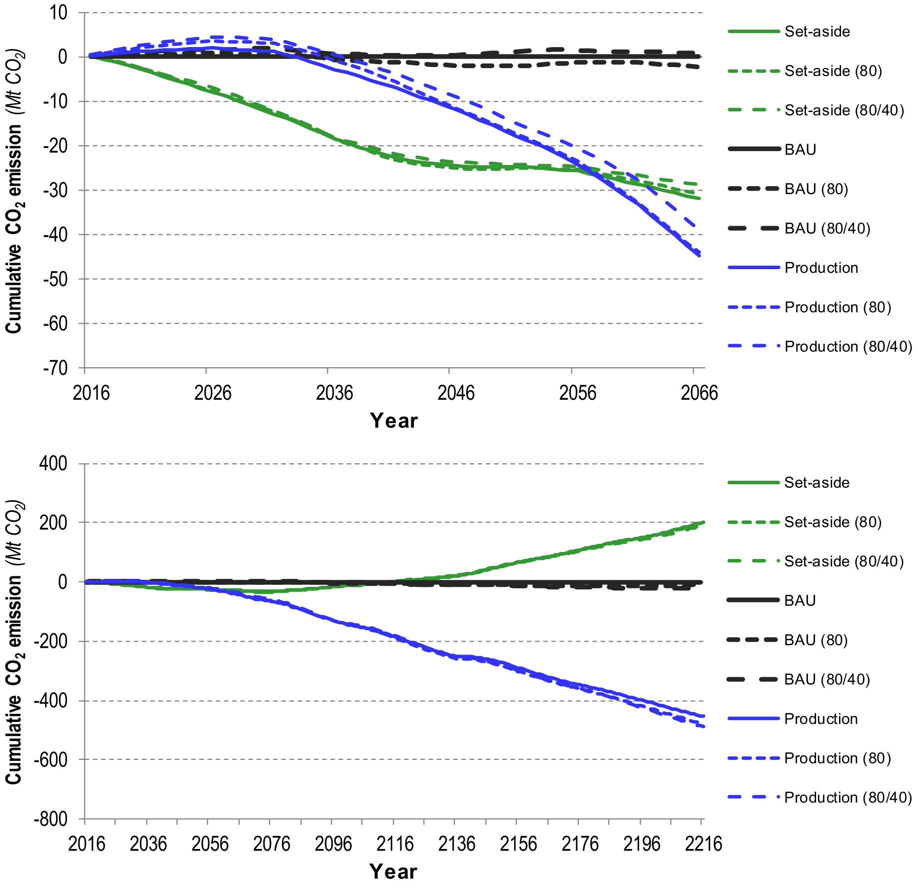

Fig. 12. Differences of cumulative CO_2 emissions for different forest management scenarios compared to BAU (zero line) when biomotor fuels and modular timber frame buildings replace gasoline and concrete frame buildings, respectively, during first 50 years (top) and full 201-year period (bottom).

replaced per unit of biomass harvested.

3.3. Sensitivity analysis of forest management

Fig. 14 shows the cumulative total CO_2 emissions for the sensitivity analysis of varied forest scenarios, relative to the BAU scenario which is the zero line. These scenarios follow the same patterns as the main scenarios, in proportion to their scale of implementation. The Production 20 scenario, with 20% increase in forest growth, shows reduced cumulative emissions similar to the main Production scenario (which has a 40% increase in growth), but of smaller magnitude. The Set-aside 32 scenario, with 32% of forest land set aside, shows increased cumulative emissions similar to the main Set-aside scenario (which has 50% of forest land set aside), but of smaller magnitude. The Set-aside + Production scenario, in which set-aside area is as in the Set-aside scenario and the forest productivity for non-set aside area is as in Production scenario, shows initial reduction in emissions but over time becomes similar to the BAU scenario.

Fig. 15 shows the CRF for the sensitivity analysis scenarios, relative to the BAU scenario which is the zero line. Similar to the above figures

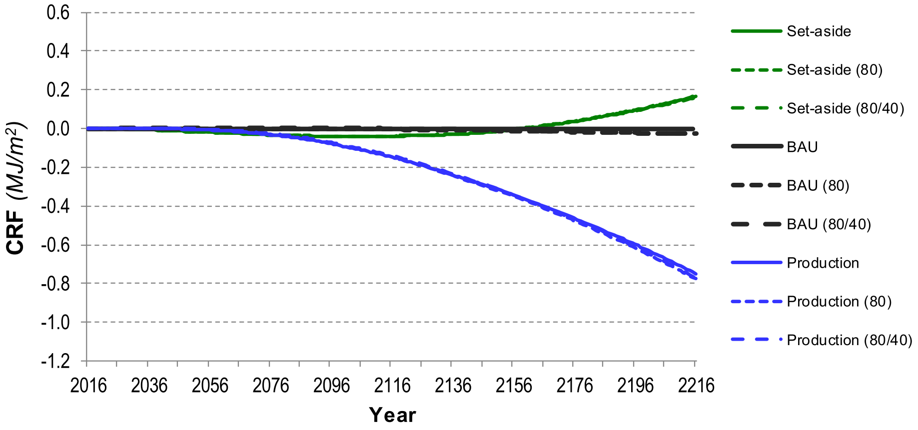

Fig. 13. Differences of cumulative radiative forcing from different forest management scenarios compared to BAU (zero line) when biomotor fuels and modular timber frame buildings replace gasoline and concrete frame buildings, respectively.

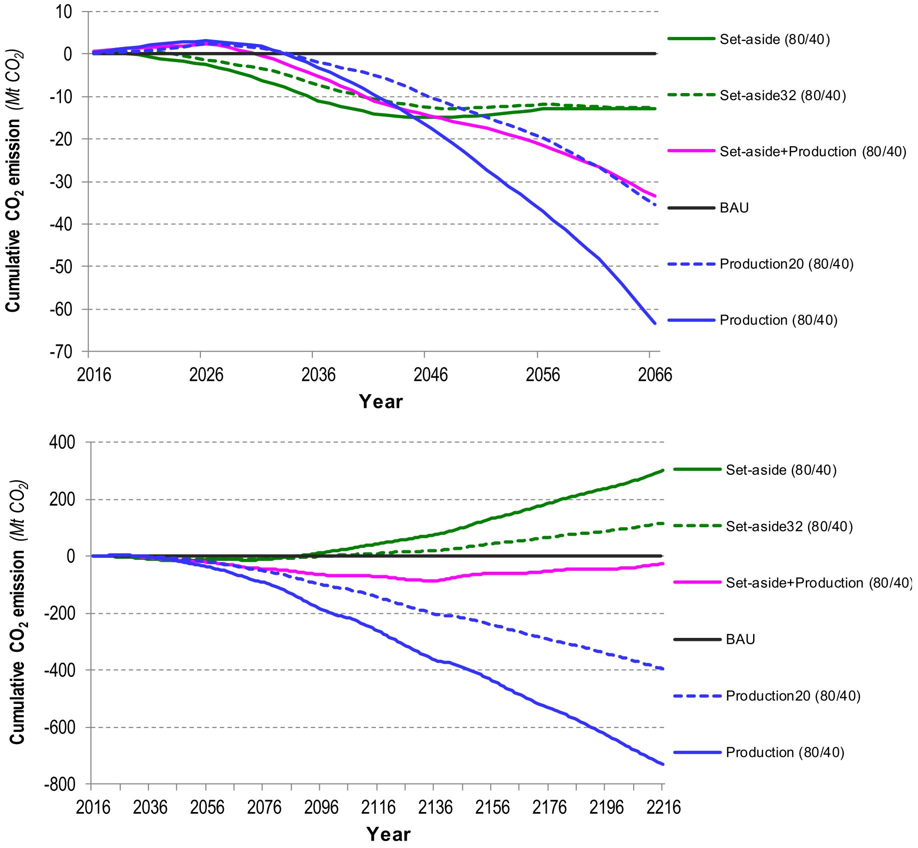

Fig. 14. Differences of cumulative CO_2 emissions for different forest management scenarios compared to BAU (zero line) when CHP-BST plants and modular timber frame buildings replace CHP-CST plants and concrete frame buildings, respectively, during first 50 years (top) and full 201-year period (bottom).

showing cumulative emissions, the sensitivity analysis scenarios follow the same patterns as the main scenarios, in proportion to their scale of implementation. The Set-aside + Production scenario has slightly reduced CRF compared to BAU.

3.4. Sensitivity analysis of building systems

Figs. 16 and 17 show the cumulative CO_2 emissions and CRF, respectively, relative to the BAU scenario which is the zero line, when saw logs are used to produce CLT buildings or modular buildings, that replace concrete buildings. The effect of the type of wood-framed building system is significant, but smaller than the effect of the type of energy system (Figs. 8–13). Using CLT building systems results in slightly less climate benefits compared to using modular building systems, when replacing concrete buildings. This is because CLT building systems require more specific wood use than the modular building systems, thus for a given amount of wood harvest, fewer concrete buildings can be replaced by CLT buildings than by modular buildings.

4. Discussion

In this study, the climate implications of forestry, bioenergy and wood construction are considered in a holistic life-cycle system perspective. The analysis is based on a detailed description of forest

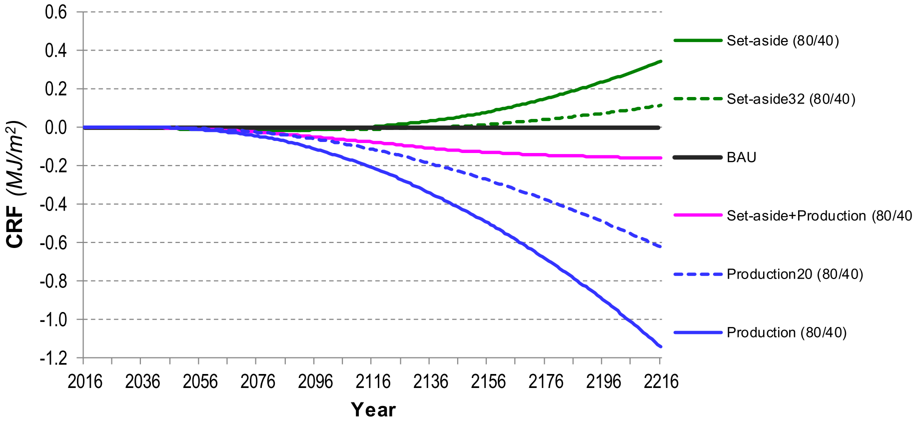

Fig. 15. Differences of cumulative radiative forcing for different forest management scenarios compared to BAU (zero line) when CHP-BST plants and modular timber frame buildings replace CHP-CST plants and concrete frame buildings, respectively.

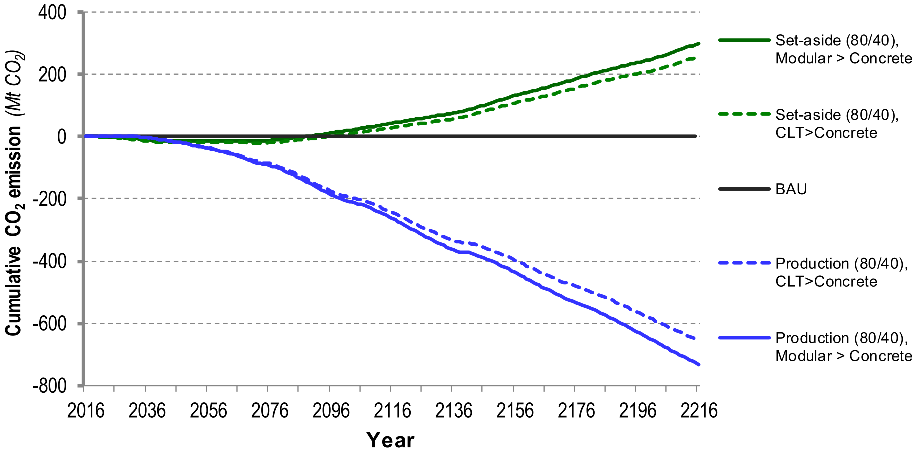

Fig. 16. Differences of cumulative CO_2 emissions for different forest management scenarios compared to BAU (zero line) when modular or CLT building systems replace concrete building system and when CHP-BST plants replace CHP-CST plants.

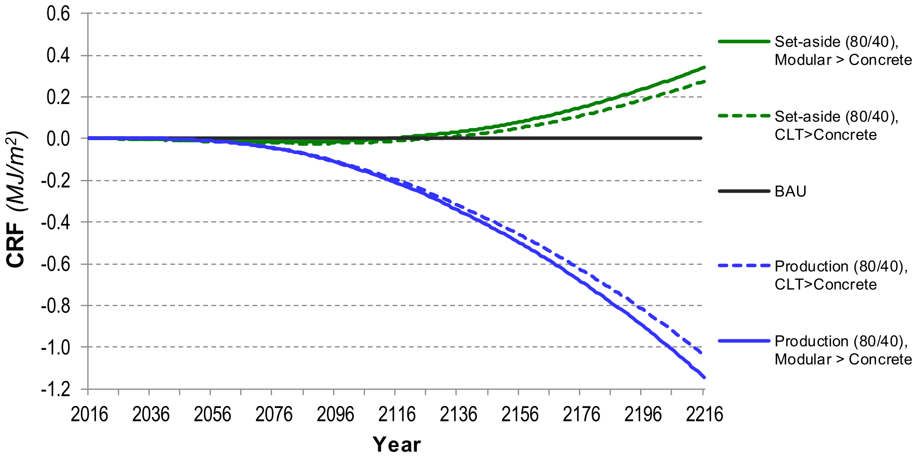

Fig. 17. Differences of cumulative radiative forcing for different forest management scenarios compared to BAU (zero line) when modular or CLT building systems replace concrete building system and when CHP-BST plants replace CHP-CST plants.

systems and technical systems, where a landscape perspective is used to assess the dynamics of productive forests in Kronoberg County in Sweden. All annual net CO_2 emissions are considered, but not other climate effects such as albedo. The timespan of 201 years appears to be long enough to establish robust trends, as multiple consecutive forest rotation periods are included in the analysis, although long-term technological development may strongly influence the results.

Key factors steering the results are forest management intensity, amount and use of harvested biomass, replaced non-wood products and fuels, and timespan of the analysis. The most important single factor is the forest management intensity, which leads to significant long-term climate benefits in the case of Production scenario, and climate impacts in the case of Set-aside scenario (Figs. 8–15). The amount of harvested biomass is a critical parameter, and climate benefits are increased as the amount of slash and stump harvest increases (Figs. 8–9). The type of fossil energy that is replaced is also important, as replacement of coal results in larger reduction of net CO_2 emission than if fossil gas or oil is replaced (Figs. 8–13). Scenarios with more set-aside land show greater climate benefits over short time horizons of several decades, while scenarios with more forest productivity show greater climate benefits over medium to long time horizons.

The Production scenario consistently results in lower net CO_2 emissions and CRF compared to the BAU and Set-aside scenarios, after an initial period of 30–35 years when the Set-aside scenario has less CO_2 emissions. The main reason is because the Production scenario gives greater sustained harvest of forest biomass that can be used to substitute carbon-intensive fuels and materials. The Set-aside scenario shows short-term climate benefits as growing forests sequester additional carbon, but eventually leads to greater net emissions and climate forcing as the set-aside forests mature and carbon uptake diminishes. Over the full 201-year period, the Production scenario yields strong emission reductions, about ten times greater than the initial reduction in the Set-aside scenario, while the Set-aside scenario shows increased emissions.

The type of energy system has an important effect, and a large reduction of CO_2 emissions and climate forcing is achieved when biomass replaces coal-based energy systems. A much smaller reduction is achieved when gasoline is replaced, due to the low efficiency of converting woody biomass to liquid fuel. During a transition to renewable based societies, fossil coal may be replaced first and then fossil gas for electricity and heating, by using suitable biomass-based energy-efficient technologies, like highly efficient CHP plants producing electricity and heat. Such dispatchable plants will also help to integrate large scale intermittent electricity such as solar and wind energy.

Our results show that if gasoline is replaced instead of fossil coal, the CO_2 emission benefits of BAU scenario, compared to the Set-aside scenario, is delayed by about 35–38 years and the cumulative CO_2 reduction over the full simulation period is reduced by about 110 to 160 Mt CO_2. This is in line with the results given by Ref. [57] that it may take 30–40 years to get net CO_2 emission reductions of biomotor cars using forest residues compared to gasoline cars. Also, bioenergy-based electric cars give much higher net CO_2 emission reductions per unit of consumed biomass than biomotor fuel cars in the long run [57]. This is due to the high instantaneous biogenic CO_2 emission per driven distance for biomotor cars.

In contrast, electric cars with electricity from CHP plants using forest residues give almost immediate net CO_2 emission reduction compared to fossil alternatives. The need for biomotor fuels may be avoided or at least strongly reduced by electrification of the transportation sector. There is also an issue of lock-in effects, as the construction of large-scale infrastructure for biomotor fuel production may take at least 10 years, and such investments may have a lifespan of 30–50 years. Hence, following a biomotor fuel path may help to continue the lock-in of combustion engine technology and may hinder the electrification of the transportation sector.

A basic assumption in this study is that forest products play a central role in a global society based on renewable resources. If other solutions appear in the future, forest products and the forest industry may not be needed, but transforming production forests to conservation forests and phasing out the forest products industry may be difficult. The reverse, to transform conservation forests to production forests and to develop new forest industries, may be even more difficult.

In a sustainable society, the use of fossil energy and carbon intensive materials will decrease, and the substitution effects will change compared to the current situation. However, even if very little fossil energy is used, the specific substitution effect would still be high when substituting the remaining part of fossil energy. In a future energy supply without fossil energy, the calculation of energy substitution is less relevant, but woody biomass may still play important roles as both fuel and material in a society based on renewable resources.

The type of wood-based building system that is used to replace concrete buildings is found to be less significant than the type of replaced energy system, though modular timber buildings give greater climate benefits compared to CLT buildings. However, CLT constructions may have a broader application than light timber construction, and the light timber construction may not be an alternative in some contexts. Off-site building production in large-scale centralized facilities may also bring other advantages including lower cost, higher quality control, and more rapid construction than on-site construction. The assumed building lifetime of 80 years is rather short, and a longer lifetime will support a sustainable built environment as the natural resources are more efficiently used. Also, with a longer building service life, the carbon in the buildings is locked in for a longer time, giving some climate benefits.

As with any future-oriented study, there are substantial uncertainties regarding our analysis. The models we used, though relatively sophisticated, are necessarily an incomplete representation of reality, and are limited by the methods, assumptions and data that were used. For example, our modelling assumes that future climate change will follow the RCP 4.5 trajectory, with moderate temperature rise. Other climate trajectories are possible, depending on the success or failure of global mitigation efforts, which may strongly affect forest ecosystems. Even under the RCP 4.5 scenario, there is uncertainty about future forestry conditions and the emergence of drought, wildfires, insect infestation and other major forest disturbances. Another inherent uncertainty is the extent of future technology advances in both the energy and building sectors, which could increase or decrease the climate benefits of wood substitution. The long time horizon of this study (201 years) increases the significance of such uncertainties.

Our results are in line with other studies that have compared the climate effects of different forest management strategies [3,5–9]. While trends and conclusions are largely consistent between studies, variations could be due to differences in geographical areas, methods and assumptions. For example, the harvest of forest residues in relation to harvest of pulp and saw logs are much higher in Ref. [5] compared to this study, giving higher climate benefits per forest land area. The reason for this may be the geographic differences between studies and the corresponding differences in tree species, management regimes and the logistics of biomass harvest.

Generally, holistic system analyses have found that as the time horizon of interest increases, it becomes more climatically beneficial to actively manage forests and use renewable forest-based fuels and products. In the short term, however, conserving forests to maintain carbon storage typically provides some climate benefits compared to other alternatives. While modelling studies can illuminate these temporal trade-offs of alternate forest management practices, the decision of which practices to implement will depend on several factors including time perspectives and societal preferences.

5. Conclusions

In this study we found that the Production scenario consistently resulted in less net CO_2 emissions and CRF compared to the BAU and Set-aside scenarios, after an initial period of 30–35 years when the Set-aside scenario had slightly lower emissions. Forest management intensity critically affects the climate effects of a forest system, and climate benefits increase as the amount of biomass harvest including slash and stumps increases. The type of fossil energy that is replaced is also climatically important, and replacing coal results in larger reduction of net CO_2 emission than if fossil gas or oil is replaced.

The Set-aside scenario showed initial climate benefits as the growing forests sequestered additional carbon. After several decades, however, this carbon sink saturated as the set-aside forests matured and carbon uptake diminished, leading to greater net emissions and climate forcing due to the use of carbon-intensive fossil fuels and materials. By the end of the full 201-year modelling period, the cumulative emissions of the

Set-aside scenarios are greater than those of BAU. The Production scenario after 201 years had an emission reduction about ten times greater than the initial temporary reduction in the Set-aside scenario.

The finite area of global forest land makes forest products a limited resource, thus the energy and material chains may be selected so they give high specific service to the society and be as efficient as possible. For example, using biomotor fuel from woody biomass results in much higher specific biomass use than using electric vehicles with electricity from woody biomass [57]. Similarly, the specific woody biomass use is higher for cross-laminated timber building systems than modular timber building systems [28].

In the long run, active forestry with high harvest levels and efficient use of harvested biomass to replace carbon-intensive non-wood products and fuels provides significant climate mitigation, in contrast to setting aside forest land to store more carbon in the forest and reduce the amount of harvested biomass. This general conclusion may apply to other regions with similar boreal forest conditions as Sweden and with a large proportion of the forest area under management.

Author contributions

L. Gustavsson: Conceptualization, Methodology, Writing, Supervision; T. Nguyen: Methodology, Analysis, Writing; R. Sathre: Methodology, Analysis, Writing; U.Y.A. Tettey: Analysis, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of abbreviations

BAU	Business as usual
CHP	Combined heat and power
CHP-BIGCC	Combined heat and power plant using biomass gasification technology with combined cycle
CHP-BST	Combined heat and power plant using biomass-fired steam-turbine technology
CHP-CST	Combined heat and power plant using coal-fired steam-turbine technology
CHP-FGCC	Combined heat and power plant using fossil gas combined cycle
CH_4	Methane
CLT	Cross-laminated timber
CO_2	Carbon dioxide
CRF	Cumulative radiative forcing
EPS	Expanded polystyrene
GHG	Greenhouse gas
GWP	Global warming potential
MF-MeOH	Methanol motor fuel
NEE	Net ecosystem exchange
NFI	Swedish national forest inventory
N_2O	Nitrous oxide
RCP	Representative concentration pathway

References

[1] Dewar RC. Analytical model of carbon storage in the trees, soils, and wood products of managed forests. Tree Physiol 1991;8(3):239–58.

[2] Nabuurs GJ, Mohren GMJ. Carbon Fixation through Forestation Activities. A study of the carbon sequestering potential of selected forest types. In: IBN research report 93/4. Wageningen, The Netherlands: Face/Institute for Forestry and Nature Research (IBN-DLO); 1993.

[3] Schlamadinger B, Marland G. The role of forest and bioenergy strategies in the global carbon cycle. Biomass Bioenergy 1996;10(5):275–300.

[4] Börjesson P, Gustavsson L. Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. Energy Pol 2000; 28(9):575–88.

[5] Lippke B, Wilson J, Perez-Garcia J, Bowyer J, Meil J. CORRIM: life-cycle environmental performance of renewable building materials. For Prod J 2004;54 (6):8–19.

[6] Eriksson E, Gillespie AR, Gustavsson L, Langvall O, Olsson M, Sathre R, et al. Integrated carbon analysis of forest management practices and wood substitution. Can J For Res 2007;37(3):671–81.

[7] Werner F, Taverna R, Hofer P, Thürig E, Kaufmann E. National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environ Sci Pol 2010;13(1):72–85.

[8] Gustavsson L, Haus S, Lundblad M, Lundström A, Ortiz CA, Sathre R, et al. Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels. Renew Sustain Energy Rev 2017;67:612–24.

[9] Xu Z, Smyth CE, Lemprière TC, Rampley GJ, Kurz WA. Climate change mitigation strategies in the forest sector: biophysical impacts and economic implications in British Columbia, Canada. Mitig Adapt Strategies Glob Change 2018;23(2):257–90.

[10] IEA. World energy outlook 2019. International Energy Agency; 2019.

[11] Zabalza Bribián I, Valero Capilla A, Aranda Usón A. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 2011;46(5): 1133–40.

[12] Dodoo A, Gustavsson L, Sathre R. Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems. Energy Build 2014;82: 194–210.

[13] Haus S, Gustavsson L, Sathre R. Climate mitigation comparison of woody biomass systems with the inclusion of land-use in the reference fossil system. Biomass Bioenergy 2014;65:136–44.

[14] Nilsson C. Windstorms in Sweden - variations and impacts. In: Dept of physical geography and ecosystem science. Sweden: Lund, Sweden: Lund University; 2008.

[15] Fridman J, Lundström A, Löfvenius MO, Valinger E. Analysis of storm damage after Gudrun - an application of continuous environmental analysis (in Swedish: Analys av stormskador efter Gudrun - en tillämpning av fortlöpande miljöanalys), 8. Fakta Skog; 2006.

[16] Claesson S, Duvemo K, Lundström A, Wikberg P-E. Forest impact assessments 2015. Swedish Forest Agency report no. 10 (in Swedish: Skogliga konsekvensanalyser 2015 – SKA15. Skogsstyrelsen rapport nr. 10). Swedish Forest Agency; 2015. Web-accessed at, http://shop.skogsstyrelsen.se/sv/publikationer/rapporter/skogliga-konsekvensanalyser-2015-ska-15.html.

[17] Swedish Forest Agency. The statistical database. 2020. Web-accessed at, https://www.skogsstyrelsen.se/statistic.

[18] IPCC Intergovermental Panel on Climate Change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, editors. Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013. p. 1535.

[19] Wikström P, Edenius L, Elfving B, Eriksson LO, Lämås T, Sonesson J, et al. The Heureka forestry decision support system: an overview. Math Comput For Nat Resour Sci 2011;3(2):87–95 (8).

[20] Ågren GI, Hyvönen R. Changes in carbon stores in Swedish forest soils due to increased biomass harvest and increased temperatures analysed with a semi-empirical model. For Ecol Manag 2003;174(1):25–37.

[21] Fridman J, Holm S, Nilsson M, Nilsson P, Hedstrom Ringvall A, Ståhl G. Adapting national forest Inventories to changing requirements - The case of the Swedish national forest Inventory at the turn of the 20th century. Silva Fenn 2014;48(3). Article ID 1095.

[22] Berg S, Lindholm E-L. Energy use and environmental impacts of forest operations in Sweden. J Clean Prod 2005;13(1):33–42.

[23] Lindholm E-L, Berg S. Energy use in Swedish forestry in 1972 and 1997. Int J For Eng 2005;16(1):27–37.

[24] Davis J, Haglund C. Life cycle inventory (LCI) of fertiliser production: fertiliser products used in Sweden and Western Europe. SIK; 1999. SIK rapport volume 654; ISSN 0436-2071.

[25] Mead DJ, Pimentel D. Use of energy analyses in silvicultural decision-making. Biomass Bioenergy 2006;30(4):357–62.

[26] Mangoyana RB. Bioenergy from forest thinning: carbon emissions, energy balances and cost analyses. Renew Energy 2011;36(9):2368–73.

[27] Building Codes, Swedish National Board of Housing, Building and Planning (in Swedish: Boverkets Byggregler, Boverkets Författningssamling). 2015. https://www.boverket.se/en/start/publications/publications/2015/application-of-the-european-construction-standards-eks-10/.

[28] Tettey UYA, Dodoo A, Gustavsson L. Effect of different frame materials on the primary energy use of a multi storey residential building in a life cycle perspective. Energy Build 2019;185:259–71.

[29] Dodoo A, Gustavsson L, Sathre R. Carbon implications of end-of-life management of building materials. Resour Conserv Recycl 2009;53(5):276–86.

[30] Sathre R, Gustavsson L. Energy and carbon balances of wood cascade chains. Resour Conserv Recycl 2006;47(4):332–55.

[31] Björklund T, Tillman A-M. LCA of building frame structures: environmental impact over the life cycle of wooden and concrete frames. In: Technical environmental planning report 2. Gothenburg, Sweden: Chalmers University of Technology; 1997.

[32] Lehtonen A, Mäkipää R, Heikkinen J, Sievänen R, Liski J. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. For Ecol Manag 2004;188(1):211–24.

[33] Gustavsson L, Sathre R. Variability in energy and carbon dioxide balances of wood and concrete building materials. Build Environ 2006;41(7):940–51.

[34] EEA. Primary energy consumption by fuel. Indicator specification, data and maps. European Environment Agency; 2017. Web-accessed at: https://www.eea.europa.eu/data-and-maps/indicators/primary-energy-consumption-by-fuel-6 on 21/5/2018.

[35] Elam N. The bio-DME project, phase 1. In: Report to Swedish national energy administration Atrax Energi AB; 2002. Stockholm, Sweden.

[36] Nyström I, Ahlgren E, Andersson E, Börjesson M, Fahlén E, Harvey S. Biokombi Rya–biomass gasification as a system–final report of the research project Biokombi Rya. In: CEC report; 2007.

[37] Boding H, Ahlvik P, Brandberg Å, Ekbom T. BioMeeT II: stakeholders for biomass-based methanol/DME/Power/Heat energy combine. In: Stockholm, Sweden, ecotraffic R&D AB; 2003.

[38] Thunman H, Lind F, Johnsson F. Inventory of future electricity and heat production technologies (in Swedish: Inventering av framtidens el-och värmeproduktionstekniker–Delrapport Energikombinat). Elforsk rapport 2008;8:79.

[39] Åhman M. Biomethane in the transport sector—an appraisal of the forgotten option. Energy Pol 2010;38(1):208–17.

[40] Semelsberger TA, Borup RL, Greene HL. Dimethyl ether (DME) as an alternative fuel. J Power Sources 2006;156(2):497–511.

[41] Gustavsson L, Eriksson L, Sathre R. Costs and CO_2 benefits of recovering, refining and transporting logging residues for fossil fuel replacement. Appl Energy 2011;88(1):192–7.

[42] Nohlgren I, Svärd SH, Jansson M, Rodin J. Electricity from new and future plants 2014. 2014. Elforsk AB, Stockholm (SE). Web-accessed at, http://www.elforsk.se/Programomraden/El–Varme/Rapporter/?rid=14_40 on 14/4/2017.

[43] Ahlgren, E., Andersson, E., Axelsson, E., Börjesson, M., Fahlén, E., Harvey, S., et al., Biokombi Rya - final report from sub-projects (in Swedish: Biokombi Rya - slutrapporter från ingående delprojekt), in CEC report 2007:3 2007, centre for coordinated energy research (chalmers EnergiCentrum-CEC), Chalmers University of Technology, Göteborg, Sweden. Web-accessed at http://publications.lib.chalmers.se/records/fulltext/65604.pdf on 1/4/2017.

[44] Danish Energy Agency. Technology data for energy plants for electricity and district heat generation. Updated October 2018. Danish Energy Agency; 2016. Web-accessed at: https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-andon15/12/2018.

[45] Thunman H, Lind F, Johnsson F. Inventory of future electricity and heat production technologies - interim Report Energy combines (in Swedish: inventering av framtidens el- och värmeproduktionstekniker – delrapport Energikombinat). Elforsk rapport 08:79. 2008. ELFORSK. Web-accessed at: https://www.energiforsk.se/program/elproduktionskostnader/rapporter/inventering-av-framtidens-produktionstekniker-for-el-och-varmeproduktion-1/on14/04/2019.

[46] IEAGHG. Potential for biomass and carbon dioxide capture and storage. Report: 2011/06. July 2011. International Energy Agency; 2011. Web accessed at: http://ieaghg.org/docs/General_Docs/Reports/2011-06.pdf.

[47] Koornneef J, van Breevoort P, Hamelinck C, Hendriks C, Hoogwijk M, Koop K, et al. Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. Int J Greenh Gas Contr 2012;11:117–32. 0.

[48] IPCC Intergovernmental Panel on Climate Change. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, editors. Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014. p. 688.

[49] SMHI (Swedish Meteorological and Hydrological Institute). Climate indicators - temperature. Available at: http://www.smhi.se/en/climate/climate-indicators/climate-indicators-temperature-1.91472; 2015.

[50] IPCC Intergovernmental Panel on Climate Change. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC, editors. Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press; 2014.

[51] Mora C, Frazier AG, Longman RJ, Dacks RS, Walton MM, Tong EJ, et al. The projected timing of climate departure from recent variability. Nature 2013;502:183–7.

[52] Sathre R, Gustavsson L. Time-dependent climate benefits of using forest residues to substitute fossil fuels. Biomass Bioenergy 2011;35(7):2506–16.

[53] Joos F, Roth R, Fuglestvedt JS, Peters GP, Enting IG, von Bloh W, et al. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos Chem Phys 2013;13(5):2793–825.

[54] IPCC, *Anthropogenic*, Natural Radiative Forcing. Supplementary material to chapter 8, climate change 2013: the physical science basis. Geneva, Switzerland: IPCC; 2013. p. 51. Web-accessed at, http://www.ipcc.ch.

[55] Zetterberg L. A method for assessing the expected climatic effects from emission scenarios using the quantity radiative forcing. Stockholm: Swedish Environmental Research Institute; 1993. p. 51. IVL Report No.: B1111.

[56] Myhre G, Highwood EJ, Shine KP, Stordal F. New estimates of radiative forcing due to well mixed greenhouse gases. Geophysical Research Letters 1998;25(14):2715–8.

[57] Gustavsson L, Truong NL. Bioenergy pathways for cars: effects on primary energy use, climate change and energy system integration. Energy 2016;115(3):1779–89.