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Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization

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ABSTRACT

In this study we analyze the primary energy and greenhouse gas (GHG) implications of increasing biomass production by fertilizing 10% of Swedish forest land. We estimate the primary energy use and GHG emissions from forest management including production and application of N and NPK fertilizers. Based on modelled growth response, we then estimate the net primary energy and GHG benefits of using biomaterials and biofuels obtained from the increased forest biomass production. The results show an increased annual biomass harvest of 7.4 million t dry matter, of which 41% is large-diameter stemwood. About 6.9 PJ/year of additional primary energy input is needed for fertilizer production and forest management. Using the additional biomass for fuel and material substitution can reduce fossil primary energy use by 150 or 164 PJ/year if the reference fossil fuel is fossil gas or coal, respectively. About 22% of the reduced fossil energy use is due to material substitution and the remainder is due to fuel substitution. The net annual primary energy benefit corresponds to about 7% of Sweden's total primary energy use. The resulting annual net GHG emission reduction is 11.9 million or 18.1 million tCO_{2equiv} if the reference fossil fuel is fossil gas or coal, respectively, corresponding to 18% or 28% of the total Swedish GHG emissions in 2007. A significant one-time carbon stock increase also occurs in wood products and forest tree biomass. These results suggest that forest fertilization is an attractive option for increasing energy security and reducing net GHG emission.

1. Introduction

The forest sector can play an important role in climate change mitigation. The portfolio of forest-related mitigation activities includes reducing deforestation, enhancing carbon stocks in forests, and using sustainable forest harvests to substitute for more greenhouse gas (GHG)-intensive fuels and materials [1]. Increasing the management intensity of forest land may augment the potential of the forest for mitigating climate change, if more carbon is stored in forest biomass and/or a greater supply of renewable fuels and materials is available for substitution.

Transitioning from traditional, low-intensity forest management practices to high-intensity management regimes is analogous to the agricultural transition from foraging and hunting to dedicated food production that occurred in our societies long ago [2]. This can result in a greater and more dependable supply of biomass to assist in a societal shift from the use of fossil fuels and non-renewable materials towards the use of sustainably-produced renewable resources. Forest biomass can play a dual role in this shift, serving as an industrial material as well as a fuel source, both produced from solar energy captured in forest ecosystems.

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The high productivity achieved in intensively-managed forests may allow other forest land areas to be dedicated to other purposes including biodiversity preservation, watershed protection and recreation.

Fertilization is one element of forest management intensification that has shown particular promise in increasing yields in boreal forests [3,4]. Forest growth on mineral soils in boreal regions is often limited by a low availability of nitrogen (N) [5]. In Sweden, increased attention is being placed on optimized fertilization of forest land [6]. Beginning with the first field experiments with N fertilization in the 1920s, substantial experience has been accumulated in the effects of fertilization on Swedish forests [3]. Experiments have shown that it is possible to more than double the rate of stemwood production in some forest stands by optimising the availability of essential nutrients while avoiding the leaching of nutrients to the groundwater [7].

In this study we explore the primary energy and climate implications of fertilizing part of the Swedish forest land area. We estimate the primary energy and GHG emissions (including CO_2, N_2O and CH_4) from forest management activities including production and application of fertilizer, the effects of fertilization on forest carbon stock and yield, and the net primary energy and GHG benefits of the increased biomass production that can substitute for non-wood materials and fossil fuels.

2. Methods and data

This analysis is conducted on the basis of unit hectares of forest land located in different regions of Sweden, scaled up to the national level. Our baseline is the current method of non-fertilized forest production. We quantify the additional primary energy use and GHG emissions caused by intensified forest management, and the avoided fossil primary energy use and GHG emissions due to increased potential for fuel and material substitution. We distinguish between continuous GHG flows which we calculate on an annual basis averaged over forest rotation periods in different geographic regions, and one-time carbon stock changes associated with the transition from a non-fertilized to a fertilized forest management regime.

Estimates of forest biomass production are made using the DT model. This model forecasts the stand development from >5 years of age to final harvest, where stand characteristics are calculated with a yearly time step. Calculations are made of growth, height, stem shape, quality, harvest volumes in thinnings and final harvests, costs and incomes. The initial conditions are based on circular plots with 10 m radius. Stand development in young stands is described by functions of height development and statistical relations between diameter and height [8]. Height and diameter are calculated for individual trees, using specific functions for Scots pine, Norway spruce and birch. Stand development in established stands is driven by diameter growth functions [9]. Separate functions for Scots pine, Norway spruce and birch are used to calculate the growth of individual trees with a five-year time step. The diameter and basal area growth of individual trees is adjusted so it corresponds with the basal area of the whole stand derived from the ProdMod2 forest generator [10].

The modelled tree species is Norway spruce. Thinning regimes are in accordance with the recommendations of the Swedish Forest Agency [11]. The fertilization regime includes both N and nitrogen-phosphorous-potassium (NPK) fertilizers applied in differing amounts, based on nutrient analysis of tree needles. Beginning when the stand height is 2–4 m and continuing until canopy closure, a biannual dose is applied of 100–150 kg N/ha plus other nutrients as needed based on needle analysis. This takes normally 4–5 applications in southern Sweden and 6–7 applications in northern Sweden. After canopy closure, doses of 100–125 kg N/ha plus other nutrients as needed are applied every 7–10 years until final harvest. This implies that 1–3 applications are applied to closed stands, since the rotation period is considerably shortened by the increased growth. Depending on region and initial site productivity, the total amount of N applied during a full rotation period is 800–1500 kg/ha, with about 75% of that amount applied while the stand is young. The timing of final harvest is determined by when the current annual increment is about equal to or less than the mean annual increment.

We scale up fertilization response data from unit hectares of fertilized land in different regions, up to a national scale. The forest production is based on growth response data from four different geographic regions of Sweden, and three different site indexes within each region. The regions considered are Norra Norrland (~64°N), Södra Norrland (~62°N), Svealand (~60°N) and Götaland (~57°N). Table 1 shows data on total forest land area in the different regions of Sweden [12]. These figures are based on the Swedish government's definition of forest land, and include national parks and other protected forest areas which comprise 3.3% of the total area. Table 1 also shows the assumed fertilized forest land areas in the four geographic regions. We weight the national scale fertilization based on where the best fertilization effect and economy is found, where the Swedish forest companies have their estates, where the environmental risk (e.g. nutrient leakage) is likely small and where the conflict of interest with other land uses (e.g. recreation) is low. Thus, proportionally more land is assumed to be fertilized in northern Sweden than in southern Sweden.

The increased amount of biomass production per hectare due to fertilization is determined by modelling of N-use efficiency vis-à-vis growth response of tree biomass components. Biomass data are broken down into dry mass of stems, tops, branches, needles, and roots. We assume that 40% (by mass) of stemwood is small-diameter logs ("pulpwood") and the other 60% is larger-diameter logs ("sawtimber"). Data are

Table 1 – Total forest land area and assumed fertilized forest land area in different regions of Sweden.

Region	Total forest land		Fertilized forest land	
	Land area (10^3 ha)	% of total forest land	Land area (10^3 ha)	% of fertilized forest land
N. Norrland	6795	29.7%	747	32.6%
S. Norrland	5919	25.8%	871	38.0%
Svealand	5197	22.7%	425	18.6%
Götaland	4995	21.8%	247	10.8%
Total	22906	100.0%	2291	100.0%

further broken down into biomass in trees that are cut during thinning operations and the remaining biomass in trees cut during final felling. Based on this breakdown of tree biomass we analyze the harvest and use of the following assortments for both fertilized and non-fertilized stands:

- Large-diameter stemwood: 100% used for production of wood construction material.
- Small-diameter stemwood: 100% used either for biofuel or for pulp.
- Thinning residues: 75% of branches and 25% of needles cut during thinning operations, used for biofuel.
- Harvest residues: 75% of branches and 25% of needles cut during final harvest, used for biofuel.
- Stumps: 50% of recoverable stumps and roots, not including fine roots, used for biofuel.

The analysis includes primary energy and emissions from additional fossil fuels used for production, recovery and transport of the additional biomass resulting from fertilization. Because our baseline is traditional non-fertilized forestry, we do not include energy use and fossil emissions from baseline production, but only the additional energy and emissions due to intensified production. Primary energy used in forest operations (establishment, thinning, harvest, and transport) per unit of biomass production is an average value for northern, central and southern Sweden [13]. Primary energy used for recovery and transport of harvest residues and stumps is based on [14].

GHG emissions associated with the production and use of fertilizers include CO_2, N_2O and CH_4. In our calculations we use global warming potentials (GWP) of 298 for N_2O and 25 for CH_4, relative to the radiative forcing of CO_2 over a 100-year time horizon [15]. Primary energy use and GHG emissions for the production of Skog-CAN fertilizer (27-0-0) and Opti-Crop fertilizer (24-4-5) are based on [16]. Total GHG emissions due to fertilizer production are 9.0 kg CO_{2equiv} per kg N applied, of which 62% is N_2O, 37% is CO_2 and 1% is CH_4 emission. Aerial application of fertilizer is assumed in this study, because this method is not restricted by wet soil conditions or interference by growing trees. The amount of fossil fuel used for fertilizer application by helicopter is based on [17], corresponding to 0.022 kg CO_2 emission per kg fertilizer. The use of N fertilizer may lead to emission of N_2O from the soil, due to the microbiological processes of nitrification and denitrification. Nordin et al. [18] state that between 0.5% and 1% of the N in the applied fertilizer in Sweden can be expected to be released as N_2O, and MacDonald et al. [19] found that 1% of the N deposited on upland spruce forests in Scotland was emitted as N_2O. In this study we assume that 1% of the N in the applied fertilizers is released as N_2O. We do not consider the potential for N addition to inhibit the oxidation of CH_4 by soil microorganisms, which is expected to be negligible in comparison to soil carbon stock changes due to fertilization [18].

To maintain consistency with units we account for carbon stocks in soil, living trees and wood products in units of CO_{2equiv}, which we calculate as 44/12 times the mass of carbon stock. Carbon stocks in forest soils can be affected positively by fertilization and negatively by removal of biomass residues. We estimate separately the increased soil carbon stock due to fertilization and the decreased soil carbon stock due to increased biomass removal, but we do not consider potential interactions between the two effects. N fertilization generally causes an increase in soil carbon stock [20], due to both an increase in litter input from the enhanced aboveground growth and a decrease in soil microbial activity leading to slower decomposition of soil organic matter [21]. We base our estimate of soil carbon increase on data from Eriksson et al. [14], who modelled a Norway spruce stand over a 300-year time frame in Sweden and found that NPK-fertilization led to an increased soil carbon stock of 88 tCO_{2equiv}/ha compared to traditional forest management. Most of that increase was evident during the first rotation period, though with each successive rotation the fertilized stand continued to accumulate more carbon than a non-fertilized stand. We use a simplified assumption that the soil carbon increases linearly at a rate of 290 kg CO_{2equiv}/ha-yr.

The removal of biomass from the forest ecosystem results in a reduction in soil carbon stock compared to the potential carbon stock if no biomass were removed. We estimate the soil carbon effects of removing thinning residues, harvest residues (branches and tops) and stumps, but do not consider the soil carbon effect of stemwood removal. We use data from Holmgren et al. [22], and base our estimates on the average value of the various studies they surveyed. Thus, we estimate that the removal of harvest residues and stumps causes a decrease in soil carbon of 79 and 181 kg CO_{2equiv}/ha-yr, respectively. We assume that removal of thinning residues causes the same decrease as removal of harvest residues, proportional to the amount of biomass removed. The residues are assumed to be used as biofuel.

Large-diameter stemwood is assumed to be used to produce wood construction material that substitutes in place of conventional reinforced concrete. The material substitution impacts are based on a case study of a multi-story apartment building constructed in Sweden using wood structural framing, compared to a functionally equivalent building constructed with a reinforced concrete frame [23]. The reference concrete building uses some wood materials, and the substitution benefit is calculated based on the reduction in primary energy use and net GHG emission per unit of additional wood needed to make the wood-frame building. Emission calculations take into account the differences between the buildings due to the emission from fossil fuels used to manufacture and transport the materials, the avoided cement calcination and carbonation process emissions from concrete substituted by wood material, and substitution of fossil fuel by residues from wood processing, construction and demolition. Large roundwood is converted into a mix of sawn lumber, plywood and particleboard, with a product/roundwood dry weight ratio of 0.53. Some wood processing residue is used for particleboard manufacture, some is used internally as energy for e.g. kiln-drying lumber, and the remainder is available externally for use as biofuel. Bark is used as biofuel. We assume that 100% of wood-based construction site waste and demolition wood is recovered and used as biofuel, as recovered wood is increasingly used to generate district heat and electricity in Sweden [24]. Demolition materials are increasingly recovered as efficient management of post-use building materials becomes a priority in many European countries, including Sweden [25].

Landfilling demolished wood is prohibited in Sweden and many parts of the European Union. Energy used for recovery and transport of demolition wood is based on [14].

Small-diameter stemwood is often used in Sweden for pulp and paper production. In this study we analyze the use of additional quantities of biomass produced through fertilization, but we have not analyzed whether there is demand for additional pulpwood in the Swedish pulp industry. We therefore show the GHG effects of using this small-diameter stemwood as biofuel, acknowledging that this may not be the most economically beneficial use of this wood [26]. If it is not used as biofuel, its calculated impact can be deducted from the results without any other effect on the energy and GHG balances within the system boundaries of this study.

The energy source that recovered biofuels replace influences the resulting GHG balance [27]. Globally, we are heavily dependent on fossil fuels. Coal, oil and fossil gas provide 26%, 34% and 21% of global primary energy supply, respectively [28]. The amount of CO_2 emitted per unit of heat energy varies between fossil fuels, with coal emitting most and fossil gas emitting least. To show the range of climate impact of replacing fossil fuel in stationary plants, we consider cases where biofuel replaces either coal or fossil gas with relative conversion efficiencies of 100% and 96%, respectively [23]. Values of specific CO_2 emission from the combustion of fossil fuels used are 110 kg CO_2 per GJ for coal, 81 kg CO_2 per GJ for oil, and 66 kg CO_2 per GJ for fossil gas, and include emissions during the entire fuel-cycle from the natural resource to the delivered energy service [29].

We also track the changes of carbon stock in forest tree biomass and in wood-based building materials. The carbon in forest biomass is calculated as the mean carbon stock over an entire rotation period, and we differentiate between the carbon stock in unfertilized stands and the same stands under fertilized management. Thinning residues, harvest residues and stumps that are not removed from the forest are assumed to decay at a negative exponential rate with decay constants of −0.046, −0.074, and −0.170 for stumps [30], branches and needles [31], respectively. Carbon stock in wood products is based on the case study building described above [23], assuming a building life span of 50 years after which it is replaced by a building with similar wood content.

3. Results

The amount of N fertilizer applied annually is about 48,700 t N or about 21 kg N per average hectare. The resulting annual increase in total biomass production is shown in Table 2, and averages about 4 t of oven-dry biomass per hectare. Annual production of stemwood volume increases by about 5.5 m^3/ha. The N-use efficiency of the fertilization, here calculated as the amount of fertilizer applied per unit of increased stemwood growth, is 3.86 kg N per m^3 stemwood. The increased annual harvest of biomass totals 7.4 million t dry matter, of which 41% is large-diameter stemwood. The rotation length varies by location, and is shortened significantly by fertilization. The average rotation length in non-fertilized stands is about 70, 90 and 110 years in southern, central and northern Sweden, respectively. In fertilized stands the rotation length is reduced to about 50, 60 and 70 years in these respective locations.

Table 2 – Increased annual oven-dry biomass production; total on all fertilized land (10^3 t/yr) and per average hectare (t/ha-yr).

	10^3 t/yr	t/ha-yr
Stemwood biomass	5076	2.22
Branch biomass	1721	0.75
Needle biomass	597	0.26
Root biomass	1785	0.78
Total tree biomass	9179	4.01

The annual average primary energy implications of fertilization are shown in Table 3. Positive numbers denote additional primary energy that is used, while negative numbers denote avoided fossil primary energy use due to using biomass for material and fuel substitution. Table 4 shows the annual average GHG implications of fertilization, with positive numbers denoting additional GHG emitted to the atmosphere and negative numbers denoting avoided GHG emissions. The largest single impact, in terms of both primary energy and GHG emissions, is the material substitution impact due to using wood material instead of concrete material. Material substitution impacts include reduced material production fossil fuel use and avoided cement process reaction emission due to using wood construction material instead of reinforced concrete. Other significant impacts are the substitution of fossil fuel by small-diameter roundwood, wood processing

Table 3 – Annual primary energy (PJ/yr) implications of fertilization, with reference fossil fuel of coal or fossil gas. Positive numbers denote additional primary energy use, and negative numbers denote avoided fossil primary energy use due to biomass substitution.

	Coal	Fossil gas
Forest management and fertilization		
Establishment, thinning, harvest	0.9	0.9
Fertilizer production and application	2.3	2.3
Sub total	3.2	3.2
Large-diameter stemwood		
Transport	0.7	0.7
Material substitution (avoided fossil fuel)	−35.3	−32.8
Fuel substitution (wood processing residue)	−26.9	−24.7
Fuel substitution (construction residue)	−2.8	−2.6
Fuel substitution (demolition residue)	−25.0	−22.9
Sub total	−89.3	−82.2
Small-diameter stemwood		
Transport	0.5	0.5
Fuel substitution	−34.3	−31.4
Sub total	−33.8	−30.9
Thinning residues (branches, foliage)		
Recovery/transport	0.4	0.4
Fuel substitution	−8.8	−8.0
Sub total	−8.4	−7.6
Harvest residues (branches, foliage)		
Recovery/transport	0.7	0.7
Fuel substitution	−15.5	−14.2
Sub total	−14.8	−13.5
Stumps		
Recovery/transport	1.4	1.4
Fuel substitution	−15.1	−13.8
Sub total	−13.7	−12.4
Total	−156.7	−143.4

Table 4 – Annual GHG (10^3 tCO_{2equiv}/yr) implications of fertilization, with reference fossil fuel of coal or fossil gas. Positive numbers denote additional emissions and negative numbers denote avoided emissions.

	Coal	Fossil gas
Forest management and fertilization		
Establishment, thinning, harvest	77	74
Fertilizer production and application	441	441
N_2O emission from forest soil	228	228
Soil C stock change due to fertilization	−672	−672
Sub total	74	72
Large-diameter stemwood		
Transport	62	57
Material substitution (avoided fossil fuel)	−3124	−2402
Material substitution (avoided cement process)	−3197	−3197
Fuel substitution (wood processing residue)	−2701	−1546
Fuel substitution (construction residue)	−280	−160
Fuel substitution (demolition residue)	−2503	−1434
Sub total	−11744	−8683
Small-diameter stemwood		
Transport	41	38
Fuel substitution	−3425	−1973
Sub total	−3384	−1935
Thinning residues (branches, foliage)		
Recovery/transport	32	32
Soil C stock change	102	102
Fuel substitution	−875	−504
Sub total	−741	−370
Harvest residues (branches, foliage)		
Recovery/transport	57	57
Soil C stock change	181	181
Fuel substitution	−1553	−895
Sub total	−1316	−657
Stumps		
Recovery/transport	110	110
Soil C stock change	416	416
Fuel substitution	−1506	−867
Sub total	−980	−341
Total	−18090	−11915

residues, demolition residues, stumps, harvest residues and thinning residues. The reference fossil fuel is an important determinant of the GHG benefits, with greater avoided emissions when coal is replaced than when fossil gas is replaced. The reference fossil fuel also affects the primary energy implications due to differences in relative conversion efficiencies and fuel-cycle energy inputs of the fuels. The primary energy use and emissions related to forest operations, including the production and application of fertilizer, are minor in relation to the available bioenergy and the avoided emissions due to material and fuel substitution. The increased soil carbon stock due to fertilization is balanced by a decreased carbon stock of about the same amount due to biomass residue removal.

The average carbon stock in forest tree biomass increases under the fertilization regime, due to faster initial growth and larger carbon stock at maturity. Table 5 shows the tree biomass averaged over full rotation periods in the 4 regions with and without fertilization. Compared to the unfertilized forests the average carbon stock increases by 22%, 26%, 28% and 12% in N. Norrland, S. Norrland, Svealand and Götaland, respectively.

The carbon stock changes in wood products and tree biomass are shown in Table 6. The stock change due to carbon

Table 5 – Average tree biomass (t dry matter/ha) in four geographic regions, with and without fertilization.

Region	Without fertilization (t dry matter/ha)	With fertilization (t dry matter/ha)	Increase (%)
N. Norrland	189	230	22
S. Norrland	199	251	26
Svealand	209	267	28
Götaland	251	280	12

stored in an individual wood product is temporary and will be lost at the end of the product's life span. However, if wood is used to make buildings that would otherwise have been built with non-wood materials and if the buildings are eventually replaced with new buildings with an equivalent wood content, then a one-time permanent step change in carbon stock will occur [23]. The total carbon stock in tree biomass, scaled up from the unit hectare increases shown in Table 5, will also have a one-time step change increase of a similar magnitude, assuming that fertilized forest management is continued.

The time dynamics of carbon stocks and GHG flows are illustrated in Fig. 1, showing the development of living tree biomass, decaying biomass and soil carbon stock changes, and net substitution effects over an extended period. The data in Fig. 1 represent a typical fertilized and unfertilized forest stand in northern Sweden. The difference in rotation length and final harvest volume between fertilized and unfertilized stands will be less significant in central and southern Sweden. Year 0 of the figure is assumed to immediately follow a harvest, though the effects of the previous harvest (e.g. decaying biomass) are not included in the figure. During the 240-year period, 3 full rotations occur in the fertilized stand while 2 rotations occur in the unfertilized stand. The average carbon stock in living biomass is greater in the fertilized stand due to its more rapid initial development and its greater final yield. The rate of biomass production is greater in the fertilized stand due to its shorter rotation period and higher yield per rotation. A greater amount of decaying biomass is left in the fertilized stand due to its higher biomass yield and more frequent thinning and harvest events. In contrast to the cyclical time patterns of living and decaying biomass, the cumulative substitution benefits of forest product use continue to rise over time. The fertilized stand produces significantly greater substitution benefits due to the increased production of biomass per unit of time.

Table 6 – Carbon stock changes (10^3 tCO_{2equiv}) in wood products and tree biomass.

Temporary C stock increase in wood products (per year)	2980
One-time C stock increase in wood products[a]	149,100
One-time C stock increase in tree biomass[b]	197,600

a Assuming a 50-year life span for wood products, and continued replacement of demolished buildings with new buildings of equivalent wood content.
b Assuming continuation of fertilized management and sustainable yield.

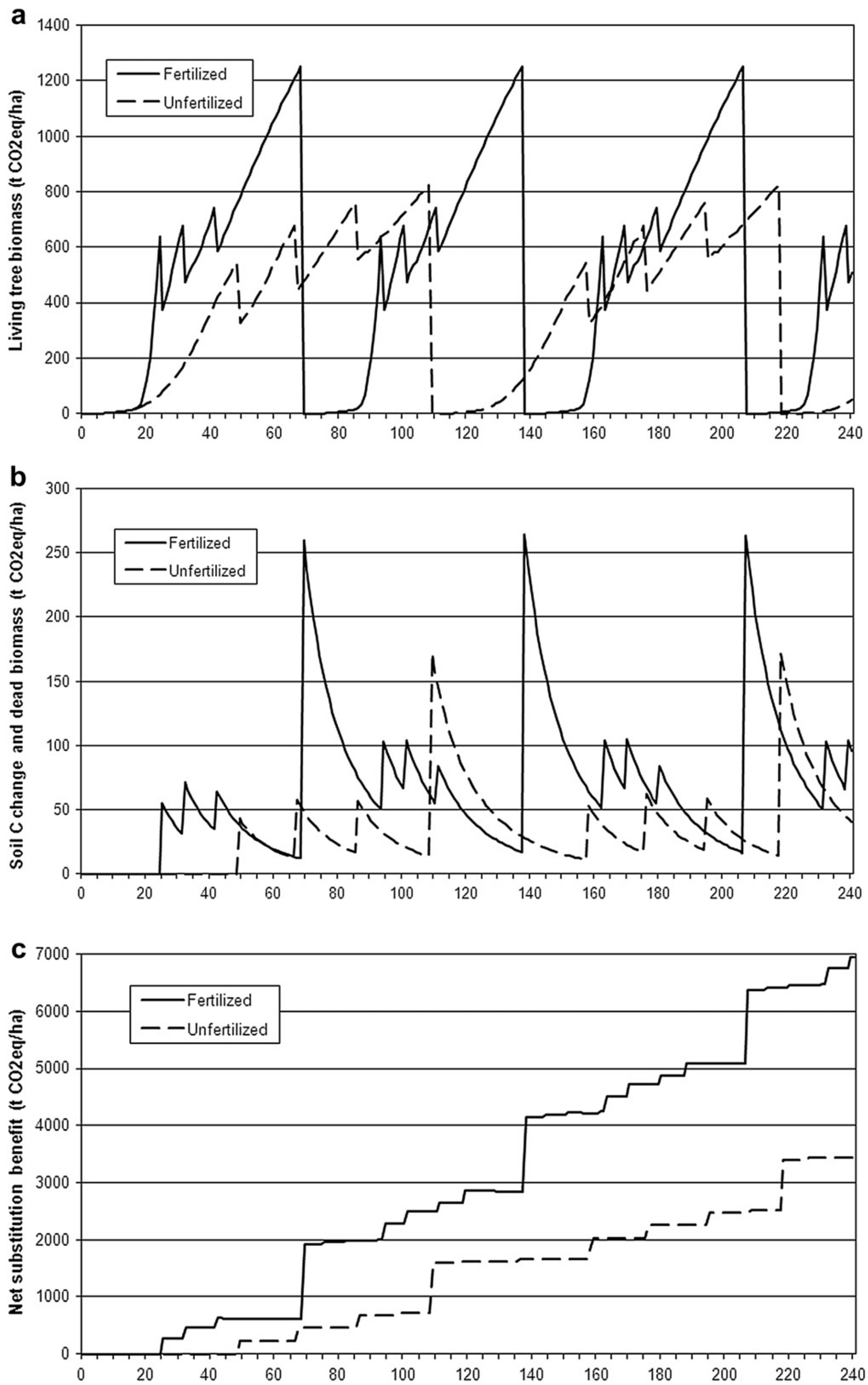

Fig. 1 – Development of carbon stocks and GHG flows over a 240-year period for typical fertilized and unfertilized stands in northern Sweden. Note differences in y-axis scales. (a) shows living tree biomass. (b) shows soil C stock changes and decaying biomass. (c) shows net substitution benefits of wood product use assuming coal reference fuel, with deductions made for N_2O, CH_4 and fossil CO_2 emissions.

4. Discussion

Our results show that forest fertilization can lead to increased primary energy availability due to additional biofuel supply and reduced energy use for material production. Forest fertilization can also significantly reduce net GHG emissions, due primarily to the greater quantities of biomass that can substitute for GHG-intensive materials and fuels. The largest single impact is the material substitution effect due to using wood construction material instead of concrete material. This includes the reduced fossil fuel use for material production, and reduced cement process reaction emission due to the avoided production of concrete. The material substitution effect comprises about 35% and 47% of the annual GHG benefits when the reference fossil fuel is coal and fossil gas, respectively. There is growing interest in Sweden for using wood material in place of concrete [32], yet the total number of new buildings built per year in Sweden is small in relation to the quantity of wood material potentially available from fertilization. If this material is not exported, the additional biomass would then be used for other uses with lower efficiency of emission reduction, or would be left in the forest. However, if additional biomass is exported and used in place of non-wood construction in other countries, the higher emission reduction per unit of biomass could be gained by a larger share of the biomass, thus resulting in a greater overall emission reduction globally. The inter-European and intercontinental trade in wood-based products and fuels is increasing, and there is a large potential for exporting prefabricated wooden buildings, or lumber to be used for wood construction, from forest-rich countries in northern Europe to other regions that predominately use brick or concrete construction. This process would be encouraged by the wider establishment of economic policy instruments for climate change mitigation, e.g. taxation of carbon emission and fossil fuel use, which economically favour less GHG-intensive materials such as wood [33].

The use of increased biomass production for substitution of fossil fuel is also found to be very significant in this analysis. Taken together, this impact is greater than the material substitution effect. In descending order, the most significant biomass fractions used for bioenergy are small-diameter roundwood (if not used for pulp production), wood processing residues, demolition residues, harvest residues, stumps and thinning residues. Fuel substitution benefits are greater when coal is substituted than when fossil gas is substituted, thus biofuels should replace coal if possible. International trade in bioenergy is increasing rapidly, made feasible by the development of efficient long-distance transport methods allowing biofuel produced in one region to replace fossil fuel in another region [34]. Gustavsson and Eriksson [35] showed that woody biofuels can be economically transported internationally, and the GHG reduction per unit of biofuel depends more on the fossil fuel replaced than on the transport distance. By exporting biofuels to be used in applications that result in high GHG emission reductions per unit of biomass, the total GHG emission reduction from the available supply of biomass could by increased.

The carbon stocks held in living tree biomass and wood products both increase when forest fertilization is implemented. The increased carbon stock is significant, but in the long term is outweighed by the substitution effects. The one-time step change in carbon stock in trees, due to the increase in average biomass during the forest rotations and assumed to continue as long as the management regime continues, corresponds to about 11 years or 17 years of calculated annual emission reduction with coal or fossil gas reference fuel, respectively. Assuming a 50-year life span for wood building materials and continued replacement of demolished buildings, the one-time carbon stock increase in wood products corresponds to about 8 years or 13 years of annual emission reduction with coal or fossil gas reference fuel, respectively. The longer the life span of the wood products, the larger will be the total carbon stock, though eventually the carbon stock will stabilize at a higher level when the quantities of wood removed from service balance the quantities of new wood entering service.

The primary energy use and GHG emissions related to the forest operations, including the production and application of fertilizer and N_2O emission from forest soils, are small in relation to the increased biomass availability and the avoided emissions resulting from the use of the increased biomass. Forest operation emissions comprise about 4% and 6% of the annual GHG balance when the reference fossil fuel is coal and fossil gas, respectively. The emission of N_2O from forest soils is subject to considerable uncertainty. For example, Crutzen et al. [36] suggest that 3–5% of N applied globally for agricultural biofuel production is emitted as N_2O, while Maljanen et al. [37] found no significant difference in N_2O emission from a fertilized and non-fertilized spruce forest site in Finland. Nevertheless, our results show that N_2O emission of 1% of the N in applied fertilizer is a minor component of the overall GHG balance of forest fertilization.

The increase in soil carbon stock due to fertilization is uncertain and depends on, inter alia, dosage of N, dosage of other nutrients, soil type, tree species and climate. The literature contains few studies of the effects of fertilization on carbon stocks in boreal forest soil, and definitive conclusions cannot be drawn because the studies differ in e.g. species, dosage, timing and soil profiles sampled. Nohrstedt et al. [38] analyzed two Scots pine sites in Sweden and found soil carbon stock to increase by 10–26% in N-fertilized plots over a 15 year time frame. The absolute increase in soil carbon stock was on the order of 12–20 tCO_{2equiv}/ha. Mäkipää [39] studied five Scots pine sites and one Norway spruce site in Finland that were N-fertilized over a 30-year time frame. Carbon stock increased in the humus layer by 14–87% and in the mineral soil by 15–167%, and the absolute increase was greatest at the spruce site where it was about 70 tCO_{2equiv}/ha. Hyvönen et al. [40] analyzed 15 sites in Sweden and Finland that received varying dosages of N and NPK fertilizer over a time frame of 14–30 years. They found the fertilized plots to have consistently higher soil carbon stock than the non-fertilized plots. The soil carbon stock of the fertilized plots increased an average of 2.4 and 0.9 tCO_{2equiv}/ha-yr more than the non-fertilized plots for Norway spruce and Scots pine sites, respectively.

The increase in soil carbon also appears to depend on the duration of N application and the time since application, with an initial strong response giving way to continued accumulation at a slower rate [14] and with a gradual decrease toward prior conditions if the treatment is discontinued [21]. Our estimate of soil carbon stock increase is thus simplified as we assume a linear increase based on average response over a 300-year period of fertilization. The actual soil carbon stock increase due to fertilization will likely be greater than our estimate during the first rotation period, and less than our estimate during later rotation periods. We expect that this will have insignificant effect on our general conclusions however, as soil carbon stock change is minor in relation to other GHG flows quantified in this study.

Our results suggest that the soil carbon stock increase due to fertilization is counterbalanced by a decrease in soil carbon stock of roughly the same magnitude due to the removal of a greater proportion of biomass from the forest. Our analysis, however, does not consider potential interactions between the two effects. We also do not consider the effects on radiative forcing of the differing time dynamics of forest residue oxidation. Forest residues left to decompose naturally in the forest slowly release CO_2 into the atmosphere over a time scale of decades (Fig. 1b). Residues removed from the forest and used as biofuel release CO_2 immediately, resulting in a greater total radiative impact [22]. This effect is more pronounced for slower-decaying biomass such as stumps. Additional work is needed to more accurately depict the soil carbon interactions and time dynamics of fertilized forest management with intensified biomass removal.

GHG balances can be analyzed under different time perspectives, from an instantaneous snapshot of carbon stocks existing in different pools at a given moment to a long-term tracking of GHG flows between pools over an extended period. Results can differ due to temporal inconsistencies in GHG effects of different system components and processes. The time horizon of study could be e.g. one year averaged from a longer period, one rotation period (and assuming identical subsequent rotations under sustainable management), multiple rotation periods, or a fixed time period such as 240 years. Assuming long-term system stability, consistent patterns will develop allowing recommendations for appropriate management. In this study, because rotation periods vary substantially in different regions and with different management intensity, we calculate annual GHG flows averaged over individual rotation periods for each geographic region and management regime. In addition, we estimate the one-time carbon stock changes associated with the transition from a non-fertilized to a fertilized forest management regime. These estimates of one-time changes and continuous linear changes are simplifications of the actual dynamics of GHG stocks and flows, which may involve non-linear changes at differing time scales.

This study considers several innovative technologies: forest fertilization, forest-fuel systems, and wood-based construction. The diffusion of innovative technologies takes time to overcome hindrances such as socio-economic and cultural aspects, entrenched traditions, price and scale dynamics, and complexities of structural and technical change [41]. Criteria for the eventual emergence of innovative technologies include investments in knowledge creation, incentives for entry of new firms, and the formation of actor networks [42]. It may take several decades for these technologies to diffuse to significant levels. Forest fertilization, forest-fuel systems, and wood-based construction are complementary technologies that may develop synergistically during the coming decades, with fertilized forests providing raw materials and fuels for wood-based construction and climate-appropriate energy systems, while the construction and energy sectors provide markets for the additional biomass produced by forest fertilization.

5. Conclusions

In this study we have endeavoured to understand the overall energy and climate impacts of fertilizing 10% of Swedish forest land. We find that optimized fertilization with N and NPK can significantly increase forest biomass production, which can increase energy availability and reduce net GHG emissions by substituting in place of GHG-intensive materials and fuels. About 6.9 PJ/year of additional primary energy input is needed for fertilizer production and forest management. Using the additional biomass for fuel and material substitution can reduce fossil primary energy use by 150 or 164 PJ/year if the reference fossil fuel is fossil gas or coal, respectively. About 22% of the reduced fossil energy use is material production energy due to wood material substitution, 21% is biofuel from small-diameter stemwood, 18% is biofuel from wood processing and construction residues, 15% is biofuel from building demolition residues, 9% is biofuel from harvest residues, 9% is biofuel from stumps and 5% is biofuel from thinning residues. The net annual primary energy benefit corresponds to about 7% of Sweden's total primary energy use [43]. Fertilizing 10% of Swedish forest land can result in an annual GHG emission reduction of 11.9 million or 18.1 million tCO_{2equiv} if the reference fossil fuel is fossil gas or coal, respectively. Swedish GHG emissions in 2007 were 65.4 million tCO_{2equiv} [44], thus the potential annual emission reduction corresponds to 18% and 28%, respectively, of the total Swedish GHG emission in 2007. Part of this emission reduction would occur outside of the borders of Sweden if biomass is exported to other regions to replace non-wood fuels and materials. An additional one-time increase in average carbon stock in wood products and forest trees, corresponding to 149 and 197 million tCO_{2equiv}, respectively, would occur if 10% of Swedish forest land is fertilized. These results suggest that forest fertilization is an attractive option for increasing energy security and reducing net GHG emission.

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