"This We Know. All Things Are Connected."

Chief Seattle (c. 1786 - 1866)

CLIMATE IMPACT
OF SWEDISH FORESTRY

Absorption and emissions of carbon dioxide

CONTENTS

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ISBN: 978-91-88277-09-1

FOREWORD

In 1896, an article, *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground*, was published. The author, the Swedish chemist Svante Arrhenius, argued that increased carbon dioxide levels in the atmosphere would, in the long term, lead to general global warming and a changed climate. He argued that the carbon dioxide level in the atmosphere was a contributory cause of the Earth's glacial and warmer periods. His theory was received with great scepticism.

However, in recent decades, his pioneering article about the greenhouse effect of carbon dioxide has gained strong support. Human activities, on a scale that Arrhenius could never have foreseen, have added enormous quantities of carbon dioxide to the atmosphere. Levels of carbon dioxide in the atmosphere have increased from less than 300 ppm when he conducted his research to over 400 ppm today.

The Earth's climate is driven by interacting processes. The connections are not yet fully understood, but sophisticated models of the global climate and analysis of climate data strongly support the theory that 'greenhouse gases' contribute to global warming. Today, it is accepted that the carbon dioxide levels in the atmosphere is a factor that is influencing the climate, through the greenhouse effect.

The climate issue is largely a matter of managing and controlling the carbon flows. This gives forest management a key role, because forest trees absorb carbon dioxide from the atmosphere and store carbon through their increment. Products based on forest biomass also store carbon and can reduce the use of carbon from fossil sources. In Sweden, the forestry sector, through its activities, is managing the largest flows of carbon. This is the background to this attempt to summarise a large and complicated subject: how Swedish forestry impacts the climate.

It is my hope that the reader will learn something new and find inspiration in this text.

Uppsala, July 2019
Rolf Björheden, Skogforsk

SUMMARY

One important goal for climate policy is to reduce emissions of carbon dioxide. The forest sector can play a major role in this, and its contribution is immediate. The current annual increment in Sweden's forests corresponds to over three times the country's emissions of carbon dioxide, 53 million tonnes.

For greatest effect, net yield must be maximised and maintained, without neglecting other objectives, and goods and energy must be produced from forest raw materials as far as possible. Forest products already reduce annual emissions by 40 million tonnes through substitution effects, and using more of the felled biomass would increase the climate benefit by a further 50%.

PHOTO: ERIK VIKLUND

Carbon dioxide levels in the atmosphere have increased from 280 ppm to over 400 ppm in the past century. The main reason is the extensive use of fossil fuels – coal, oil and natural gas. When fossil carbon compounds are burned, carbon that was previously stored is released as carbon dioxide. Higher levels of carbon dioxide in the atmosphere are now accepted as a driving factor in the rising average global temperatures, through the greenhouse effect.

In recent years, the forestry sector has come into focus as a way to counteract increasing carbon dioxide levels. Growing forests absorb carbon dioxide from the air. Over time, a significant store of organic carbon accumulates in forest soils. But how does active forestry affect the dynamics of the carbon cycle? In this report, forest management strategies and approaches are presented and discussed from the perspective of carbon sequestration and mitigation of climate change.

Through photosynthesis, using solar energy, green plants convert water and carbon dioxide to sugar. Trees use the sugar to produce the substances they need for growth and as an energy source for their vital processes. Oxygen is a residual product of this process. When a plant dies, its biomass is decomposed by organisms that live on the dead biomass, and the assimilated carbon is released as carbon dioxide. A natural plant community is carbon neutral, because increment and decomposition are in balance over time, apart from a small proportion of organic carbon transferred to the soil.

In a production forest, this equilibrium is upset. Wood is extracted for use in products and materials, with varying lifespans. Biomass is removed, instead of being left to the natural decomposers. However, if biomass is used to substitute products or fuels based on fossil carbon, the forest products also reduce the amount of carbon dioxide in the atmosphere.

Swedish production forest assimilates carbon dioxide each year through increment. The total increment is currently 120-130 million m^3s st/yr (stem volume above stump, over bark). If the total tree biomass, including stumps, roots, branches and foliage, is calculated instead of stem volume, this is the equivalent of 85-90 million tonnes of dry matter, half of which is carbon. One tonne of carbon is the equivalent of 3.7 tonnes of carbon dioxide, so almost 170 million tonnes of carbon dioxide are absorbed from the atmosphere each year.

Managed Swedish forests constitute a significant carbon store. The standing volume, over 3.1 billion m^3s st, corresponds to 4.3 billion tonnes of carbon dioxide. Since harvest is less than increment, the carbon store is increasing. The annual increase can be calculated by deducting the drain (felling and trees that die from other causes) from the increment. The increment, 121 million m^3s st/yr, must then be reduced by 96 million m^3s st/yr (of which 84 million m^3s st through harvest). The inventory increase is therefore 25 million m^3s st/yr, a biomass equivalent to 35 million tonnes of carbon dioxide. Since 1929, when the first Swedish National Forestry Inventory was completed, the increase in standing volume equals two billion tonnes of CO_2 or approximately 40 years of territorial Swedish CO_2 emissions, 53 million tonnes/yr, at 2016 level.

Forest soils also store organic carbon. The total storage of soil carbon, approximately 1 800 million tonnes, exceeds the quantity of carbon stored in growing trees. To this can be added 510 million tonnes stored in peatland and large quantities stored in unutilised forests. These storages are not considered here, where the focus is on production forest. Soil carbon increases only slowly. An average of 7 kg carbon/ha/yr has accumulated in forest land since the last Ice Age, compared with just over 7 tonnes carbon/ha/yr absorbed annually by the growing forest.

Analyses of the impact of forest management for carbon sequestration show the importance of maintaining high net production. Extending rotation periods increases the storage of carbon in the forest but reduces net production. These effects often balance each other out. Leaving the forest to develop naturally, such as by designating reserves, increases the carbon storage, but once the standing volume has reached its maximum, net carbon assimilation almost completely stops.

Emissions of carbon dioxide from forest operations and transports were calculated. Total emissions in 2014 were just under one million tonnes of CO_2/yr. Silvicultural activities (soil scarification, plant production, pre-commercial thinning and fertilisation) account for approximately 60 000 tonnes, logging (felling and terrain transport) approximately 386 000 tonnes, and road transports, including emissions connected with forest road construction and maintenance, 521 000 tonnes.

Fuel consumption in forestry was calculated to be 4.71 litres per harvested m^3s st. For many consecutive years, the forestry sector has increased energy efficiency in its operations. This is a result of technical advances, such as more efficient engines, but also through increased awareness of environment and climate issues and a greater focus on fuel economy. The work to reduce emissions from forestry continues. This particularly applies to road transports, which account for over half the emissions.

INTRODUCTION

During growth, green plants assimilate carbon dioxide through photosynthesis and store carbon in their tissues. In a forested country like Sweden, the management of this massive natural resource is of critical importance for the contributions to the international work to mitigate climate change.

Carbon and climate

The Earth's climate is the result of interacting processes, whose links and effects are still not completely understood. Research has shown how the climate has varied over time around an equilibrium state, with exchanges and interactive effects between the atmosphere, hydrosphere and geosphere. Distinct events, such as major volcanic eruptions, have had clear effects on the climate, which can be interpreted from the archives created through annual sedimentation on the sea floor and in glaciers.

Where and how carbon is stored plays a key role in the models that describe the climate. Human activity has become very important in this context, primarily as a result of extensive burning of fossil carbon deposits (coal, oil and natural gas), but also through, for example, cement manufacture, changes in land use, ditching in peatlands, and deforestation. These activities add large quantities of carbon dioxide to the atmosphere. An extensive switch of ecosystems from forest to agricultural land mobilises carbon dioxide, releasing significant carbon storages in plant biomass and the soil.

Carbon dioxide levels in the atmosphere have increased from 280 ppm during the 19th century to 415 ppm today, corresponding to 188 billion tonnes of carbon. Carbon dioxide is a greenhouse gas, which means that increased levels in the atmosphere reduce the amount of solar energy that is reflected back into space from the Earth. The result is increasing average temperature and a changing climate.

The equilibrium processes also affect the oceans, which contain approximately 50 times more carbon than the atmosphere (Figure 2). The increasing amount of carbon in the atmosphere means that the carbon levels in the oceans are also increasing. However, the oceans have an ability to trap carbon in the form of carbonate (CO^{2-}), mainly through the enormous numbers of calcifying plankton. When the shells from these plankton are deposited as sediment on the sea floor, the carbon is stored as calcium carbonate in the sludge. Over time, these deposits form sedimentary rocks such as chalk and limestone. Water movements in the oceans are of critical importance for the world's climate, and are probably more significant than the direct effects of the atmosphere. Today, we do not know the possible effects of the increasing carbon levels in the oceans. Because of this great uncertainty, many people support the *principle of caution*, i.e. an objective to minimise impact on the natural balance of the carbon exchange.

Sweden's emissions of carbon dioxide in an international perspective

Sweden is a country with a cold climate, a large manufacturing sector, and extensive domestic transports. In the 1970s, the country was strongly dependent on fossil energy. Emissions of carbon dioxide were around 10 tonnes per inhabitant and year (Figure 1). The 'oil crisis' in the mid-1970s showed the vulnerability of the country to disruptions in the energy supply. Ambitious work to improve efficiency in the energy sector was initiated. Sweden also became a forerunner in large-scale use of bioenergy, largely based on forest raw materials. The increased use of biofuels has meant that the net addition of 'fossil' carbon dioxide has fallen further. Total emissions of carbon dioxide in Sweden for 2016 were 52.9 million tonnes exclusive of LULUCF[1], (-42.9 million tonnes) and foreign transports (9.4 million tonnes) (The Swedish Environmental Protection Agency 2018).

Figure 1 shows carbon dioxide emissions per capita in Sweden, the world, the Eurozone and selected countries for comparison. In the 1970s, Sweden's emissions were more than double the world average. Since then, increased energy efficiency and expansion of carbon-neutral energy have more than halved the emissions. The reduction has not been at the cost of GNP, which has grown in both absolute and relative terms. Sweden's emissions of carbon dioxide per inhabitant and year are now below the world average and one of the lowest figures in Europe.

[1] Land Use, Land-Use Change and Forestry, which describes the effects of land use.

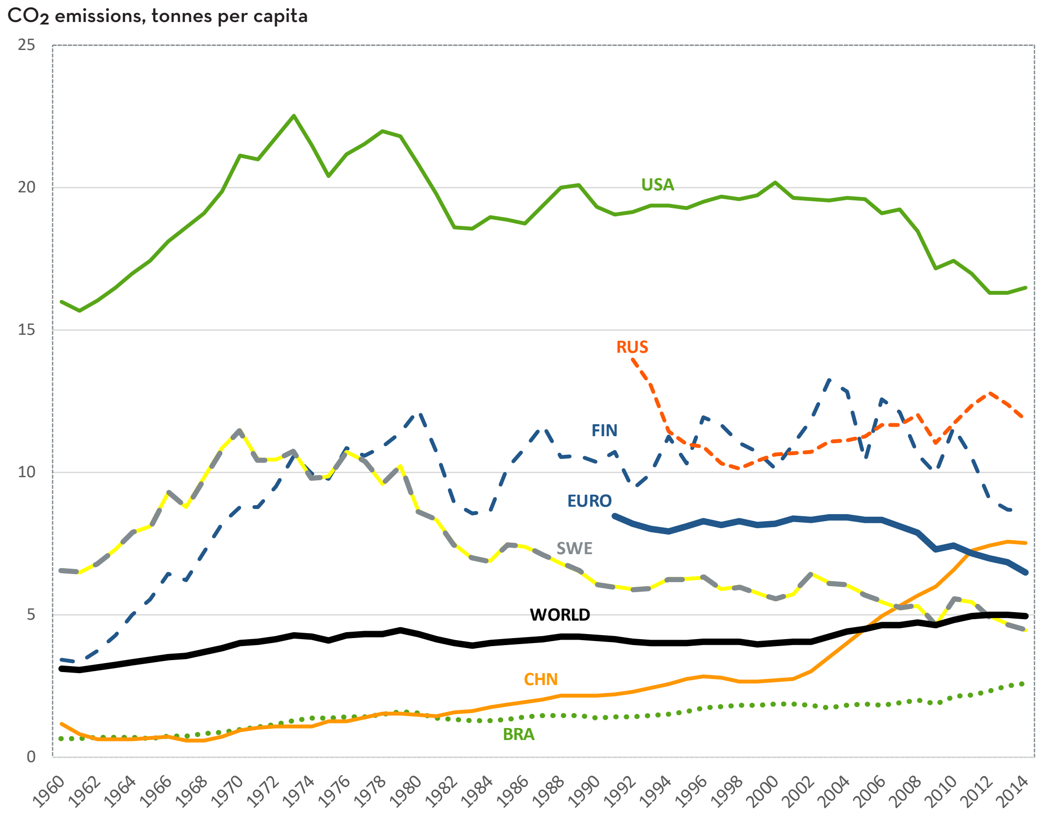

Figure 1. Carbon dioxide emissions per capita 1960-2014 in Sweden, the world, the Eurozone and some selected countries for comparison. In 2014, Sweden's per capita emissions of carbon dioxide were just under the global average. Based on data from the World Bank.

The carbon cycle – a complicated web in time and space

Forests dominate the Swedish landscape. The country's 28 million hectares (ha) of forest form a strong base for culture and traditions, contribute greatly to the economy of rural areas, and make a significant contribution to the balance of trade. In recent years, interest has grown in the ways in which the forestry sector can mitigate the atmosphere's increasing levels of carbon dioxide. Growing forest absorbs and stores carbon in biomass and in forest soils, but how does active forestry affect these processes?

Not all forest land is used for production. Of the 28.1 million ha classed as forest land, some 5 million ha are exempt from forestry because increment is lower than one cubic metre of stemwood per ha/yr, the limit for production forest. Approximately 1 million ha of production forest is exempt from forestry through formal protection (national parks, nature reserves, etc.) and a further 1.3 million ha are voluntarily set aside for conservation by forest owners.

The amount of carbon stored in vegetation and soil changes over time, depending on geographical location, climate and soil properties. The size of carbon sinks is affected by current and historical land-use practices, mainly different forestry and agriculture activities, and whether the net carbon flow over a certain period and area is positive (carbon accumulates), in balance, or negative (carbon is lost). At SLU, the Department of Soil and Environment has built up a knowledge bank about carbon cycle dynamics, based on data from the Swedish Forest Soil Inventory, combined with models of processes that contribute to carbon sequestration and the carbon cycle.

One difficulty when establishing the carbon balance is defining logic boundaries in time and space for describing the net effects of various measures. Clearfelling forestry, dominant in Sweden, extends from harvest and regeneration until the new stand is ready for harvest. Such a rotation period is normally 70-110 years, depending on the fertility of the soil and the landowner's goals. During the rotation period, the stand passes through different phases and is subjected to various measures (e.g. pre-commercial thinning and thinning) that affect both the ongoing increment and the amount of litter[2] produced, and thereby the net flow of carbon. Each of these phases can be studied separately, but when the carbon balance of boreal forests managed by clearfelling is to be calculated, the analyses should cover at least one rotation period. An alternative approach is to regard the forestry in a landscape perspective, where the forest's distribution in terms of development phases can be assumed to be relatively stable over time.

The influence of Swedish production forest on the flow of carbon in the biosphere is first presented, followed by

[2] Dead plant parts. In this text, litter has been used as a synonym for detritus, the term used in Figure 2.

a description of the store and flows of carbon. This gives a simplified picture of the carbon dynamics, with figures representing averages for Swedish forest. This is then compared with the net sequestration of atmospheric CO_2 in a forest that is not actively utilised. Forestry causes release of carbon dioxide of fossil origin, mainly in the form of exhaust from motor vehicles and forest machines in connection with activities such as felling, terrain transport, forestry, road construction and maintenance, and road transports. The size of these emissions is shown, along with how forestry can work to reduce its emissions. Finally, the different items are totalled to provide a net description of the effects of forestry on the carbon balance within Sweden's national boundaries.

The aim is to show how active forestry affects the dynamics in the carbon cycle. Strategies that may increase the capability of forests to absorb and store carbon, as well as management approaches that are less successful from this perspective, are presented and discussed.

The carbon cycle

Carbon, one of the most common elements, is an important building block in all organisms. The carbon cycle (Figure 2) describes the carbon flows in and between the geosphere, biosphere, hydrosphere and atmosphere. The amount of carbon in the atmosphere, mainly in the form of carbon dioxide, is mainly regulated through processes in the biosphere and the hydrosphere. Over a longer time perspective, the amount of carbon in the atmosphere is determined by the balance between sedimentation of calcium carbonate on the sea floor, photosynthesis, respiration and decomposition in the biosphere, weathering of rocks, and emissions from volcanic activity. This balance is now being increasingly affected by human activities, mainly when land use is switched to agriculture and when biomass and fossil deposits of carbon are burned for energy recovery

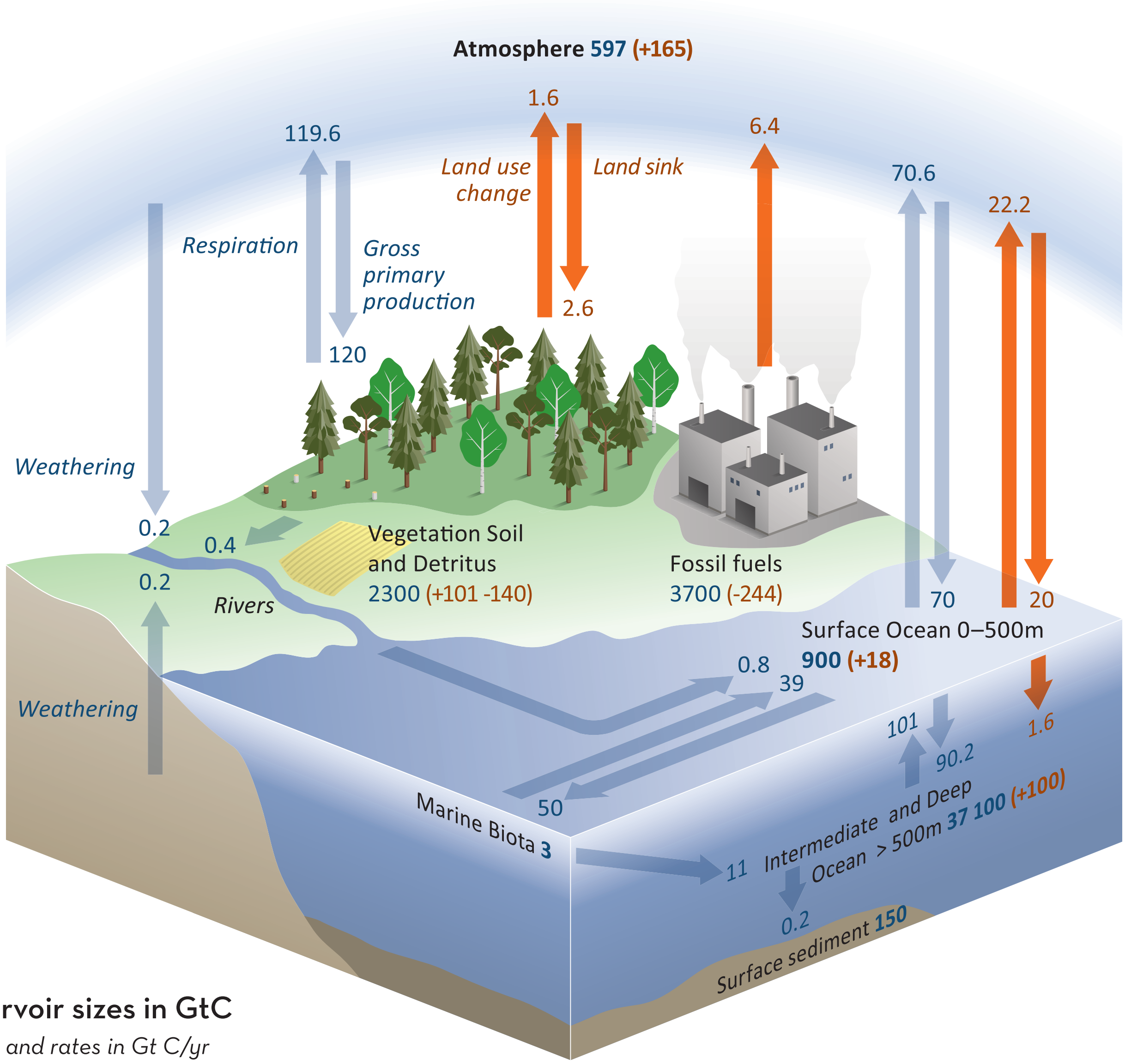

Figure 2. The carbon cycle and its global flows (after IPCC 2007). Blue figures show storages (reservoirs) in Gt (billion tonnes) of carbon and flows in Gt carbon/year before industrialisation, around 1750. Red figures show the effect of human activities on storages and flows, around 2005.

CARBON STORAGE IN NORDIC FORESTS

Trees absorb carbon

Already in the first billion years of life on Earth, cyanobacteria or blue-green algae developed the ability to utilise solar energy to enrich water for their vital processes. According to Margulis & Sagan (1986), the photosynthesis that occurred with the bacteria, leading to the green plants absorbing carbon dioxide, was *"undoubtedly the most important single metabolic innovation in the history of life on the planet"*. Trees capture and assimilate atmospheric carbon in the form of carbon dioxide, while also releasing oxygen, shown in chemical form as

$6\,H_2O + 6\,CO_2 + \text{light energy} \rightarrow C_6H_{12}O_6\,(\text{dextrose}) + 6\,O_2$

Some of the energy is used for cell respiration, but large quantities of carbon are stored in plant biomass through net increment. Carbon is absorbed and assimilated by the green parts of the trees, and stored in the form of hydrocarbons such as cellulose, hemicellulose, lignin and starch. Over time, most of the stored carbon is found in the woody parts of the trees, i.e. in stemwood, branches, twigs and roots.

Approximately half of the dry weight of the trees comprises carbon, although the proportion varies between different tree species. Conifers generally contain slightly more carbon (47-55%) than deciduous trees (46-50%), mainly because of a higher average lignin content, approximately 30%, compared with 20% for deciduous trees (Lamlon & Savidge 2003).

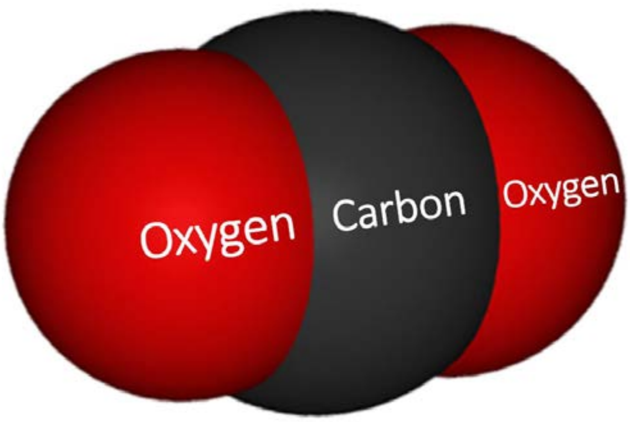

Figure 3. The carbon dioxide molecule comprises two oxygen atoms, with the atomic mass 2 x 16, and a carbon atom with the atomic mass 12. Carbon dioxide comprises 27.3% carbon.

A carbon dioxide molecule comprises one carbon atom, with the atomic mass 12, and two oxygen atoms with the atomic mass 16. The molecule has an atomic mass of 44, of which 27.3% comprises carbon (Figure 3). One kg of dry wood comprises, on average, approximately 0.5 kg carbon. In the formation of this amount of wood, 1.83 kg carbon dioxide (0.5/0.273) has been assimilated in the tree's biomass.

Decomposition and burning release carbon stored in biomass

Litter, i.e. dead plant parts in the form of branches, leaves and needles, along with stumps, branches and tops that are left behind after felling, is gradually broken down by organisms that live on the nutrients and energy they can release from the biomass. The biomass is decomposed to carbon dioxide and water, and the stored carbon is released back to the atmosphere.

Decomposition takes varying amounts of time, depending on the type of biomass. Nutrient-rich and smaller plant parts, such as leaf litter, needles and twigs decompose faster than thicker, woody plant parts. Ambient conditions – mainly temperature and access to water and oxygen – are particularly important for the decomposition process (Li et al. 2007). Under damp but anaerobic conditions, the decomposition process is very slow, as shown in peatlands. Decomposition is also slow in dry ecosystems.

SOME MEASUREMENT UNITS OF FOREST AND WOOD

Stem volume over bark (m^3s st)
The volume of the entire stem and its bark, above stump height.

Solid volume under bark (m^3s ub)
The volume of the stemwood, excluding the bark and top.

Cubic metres of biomass (m^3s biom)
The volume of the entire tree, including branches, needles, stumps and roots.

Tonnes of dry matter (tDM)
The weight of the biomass when it has dried. Approximately half of the weight of the living tree is water, and half of the dry matter comprises carbon.

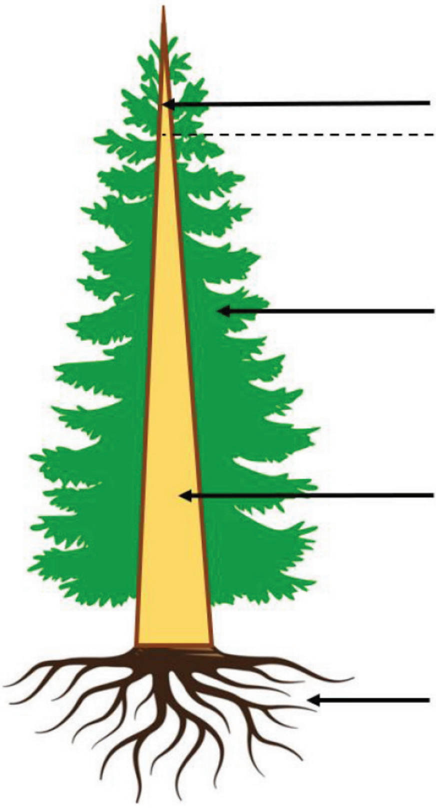

Figure 4. Some of the units of measurement of forest and wood used in this text.

Carbon stores in production forests in Sweden

Based on information from the National Forest Inventory, which publishes statistics on Sweden's forests (Skogsdata 2017), biomass in living trees comprises 2 685 million tonnes dry substance, 86% of which is in production, non-protected forest. Approximately 55% of the biomass consists of stemwood and bark and nearly 20% in branches, leaves and needles. The remaining 25% is biomass in the stump-root system.

Forests also contain a significant amount of dead wood (223 million m^3s st), approximately 5-9% of the standing volume over the whole country. The amount of dead wood is increasing, so the drain from living forest is greater than ongoing decomposition. A probable cause is that harvest of dead trees in large-scale forestry has virtually stopped. Instead, dead wood is deliberately created, in the form of high stumps as a measure to improve conditions for wood-dependent organisms (Skogsdata 2016). However, the rate of increase is slow, and an equilibrium point will be reached when the proportion of dead wood becomes quite constant. Converted into carbon, approximately 1 160 million tonnes of carbon are currently stored in living trees in Sweden's production forests, and a further 100 million tonnes of carbon in the form of dead wood.

Forest soils as a carbon sink

Some of the carbon is transferred to the ground, and large quantities are stored in the soils of forest land. Land that has previously been forested, but that is now used for agriculture, leaks carbon to the atmosphere, but if the land is reforested, this process is reversed and the storage of carbon once again increases (Post & Kwon 2000). Such a process can also be observed after clearcutting. Initially, soil carbon increases when stump-root systems and other logging residues that are left after harvest are decomposed, but the amount of carbon stored in the soil can then fall somewhat, at least on fertile soils (Stendahl 2017). Approximately at the time for a first thinning (20-30 years), the soil carbon has once again reached the level it had before the previous harvest. The reason for the decrease in the carbon storage in the soil seems to be mainly the small amount of litter in the young forest phase, compared with the conditions found in a mature forest (Stendahl 2017).

Stendahl et al. (2010) used fixed plots of the National Forest Inventory to investigate the amount of soil carbon down to a depth of 100 cm in the soil profile. The study was carried out on species-pure plots of Norwegian spruce and Scots pine on fresh to moist podzol on sandy or finer soils. The amount of soil carbon was found to differ between the spruce and pine plots. On pine plots (n=188), the average amount of soil carbon was 57 tonnes per ha, while the spruce plots (n=144) contained an average of 92 tonnes of soil carbon per ha. The difference between the species was less in better climate regions (Figure 5).

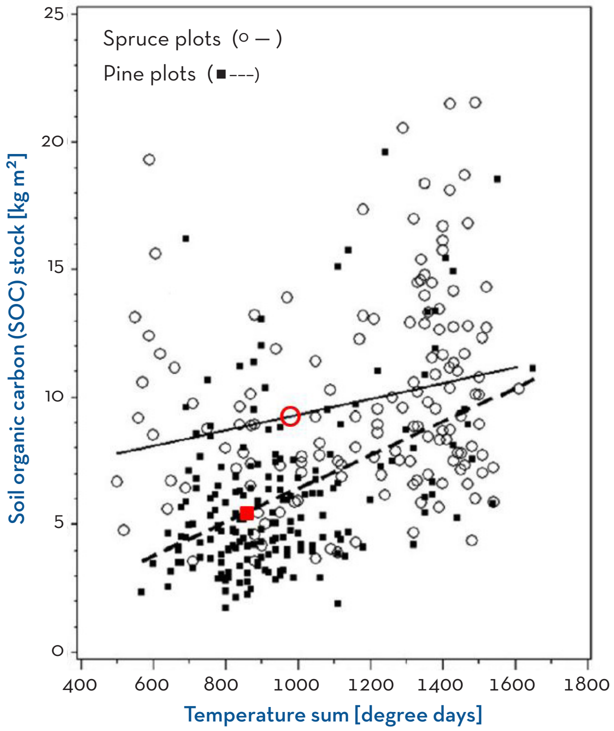

Figure 5. Linear regression of measured soil carbon (SOC) per m² to 100 cm depth. The difference between the tree species decreases with increasing temperature sum. Average values for each tree species are shown by red symbols. After Stendahl et al. 2010.

An interpolation of the data in Stendahl et al. (2010) suggests that the average storage of soil carbon in Swedish forest land is approximately 75 tonnes per ha, down to a depth of 100 cm. This indicates a total soil carbon storage in Swedish production forest land of some 1 800 million tonnes Another 510 million tonnes of carbon are stored in peatland forests (Stendahl 2017). The carbon storage in Sweden's approximately 7 million hectares of unutilised forest land, tree and bush land, is not calculated, since this area is not affected by forestry activities. However, also on these land use categories, significant quantities of carbon are stored in the soil and vegetation.

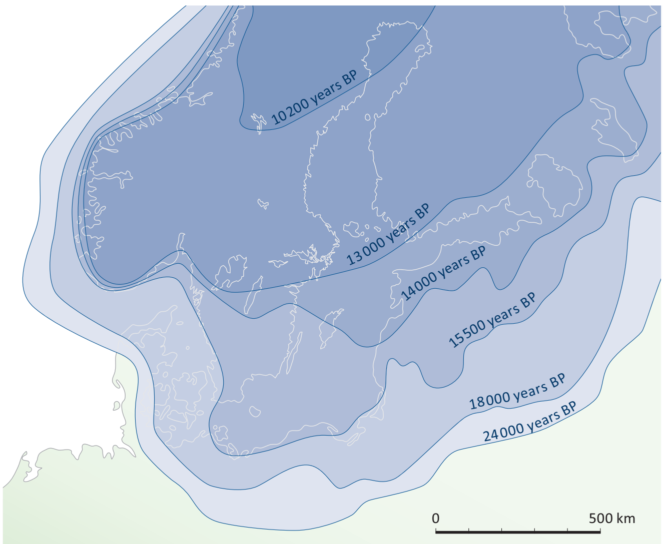

Figure 6. Extent and recession of the ice sheets in the Nordic-Baltic area.

Schlesinger (1990) studied the long-term storage of carbon in soils with a geological age of up to 12 000 years, i.e. land that has become exposed through the melting of glaciers since the most recent Ice Age. He found that carbon continually accumulated during this period, and that the process is still going on. The rate of sequestration is affected by climate, vegetation, the way the land has been used, and other factors such as storms and forest fires. The speed of the process varies greatly, from 2 kg carbon/ha/yr in arid tundra areas, up to 100 kg carbon/ha/yr on the most fertile forest land. The average for the ecosystems studied was 24 kg carbon/ha/yr.

The average storage of carbon on Swedish forest land, 75 tonnes of soil carbon per ha, has accumulated since the melting of the glaciers, a period of approximately 11 000 years (Figure 6). This means that the sequestration rate on Swedish forest land has been around 7 kg carbon per hectare and year. Although the sequestration process is not linear and has large variations, this figure is used to describe the development of the carbon store on Swedish forest land.

Annual net carbon sequestration in Sweden's forests

Carbon sequestration in tree biomass is limited to the increment season of the trees (spring-early summer). In other seasons, the amount of biomass decreases due to browsing, mortality and decomposition. Weather conditions, particularly the interaction between temperature and water availability, can make the balance between increment and drain of carbon from trees and the soil negative, even over relatively long periods (Lindroth et al. 1998), but if the amount of tree biomass increases during the observed time period, the amount of carbon stored in the trees also increases.

National Forest Inventory data (Skogsdata 2017) have also been used to calculate net carbon sequestration (increment minus drains, mainly from harvest) in tree biomass in Sweden's forests. The National Forest Inventory shows increment and harvest statistics in m^{3}s st, which is the volume of the entire stem above the stump, including bark and top. According to the National Forest Inventory, the average annual tree increment on Swedish production forest land during the period 2012-2016 was almost 121 million m^{3}s st, while the annual drain was approximately 96 million m^{3}s st, most of which, approximately 84 million m^{3}s st, comprised harvest.

Carbon is also assimilated in the tree's branches, foliage and stumps and the root system, so the volumes shown by the National Forest Inventory must be increased by the volume of these fractions. This information can also be calculated using Skogsdata 2017, which shows that one m^{3}s st comprises 0.39 tDM, and the ratio between the quantity of dry matter per m^{3}s st and the amount for the whole tree, including branches, needles, leaves, stump and root, to be 1:1.8. This proportion is applied to the data concerning annual increment and drain.

After this conversion, the tree biomass increment in Swedish forests is 85 million tDM/yr, and the annual gross carbon sequestration in Swedish forest equals 160 million tonnes of carbon dioxide. Net carbon sequestration, after deduction for the annual drains, is the equivalent of 35 million tonnes of carbon dioxide per year. Sweden's gross emissions at the 2016 level were 53 million tonnes of CO_2 equivalents/yr (Swedish Environmental Protection Agency 2018).

Much of the biomass in the drains is left in the forest. This applies to virtually the entire technically harvestable stump wood (stumps and roots >5 cm), which comprise approximately 21 million m^3s biom and most of the branches, tops and small trees, which only to a small extent (8 million m^3s biom or approximately one-third of the harvestable amount) is used for energy purposes. Consequently, harvest of these fractions could be significantly increased. This means that it is possible to further increase the climate benefits of forest, e.g. through substitution of fossil fuels.

Comparison of carbon store in unutilised and production forest

In a ***production forest***, vitality and production capacity are retained through thinning. Certain trees are harvested, to reduce competition for the trees regarded as having the best chances of growing in volume and value. All harvest removes carbon from the forest stand, reducing the size of the carbon store in the forest but also building up a carbon store in the form of products. Many of these products, such as packaging, hygiene products and paper, have a short life, while wood that is used, for example, in furniture and in construction has a longer life. When forest products have reached the end of their life, they can be recycled. Through ***cascading use***, materials such as wood fibre raw material can be recycled to form new paper qualities up to seven times, until they are finally used as biofuel for production of heat and electricity.

Approximately half of the wood harvested is used soon after felling, as an energy source, mainly for heat and electric power. This applies to the pulp industry's waste liquors[3] and bark, chips and other residual products from sawmills and other wood-mechanical industry. Some branches and tops, and the wood that cannot be used by industry because of inadequate quality and dimension, are also used for energy. Burning releases the stored carbon to the atmosphere, but this can later be assimilated by growing forests.

Harvest means that carbon sequestration in the soil decreases during the young forest phase. This is a result of the reduced litter, and because the amount of photosynthesising biomass has been reduced. Carbon can therefore be released from forest land, but in the geologically young boreal forest, soil carbon is replenished over time, although shorter periods of reduced soil carbon may occur after a harvest or through natural causes, such as extreme weather conditions, storm damage or forest fires.

In ***unutilised forest***, competition is great between the trees. Virtually every niche in the stand is utilised, and weaker trees die. If a stand is left undisturbed for a long period, the storage of biomass, and thereby carbon, will approach a maximum amount. Increment of new biomass is balanced over time by concurrent decomposition of dead trees and litter. The standing volume, and thereby the amount of carbon assimilated in the tree biomass, will remain relatively constant, close to the maximum possible level. (In practice, even unutilised forest is subject to major disruptions in the form of storm damage and fire, followed by, for example, insect damage, so the standing volume in these forests fluctuates greatly.)

Figure 7 shows how the standing volume – and thereby the assimilated carbon – develops in a production and unutilised forest. An unutilised forest may attain high levels of carbon per unit area, but from then on loses the ability to absorb more carbon, unless the fundamental conditions of the ecosystem change[4]. In the production forest, volume fluctuates with the phases of the rotation period. The average amount of stored carbon is lower, but the net carbon sequestration over time is significant. The production forest will thereby retain a capability for net absorption of carbon dioxide from the atmosphere that the unutilised forest lacks.

Forestry systems, silvicultural strategies and carbon balance

Many studies directly (carbon dioxide, substitution, bioenergy) or indirectly (biomass production, biodiversity) have examined the importance of forestry from a climate perspective (e.g. Nabuurs & Schelhaas 2002, Russel et al. 2015, Pan et al. 2011). The issues have also been studied from a Swedish or Nordic perspective (Stendahl et al. 2010, Lundmark et al. 2014, Lundmark et al. 2018). Studies that mainly compare yield and biodiversity in different silvicultural methods, such as the Skogforsk project CASS Consequence Analyses of Silvicultural Systems (Sonesson et al. 2017) are also relevant. Studies that show the effects of different silviculture strategies on net yield also show the forest's potential to assimilate carbon dioxide.

Objectives and expectations relating to forest and forestry are complex. Alongside wood and biomass production, the forest must provide a habitat for diverse animal and plant species and contribute with important ecosystem services. Forestry is expected to contribute to the aesthetics of the landscape, and allow recreation and outdoor activities. In addition, the forest owner expects revenue, and Sweden's forest sector is dependent on sustainable production of

[3]Waste liquor is the residual liquid left after pulping, and contains dissolved lignin.

[4]Magnani et al. (2007) show that increased carbon dioxide content, increased average temperature and nitrogen deposition lead to increased increment potential in boreal forests, which increases the maximum possible standing volume in the areas in question, assuming the trees have sufficient access to water (Reichstein et al. 2007).

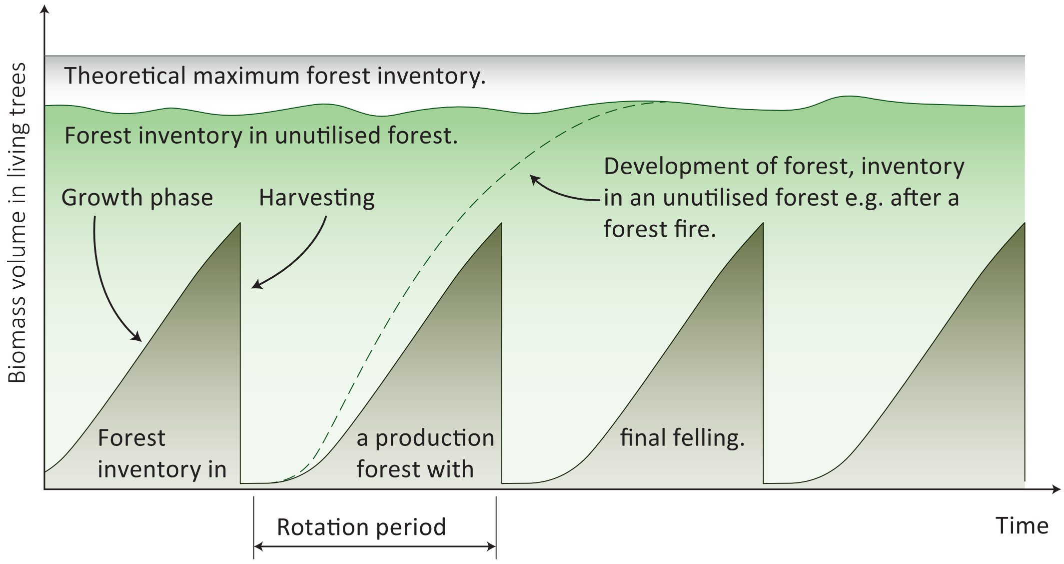

Figure 7. Diagram comparing development of standing volume in production and unutilised forest. Every harvest of standing volume from the production forest removes assimilated carbon from the forest. The net absorption of carbon can then continue in the next forest generation. Carbon is stored in the unutilised forest, but there is no net absorption.

forest products at a competitive cost. This complexity of objectives should not be forgotten, even if the aim of this study is to summarise the forest's ability to mitigate rising carbon dioxide levels in the atmosphere.

Skogforsk's CASS project studied the effects of switching to varying degrees of continuous cover forestry, with selective harvesting or shelterwood forestry over a larger area, instead of concentrated harvesting in clearcuts. The consequences of introducing continuous cover forestry on 10, 30 or 100% of the production forest were investigated. Visitor experience values would be increased with a switch to continuous cover methods, and access to blueberries, mushrooms and certain species of small wildlife would also increase. The proportion of deciduous trees would probably decline.

At a 10% level of continuous cover forestry, total yield would decrease by 2%, the equivalent of 3.4 million tonnes of CO_2/yr, an amount equal to the annual emissions from all heavy machines in Sweden. The costs of forestry would increase, because selective harvesting is more expensive than final felling, so profitability would decrease.

If 30% was managed through continuous cover methods, the effect on forest production would be approximately 5-6% lower increment, and a significantly lower proportion of pulpwood. Because it would be primarily Norway spruce stands that are affected, the supply of forest fuel would become limited, so the ability of forestry to counteract increasing carbon dioxide levels would also be reduced, because of the scarcity of wood chips for energy.

If all forest was managed through continuous cover, wood production would be reduced by 20%. The reduced fixation of carbon dioxide is the equivalent of two-thirds of Sweden's annual gross emissions of carbon dioxide. Forest fuel, in the form of logging residues, would disappear from the market, the shortage of pulpwood would limit production in industry, and the supply of timber would decrease. Forestry costs for felling and terrain transport of wood would increase significantly, thereby reducing profitability.

Lundmark et al. (2014) analysed different realistic forest management models when studying the potential for Swedish forestry to counteract the increasing levels of carbon dioxide in the atmosphere. They concluded that the current management model has a powerful effect, corresponding to 60 million tonnes of CO_2 per year, and that this effect could be strengthened in boreal forests. In their most climate-positive scenario, an increase in biomass harvest for energy and wood products, combined with yield improvement measures (fertilisation and plant selection), would reduce the carbon dioxide released to the atmosphere by a further approximately 40 million tonnes/yr.

The effect of rotation period on the forest's ability to store carbon was studied by Lundmark et al. (2018). Currently, rotation periods are based on maximising land value in terms of production economics. The analysis tool Heureka was used to compare the optimised rotation periods with the option of delaying harvest by 10, 20 or 30 years as a way to increase the forest carbon storage and extend the period of high net production of biomass.

For spruce stands on better-quality soils, a moderate (10 years) extension of the rotation period increased the climate benefit, but the higher storage of carbon in the stand was balanced by reduced increment, with the result that the climate benefit disappeared or came at a cost. Land value fell as a result of the longer rotation periods. A test was also carried out to investigate the effect of shortening the rotation period by 10 years. This resulted in reduced land value, but also decreased the carbon store and net increment. The conclusion was that the stand's net increment is a factor that weighs heavily, both in economic terms and from the perspective of climate benefit.

High and sustained net increment, combined with sustainable utilisation of forest biomass, is vital.

Overall, the studies show that *high and sustained net increment, combined with sustainable utilisation of forest biomass, is crucial for the forest's ability to counteract rising carbon dioxide levels in the atmosphere*. Consequently, if forestry is to make the largest possible contribution to reduce carbon dioxide levels in the atmosphere, the highest possible production of biomass should be the goal. To maximise the benefit, new products and materials based on tree biomass should be developed by an expanded and supplemented forest industry. The flows of biomass-based products and materials should be developed in such a way that product life cycles are extended, and so that reuse and recycling opportunities are increased.

Development of the Carbon Capture and Storage (CCS) method for carbon storage is easiest for sedimentary rocks. If the technology can also be developed for granite and gneiss, the dominant rock types in Swedish bedrock, the effect of the forest sector's biomass-based production would extend beyond substitution and avoiding the emission of fossil carbon. It would also start removing carbon from the natural cycle, an effect that so far can only be attained through increasing the forest inventory.

Concentrating only on maximising net production of forest biomass would, however, come into conflict with other important goals, some of which are indicated above. In practice, the demands of several legitimate stakeholders must be satisfied and balanced against each other.

ENERGY USE IN FORESTRY

Carbon dioxide emissions from forestry

In forestry, vehicle fuels are mainly used in *logging* (i.e. felling and terrain transport), for road building and maintenance, and for road transport of wood from landings to the users.

Use of fuel in logging was investigated by Brunberg (2006) and by Löfroth and Rådström (2006), who included diesel consumption in road transports and trends in fuel consumption. The reports show a considerable variation in fuel consumption. Apart from driving style, other important factors influencing fuel consumption include machine size, choice of tyre, chain or track equipment, length of transport distance, weather and, for the forest machines, also topography, ground conditions and stand properties. In this text, the average consumption figures per cubic metre were deemed sufficient.

Fuel consumption in forest fuel operations has been investigated in a number of case studies in the Skogforsk R&D programme, *Efficient Forest Fuel Supply Systems*.

Brunberg (2006) reports a fuel consumption in logging of 1.75 l/m^3s ub as a combined average for final felling (70% of the volume) and thinning. Of this, the harvester accounts for 1 l/m^3s ub and the forwarder for 0.75 l/m^3s ub. Löfroth and Rådström (2006), partly based on the same data, found an average fuel consumption figure of 1.7 l/m^3s ub in logging. Fuel consumption in road transport was 2 l/m^3s ub at an average transport distance of 91 km. Löfroth and Rådström also found a clear trend of improved energy efficiency in logging and transport, with fuel consumption falling from 5.4 l/m^3s ub in the mid-1980s to 3.7 l/m^3s ub 20 years later, in 2005. The explanation was thought to be a combination of technical developments, greater importance of fuel consumption for profitability, and greater environmental awareness.

Brunberg's unpublished study refers to the 2014 production year. Partly based on Skogforsk's extensive collection of follow-up data, he calculated the total consumption of fuel for logging and secondary transport of roundwood and forest fuel, and for silvicultural activities. The main results from this study are shown in Table 1. Brunberg's study also summarised how the fuel requirements can be further reduced. Road transport alone accounts for nearly half (46%) of the total fuel consumption per cubic metre. Terrain transport, wood processing and road transport of forest fuel requires fuel, but as the volumes of primary fuel are relatively small compared with the large roundwood assortment, the proportion of the total fuel consumption is small. Forest fuel accounts for 7-8% of the total consumption. Silvicultural work, mainly plant production and soil scarification, represents approximately 6% of the total fuel requirements.

An additional significant item comprises fuel consumption in maintenance, upgrading and construction of forest roads. There is no detailed subdivision of this, but Bergqvist (pers. comm.) states that the total road maintenance cost in forestry comprises 30% for materials (gravel and macadam), while the remaining 70% comprises machine costs, of which 17% are the costs of fuel. By applying these estimates of road maintenance costs for 2014 (from Skogforsk's cost surveys), it has been possible to supplement Table 1 with figures showing fuel requirements for forest road maintenance. The collective average, 4.71 l/m^3s ub, is higher than that reported by Löfroth and Rådström (2006) for 1995, probably because they only included logging and road transport of roundwood in their calculations.

Emissions of carbon dioxide from forestry operations were calculated per cubic metre and as a total per year, with an assumed harvest level of 70 million m^3s ub and an additional 8 million m^3s biom forest fuel. Diesel weighs 835 g/l and contains 86.2% carbon, giving a figure of 720 g carbon/l. Combustion uses 1920 g of oxygen, and 2 640 g of carbon dioxide is formed. With the input data as shown in Table 1, emissions are therefore 12.4 kg $CO2/m^3$ s ub or 970 000 tonnes per year.

Table 1. Fuel consumption in Swedish forestry, 2014. Total consumption and proportional percentage per activity, and aggregated to an average figure per m³ harvested wood. After Brunberg (unpublished), Skogforsk's costs survey for 2014 and Bergqvist (pers. comm.)

Fuel consumption in Swedish forestry, 2014					
Total		367 400 m^3 fuel, i.e. 4.71 l/ m^3			969 936
		Operation: ha, m^3	m^3 fuel	%	tCO_2/år
Silviculture, total		Total	22 900	6.2	60 456
Of which:	Planted area, ha	176 000	14 100	3.8	37 224
	Scarification area, ha	185 000	4 600	1.2	12 144
	Pre-commercial thinning, ha	392 000	3 900	1.1	10 296
	Fertilisation, ha	24 000	300	0.1	792
Logging, total		Total	148 200	40.3	391 248
Of which:	Harvesting m^3s ub	70 000 000	74 200	20.2	195 888
	Forwarding, roundwood, m^3s ub	70 000 000	56 000	15.2	147 840
	Forwarding, forest, m^3s biom	8 000 000	8 000	2,2	21 120
	Chipping, forest fuel, m^3s biom	8 000 000	10 000	2.7	26 400
Road transport, total		Total	196 300	53.4	518 232
Of which:	Roundwood, m^3s ub	70 000 000	161 000	43.8	425 040
	Forest fuel, m^3s biom	8 000 000	9 500	2.6	25 080
	Road maintenance, m^3s ub	78 000 000	25 800	6.8	68 112

The mechanised forestry sector in general has a modern machine fleet, where technical development focuses on high operational reliability, reduced fuel consumption, and low emissions.

Measures to reduce fossil fuel requirements in forestry

The forestry sector is working actively to continually reduce carbon dioxide emissions from its operations. The reason, in addition to growing environmental awareness, is that the cost of fuel constitutes an increasingly high proportion of the production cost. Emissions are being reduced through development of technology and methods for increased energy efficiency, and through substitution of fossil fuels. For technological advances that lead to greater energy efficiency, the forestry sector relies on the general technological development. However, a significant part of this work involves testing and implementing novel technologies in the forest engineering environment. As an effect, the mechanised forestry's emissions of carbon dioxide per cubic metre fell by one-third between the start of the 1970s until the end of the 1990s (Berg 2014). This positive trend has continued, and fuel consumption is now around half of what it was when forestry became mechanised (Brunberg, unpublished).

The tough international competition in the sector means the machine fleet and production technology is very modern in forestry compared with many other sectors (Brunberg 2006, Löfroth & Rådström 2006). Technological advances make a rapid impact.

Silvicultural activities account for only a small proportion of fuel consumption in forestry. The two major items are energy consumption in greenhouses for plant production (3.8%), which accounts for 80 l fuel per planted ha (Aldentun 1999), and soil scarification (1.3%), where fuel consumption is estimated at 25 l/ha. For nurseries, the dependency on fossil energy could be reduced by switching to biofuels. Energy requirements can also be reduced by growing smaller plants, which require less greenhouse space and shorter cultivation time.

For soil scarification, Brunberg (unpublished) reports that a switch to a three- or four-row machine, although increasing fuel consumption per hour, further increases productivity. There is clear potential for saving energy. In a slightly longer perspective, it is also desirable to increase the precision in soil scarification, i.e. to only prepare the desired number of planting points. With current methods, much of the soil scarification work is carried out where no seedlings will be planted. The rapid development of sensor and analysis technologies provide good opportunities to improve soil scarification.

In logging, mechanisation and the increasingly reliable and productive machines have led to a significant reduction in energy consumption per cubic metre. In recent decades, developments on the engine side have been focused on reducing the emissions of nitrogen oxides (NOX) and particles. The machine fleets in the forestry sector are modern, and machines meet strict requirements. This development now seems to be in a concluding stage, and several innovations aimed at fuel efficiency are now being demonstrated by the Nordic manufacturers of forest machines. Intelligent control systems are being tested that will adapt the power output to the work situation, and there is considerable work taking place involving hybrid technology. This can give lower total energy consumption and contribute to further reduced emissions, since hybrid technology often reuses potential or kinetic energy through electric or hydraulic accumulator systems.

There is again great interest in driving development towards greater energy efficiency. Reduced rut formation and more efficient hydraulics would reduce both costs and required energy. However, it is not only technical advances that afford opportunities. Significant potential can be realised through operator training. One example is the machine instructor network, RECO, which successfully runs an extensive programme focused on operational technology and issues relating to work methods. Various decision-support information systems providing tactical support, such as route choice in the forest, seem to have great potential for reducing emissions as well as other environmental impact. Such types of tools also improve coordination of the logging work, which reduces resource consumption, and thereby also the fuel requirements.

Current R&D is aimed at reducing emissions from forest machines and fuel consumption. Here, hybrid technology is being tested on the Logset 12H harvester.

FOREST INDUSTRY PRODUCTS IN A CLIMATE PERSPECTIVE

Renewable forest products can replace fossil raw materials such as coal, natural gas and oil as energy sources or for production of various materials and products. As long as new forest is planted and increment maintained, the net addition of carbon dioxide to the atmosphere from fossil deposits is reduced.

PHOTO: ERIK VIKLUND

Substitution

As forest materials are used as alternatives to products based on fossil carbon compounds, there is no addition of carbon dioxide to the atmosphere, providing the standing volume over the entire production area is constant. If the forest inventory increases, then the forest has instead reduced carbon dioxide levels in the atmosphere. This is the case in Sweden, where the total forest inventory has doubled since the first National Forest Inventory 1923-29, from 1.7 to 3.5 billion m^3s st. The carbon store in the Swedish forest has thereby increased by an amount corresponding to 40 years of Swedish CO_2 emissions at 53 million tonnes/yr (2016 level, excluding LULUCF and marine bunker oil), according to the Swedish Environmental Protection Agency (2018).

Lundmark et al. (2014) calculated the substitution effects of products based on tree biomass. They found that, through substitution, today's forest sector generates a climate benefit of 470 kg CO_2/harvested cubic metre, but also found that the substitution effects increase with a more complete utilisation of the felled biomass. The most production-focused alternative studied gave a climate benefit of 719 kg CO_2/harvested cubic metre, an increase of over 50%. The most intensive alternative included an increase in forest fuel harvest from 15% to 35% of available logging residues plus collection of 20% of the harvestable stump volume.

Later studies are less conservative. In a comprehensive review of 51 current studies of the substitution effects of wood-based products, Leskinen et al. (2018) propose an average substitution effect of 1.2 per kg carbon in the utilised biomass. This substitution factor, 1.2:1, is higher than the ratio adopted by Lundmark et al. (2014), which was only around 0.6:1 for the base level and 0.8:1 in the most intensive alternative. Clearly, further studies (as well as a holistic, unifying theory) are needed to reliably establish the benefits of forest biomass utilisation from a climate perspective, especially for the many new, emerging wood-based products and materials now being introduced to the market.

Increasing climate benefit of the Swedish forest and its products

The effectiveness of the forest as a tool in the climate work is linked to production in the industries that use the forest raw materials (Björheden & Segeborg-Fick 2014). This view chimes well with the conversion to a circular, biobased economy underway in the EU, with the objectives to increase sustainability and reduce environmental and climatic impact. This process assumes high levels of efficiency in resource utilisation, and promotes the growth of new companies, products, services and jobs. Sweden has adopted a positive and active stance (SOU 2017:22) and, in many ways, lies well advanced in aspects that are vital for increased sustainability in product and process chains.

For Swedish conditions, an expansive forest industry that drives demand for forest products is the basis of this work. The sector has the drive and desire to comprise a hub in the new bioeconomy, as articulated in the Vision document of the sector association, The Swedish Forest Industries' Federation (Skogsindustrierna 2015) and in ***Road Map for a Fossil-free Sweden*** (Fossilfritt Sverige 2018). Greater public efforts could mean a lot for the strength and rate of such a transition.

Increased support for research on the more technical aspects of wood production and wood supply is needed. Swedish research into the consequences of forest production enables us to also show how forest utilisation can be balanced against other goals than that of climate. More support and research should be aimed at the development of new products and materials, where collaboration with industry must be extended. Routes to joint funding at the country's research institutes and universities must be simplified.

Export of Swedish forest products is greater than domestic consumption. It is important that new products are developed with the aim of retaining the attractiveness of the products on the international market. For example, more construction with wood has long been a Swedish national objective. Building processes and systems for building in wood have been developed. This product segment could increase the demand for wood in long-life products and Swedish wood building systems could be exported, on condition that the national Swedish developments harmonise with the regulatory frameworks and ambitions in the EU.

A continual consultative review of taxes, charges, legislation and regulations that govern and steer the forest sector is also important for the transition towards a bioeconomy, with retained competitiveness. Fundamental structures, such as the rescue service, education and training, and infrastructure, are part of society's responsibility, and can be adapted to facilitate the ongoing transition to a green economy.

Sweden has developed successful systems for managing wood-based products from manufacture, through multiple reuse and ultimate energy recovery. But there is scope for improvement. These systems could also be launched on important export markets, which may be behind Sweden in these aspects. The climate benefit of the wood-based fuel materials (forest chips, waste liquor, recycled wood, etc) could be multiplied through more complete utilisation of the annual harvest. Production of not just heat and electricity but also of liquid fuels would further increase the usefulness of forest biomass. The technology for capturing and storing carbon in conjunction with combustion for energy could further strengthen the climate benefit, because it ***removes*** carbon from circulation, as a supplement to the growing forest's ***assimilation and storage*** of carbon, and the forest products' ***prolonged storage*** of carbon and substitution of fossil carbon.

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