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BIOENERGY FROM BOREAL FORESTS

Swedish approach to sustainable wood use

International Renewable Energy Agency

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About Svebio

Svebio, Swedish Bioenergy Association, was founded in 1980. Svebio's vision is a 100% renewable energy system, where the different renewable energy sources interact, and where bioenergy will play a central role. Svebio wants to increase the use of bioenergy in an economically and environmentally optimal way, using general incentives like carbon pricing. Svebio's members are companies and other actors along the entire bioenergy supply chain. Svebio publishes two magazines: Bioenergi in Swedish and Bioenergy International in English. The office is in Stockholm.

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ABBREVIATIONS

AWS	Available for wood supply
CHP	Combined heat and power
CO_2	Carbon dioxide
DH	District Heating
EU28	The 28 member states of the European Union
EU ETS	European Union Emission Trading Scheme
FAO	Food and Agriculture Organization of the United Nations
GPP	Gross primary production
Gt	Gigatonnes (billion tonnes)
GWh	Gigawatt-hours
ha	Hectares
HDI	Human Development Index
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
m^3	Cubic metres
Mha	Million hectares
Mm^3	Million cubic metres
Modt	Million oven dry tonnes
MtC	Million tonnes of carbon
$MtCO_2$	Million tonnes of carbon dioxide
$MtCO_2$-eq	Million tonnes of carbon dioxide equivalent
Mtoe	Million tonnes of oil equivalent
MWh	Megawatt-hours
NAWS	Not available for wood supply
NCV	Net calorific value
NPP	Net primary production
odt	Oven-dry tonnes
SDG	Sustainable Development Goal
SEA	Swedish Energy Agency
SEK	Swedish krona
SLU	Swedish University of Agricultural Sciences
t	Tonne
tC	Tonnes carbon
t-km	Tonne-kilometre
TWh	Terawatt-hours

EXECUTIVE SUMMARY

Bioenergy, most of it from forests, accounts for three-eighths of all the energy used in Sweden. Swedish forests have doubled in volume over the last century. They have therefore doubled their capacity to absorb carbon and to provide wood for energy and a variety of other uses. As the land area covered by forests has changed very little, this is due to more productive use of the land. The strategy that has brought this about may be useful to consider for other boreal forests.

Central to the strategy is active forest management, with constantly improving methods and practices, which leaves a portion of each year's forest growth in place when wood is harvested, replants the harvested area with new trees, and uses wood harvested in an efficient, sustainable manner. About three-quarters of the annual forest growth is harvested, while the remaining quarter is left in place, continuing to provide carbon uptake and other ecosystem services. Wood is typically harvested around every 60 to 100 years, allowing for new trees to be planted. New trees grow faster than old trees, collectively adding more mass to the forest than if trees were left to grow indefinitely. Actively managed and monitored forests are also more resistant to forest fires and infestations, reducing the risk of massive carbon dioxide release from such catastrophes.

Wood energy potential could be significantly enhanced by collecting a larger share of logging residues. Just slightly more than half of the harvested wood is roundwood from tree trunks, which is used for lumber, other wood products, pulp and paper. Turning roundwood into such products yields processing residues for energy use. But the rest of the fellings are tree stumps and "slash" from tops, branches and twigs. Such logging residues are mostly left in the forest to rot,

releasing carbon dioxide. While some are needed to support biodiversity by providing habitats for flora and fauna, more could be collected and combusted or otherwise used to displace carbon-intensive fossil fuels.

Carbon uptake potential from forests could be enhanced through the focused application of fertiliser. Such directed use of fertiliser has been shown to double the rate of tree growth. Carbon uptake could also be enhanced by developing wood-based alternatives to fossil fuels, such as gasification processes for converting wood to renewable jet fuel.

Further carbon uptake is possible in buildings, where wood can displace carbon-intensive construction materials like steel and concrete while continuing to store the carbon that was taken in by the trees from which it was produced. According to recent studies, about 2 tonnes of carbon dioxide emissions are avoided for every tonne of wood used in buildings. Efforts to increase the use of lumber in buildings, as well as the use of composite materials made from low-quality wood residues, could significantly improve global carbon balances.

Active forest management, greater collection of forest residues, focused use of fertiliser, and increased use of wood in buildings can be worthwhile strategies for boosting carbon uptake and energy output from any boreal forest. The potential is substantial not just in Sweden, but throughout Europe, as well as in Canada and Russia. Globally, boreal forests represent a very large carbon sink and energy source, and their role could be significantly enhanced.

1 BIOENERGY IN SWEDEN AS AN ANCHOR OF SECURITY AND SUSTAINABILITY

At the root of Sweden's push for bioenergy expansion was the desire to ensure long-term energy security. At the time of the first oil crisis in 1973, Sweden was 80% dependent on imported fossil fuels, mainly oil. At the same time, the strong political push for nuclear power was questioned. This left bioenergy as a main logical alternative to enhancing energy security.

All of the oil used in Sweden has to be imported. In the 1970s, most of this oil originated in the Middle East. The embargo of 1973 thus required oil rationing, and sharply higher oil prices throughout the decade exacted a heavy economic toll. As in many oil-importing countries, this created a political imperative to switch from oil to other energy sources. Leading options for doing so were the development of nuclear power and greater use of wood for district heating, which was almost totally dependent on heating oil.

The decision to decrease the dependence on oil was also a question of national security, at a time when Europe was still divided by the Cold War, with Sweden caught in the middle. The first subsidies to switch heating plants from oil to domestic fuels like wood chips and peat were initiated by the Civil Defence Authority. Today, most oil imports come from the North Sea (Norway) and Russia. However, oil imports still entail energy dependency and are a strain on the economy.

The use of nuclear power was questioned both by scientists and a broad environmental movement. The issue moved to the forefront of Swedish politics and divided the nation. A referendum was held in 1980, resulting in a compromise to halt construction of new reactors, keep the reactors already being built and stop electricity generation from nuclear power plants in 2010. This "stop-date" was later moved forward. Eight of the original 12 reactors were still running as of 2018, of which 2 were slated to close down by 2020.

As a part of the debate, much focus was given to the search for "alternative energy sources": energy solutions that could be used instead of the nuclear reactors. For Sweden, bioenergy and wind power were seen as the most economically viable alternatives.

Research on bioenergy potential

As Sweden began to look for alternatives to imported oil and nuclear power in the 1970s and 1980s, one obvious answer was to increase support for research on renewable energy and energy efficiency. A very broad research programme was started around 1980, with involvement of the state energy company as well as a new energy agency and research institutes. One of the major research areas was bioenergy: to investigate the potential of biomass and the methods to harvest and use it sustainably.

Much of the research and development for biomass from forestry was conducted by the Swedish University of Agricultural Sciences (SLU). This research and development focused on questions like:

- How big is the potential for biomass from forestry and agriculture? Can this potential be mobilised without competition with current uses for the forest industry and the food industry?
- What are the environmental and economic restrictions?
- How can the cost of harvesting be reduced by the development of better harvesting equipment? How can delivered feedstock costs be cut by improvements in transport?
- How can combustion technology be developed to increase the efficiency of biomass conversion to heat and power? How can emissions from heat and power plants be reduced?

- What is the potential to develop agricultural wood production from short rotation coppice of rapidly growing bush species like willow?

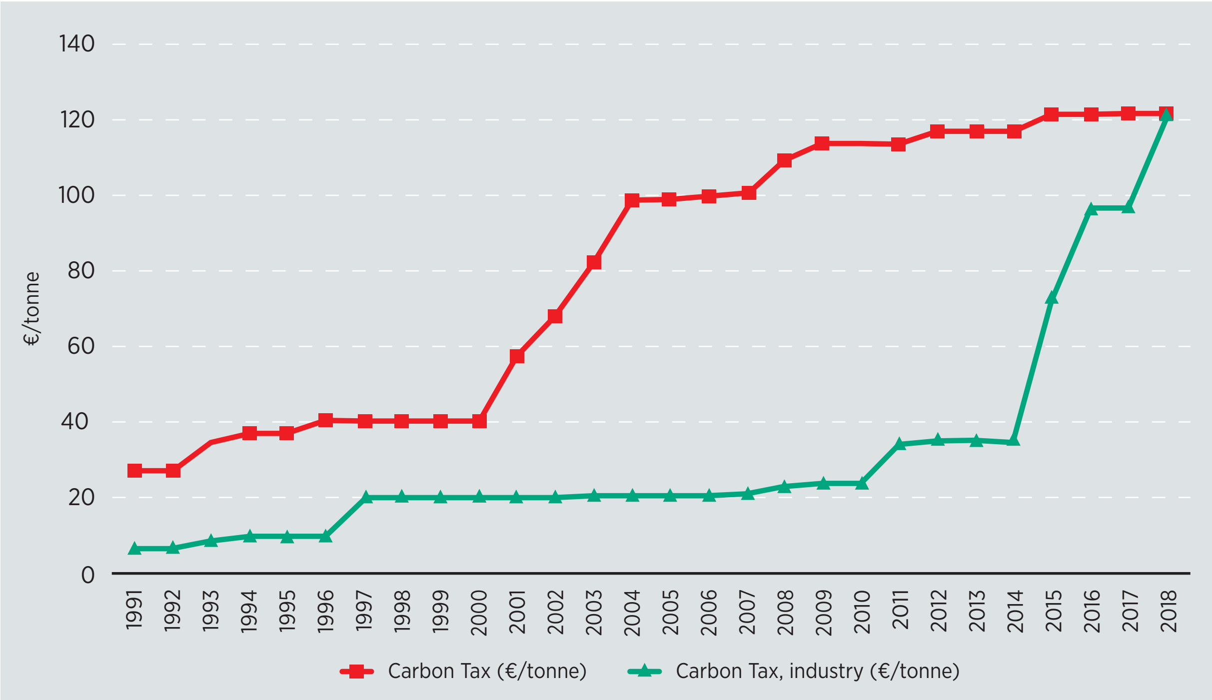
In 1990, the government appointed a special expert commission (Biobränslekommissionen 1992) to investigate the potential of biomass from forestry. The commission's report confirmed that there was large potential, and this provided a firm scientific basis for further political decisions to promote bioenergy. Previous research had already shown that residues from final felling and from thinning operations offered a very large energy source, that technology to harvest these residues was available, and that there were clear positive synergies between the harvest of industrial wood and increased use of biomass for energy.

Environmental concerns and carbon tax

While energy security concerns provided the initial impetus for Sweden's bioenergy development, a continued push was provided in the 1970s and 1980s by environmental issues. Environmental policy had been a growing theme in Swedish politics since the 1960s, but was further highlighted as Sweden hosted the United Nations environmental summit in Stockholm in 1972. Pollution of air and water, acidification from sulphur and nitrous oxide emissions, and concerns about limited supplies of food and materials were some of the issues. Pressure increased greatly as the climate issue moved to the forefront, with the Rio summit in 1992 and the Kyoto Protocol negotiated in 1997.

One discussion concerned the possibility of putting a price on emissions. Sweden's parliament decided on a carbon tax in 1990 as part of a bigger tax reform. Taxes and fees were also introduced on emissions of sulphur and nitrous oxide. The carbon tax went into effect in 1991 with a lower tax rate for industry than for households and the service sector. It has since been raised many times and is by far the highest carbon tax globally. From 2018, the tax rate will be the same for all sectors of the Swedish economy outside the European Union Emission Trading Scheme (EU ETS). Industry and power plants within the EU ETS do not pay carbon tax as the scheme will create a market value for carbon for them that is Europe-wide. The Swedish carbon tax is levied per tonne of carbon dioxide (CO_2) emissions on the different fossil fuels (heating oil, propane, fossil gas and coal).

Figure 1.1 Carbon tax in Sweden, 1991-2018 (EUR per tonne of carbon dioxide)



Source: Swedish government, Ministry of Finance, and Svebio (2018)

The carbon tax has probably been the most important factor in the promotion of bioenergy in Sweden, as it has made bioenergy more competitive with fossil fuels. It continues to be important as oil prices have weakened and may remain weak over the longer term. At the same time, increasing volumes and improved harvesting and conversion technology have reduced the cost of biomass to the point where it is competitive with fossil fuels in many applications even without incentives.

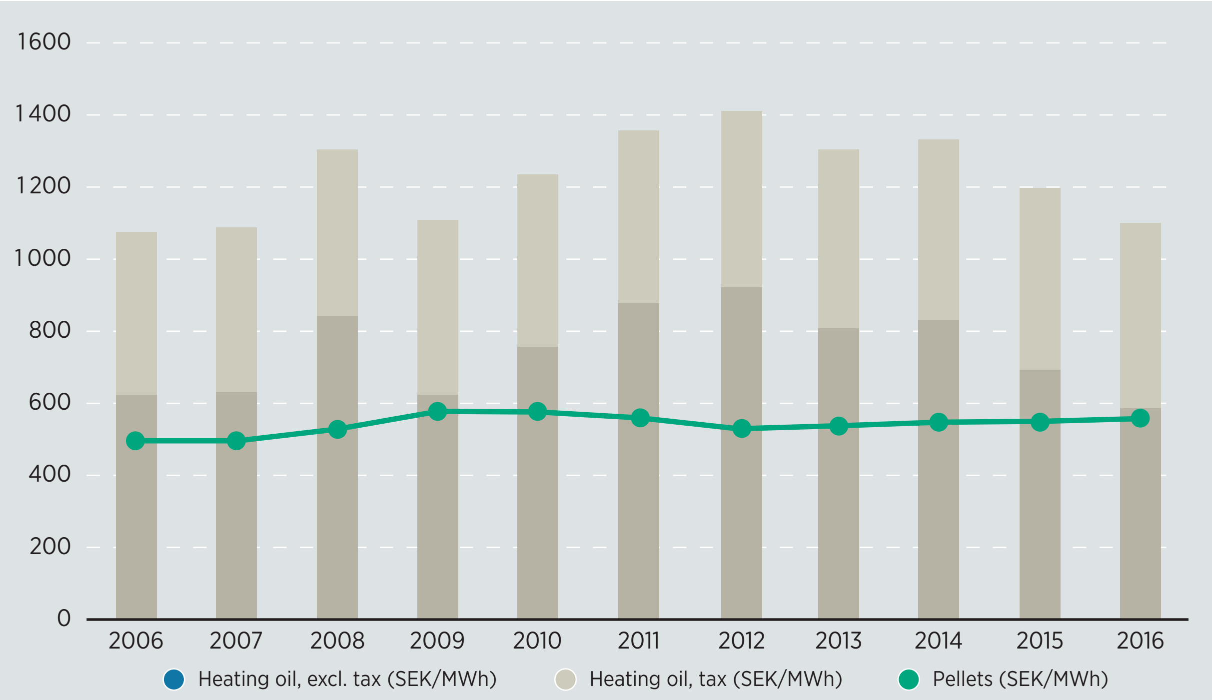
Figure 1.2 shows prices of heating oil and pellets for residential use in Sweden from 2006 to 2016. Darker bars show the market price for oil before taxes, and lighter bars show the additional oil price due to the carbon tax. The green line shows the price for pellets. The carbon tax has almost doubled the price of heating oil during this period, making wood pellets competitive. Pellets were less costly than heating oil over the entire period even without the carbon tax, but the price difference was in some years very small. To motivate fuel switching from oil to biomass, the price difference needs to be large enough to recover the cost of investment in a new boiler and new fuel storage and handling equipment.

Experience with wood for heating

Since the 1970s, Sweden has had well-developed district heating systems, usually run by municipal utilities. Most large cities had hot-water grids and heat plants. When incentives were given to switch from fossil fuels to renewable fuels, with investment grants and carbon taxation, large urban utilities rebuilt their heat plants or installed combined heat and power (CHP) plants. Many new small CHP plants were also built in smaller cities and towns.

The Swedish Bioheat Map shows all heat plants and grids using biomass and biogenic waste for district heating. The most recent map shows a total of 520 such grids. In larger cities, there may be more than one heat plant to supply a grid. Most plants use wood fuels. Waste plants are mainly used in larger cities because they need to be large enough to bear the high cost of advanced flue gas cleaning and need to run year-round to be cost effective; there is a market for the hot water they generate in summertime, as well as for district cooling.

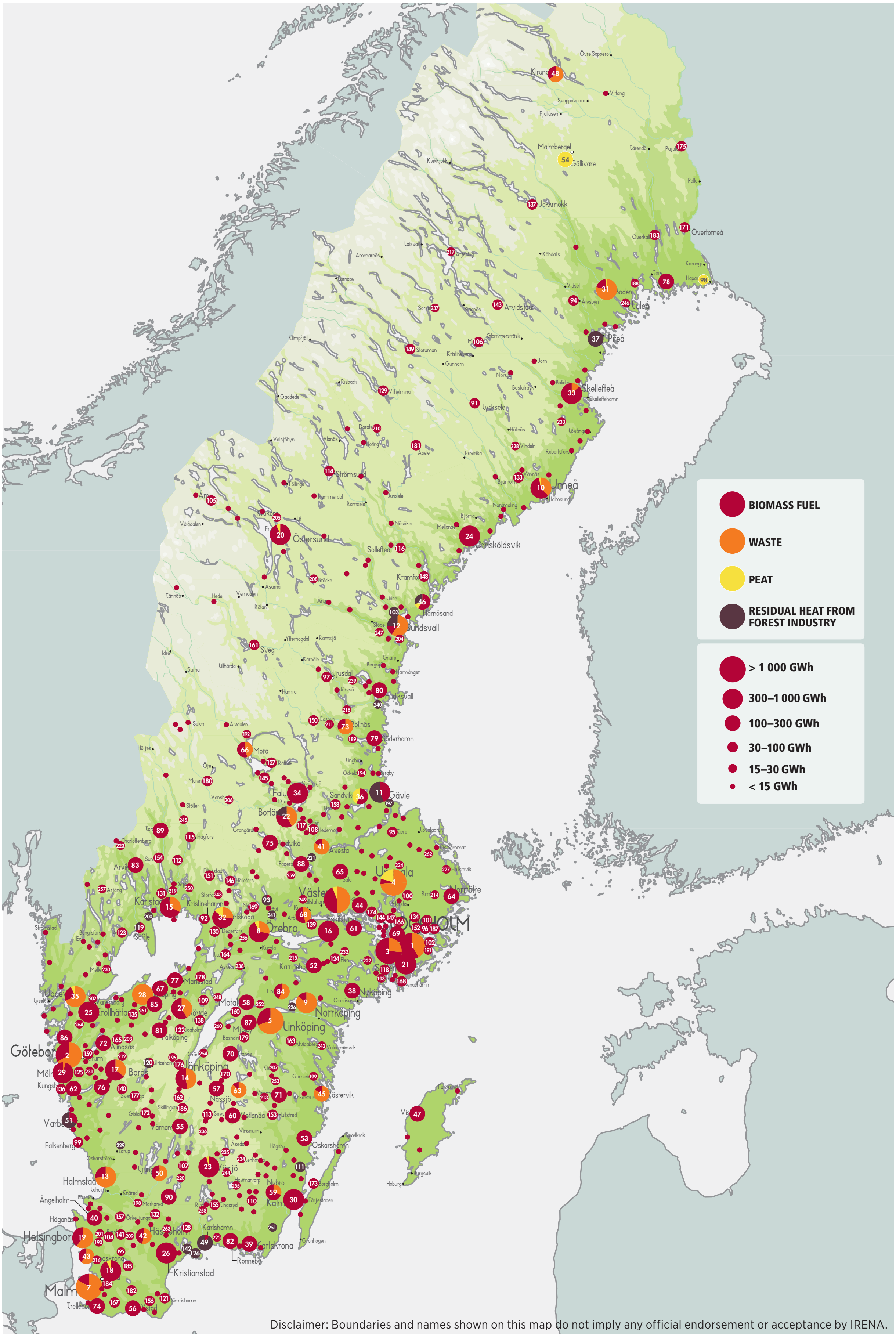
Figure 1.2 Influence of carbon tax on heating oil vs. pellet prices in Sweden (SEK/MWh)



Note: SEK = Swedish krona; MWh = Megawatt hour

Source: Svebio analysis of tax and price data from Skatteverket (Swedish Tax Agency), SPBI (Swedish Petroleum and Biofuels Institute) and Pelletsförbundet (the Swedish Pellet Council) (2018)

Figure 1.3 Swedish Bioheat Map



Source: Bioenergi and Svebio (2018)

In recent decades, almost all use of fossil fuels for district heating in Sweden has been substituted with biomass and municipal waste. By 2015, as can be seen by comparing absolute amounts shown in Figure 1.4, biomass provided roughly 60% of the fuel for district heating and municipal waste about another 15%; together they supplied three-quarters of Sweden's district heating needs. Of the industrial waste heat (8%), half came from forest industries like pulp and pellets factories.

Besides the district heating utilities, forest industries played a major part in the development of bioenergy in Sweden, which has had lengthy experience using residues. For example, the pulp industry burned black liquor to provide process heat, and sawmills used bark and other residues in their dryers. Depositing bark at landfills caused major problems with water contamination, which using bark for energy solved.

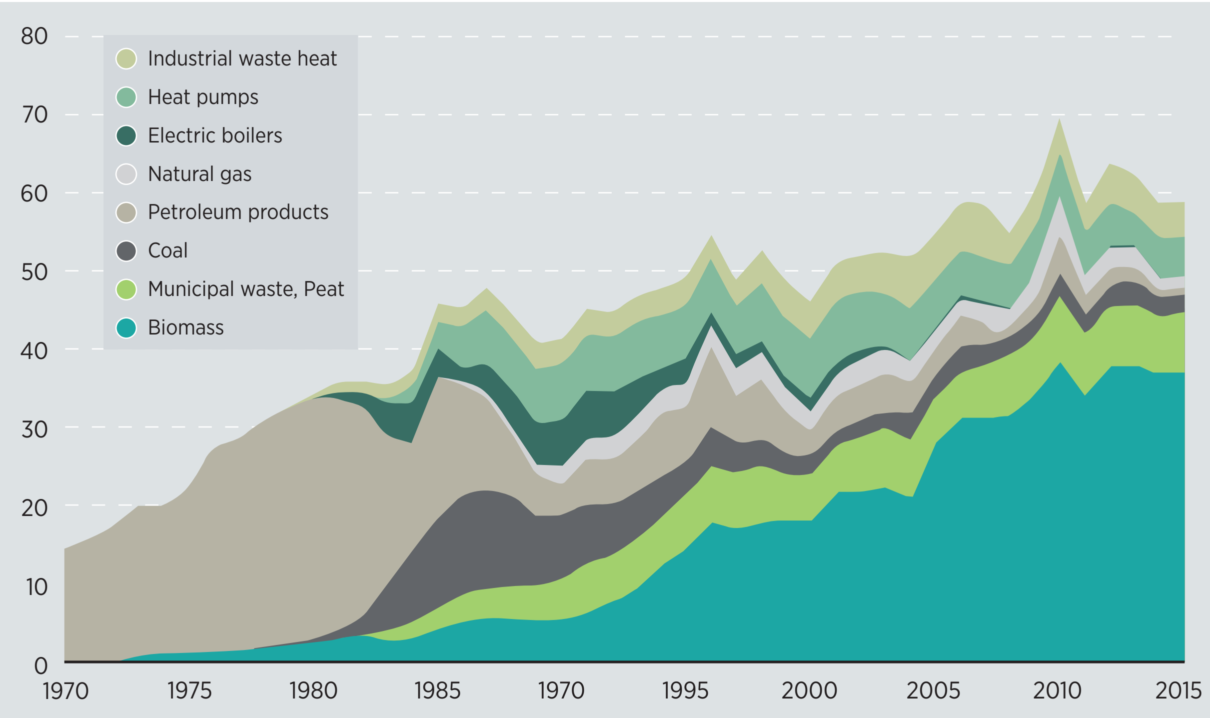
Sawmill owners saw a chance to earn additional income by selling their residues to heat plants. Similarly, forest owners realised that they could receive added income by selling forest residues for energy. In some cases, forest owners even became heat entrepreneurs, building and supplying local heat plants for district heating in rural towns and villages.

Sawmill owners and forest owner co-operatives were among the most active lobbyists for policies to promote bioenergy. An important factor in the balance of political support was also that Sweden had no "fossil fuel lobby". No domestic companies produce fossil fuels on Swedish soil. Swedish oil companies act as importers and distributors only.

Broad political support

The combination of energy security concerns, environmental pressures and experience with the efficient use of wood resources from forests made the promotion of bioenergy development a natural path for Sweden, and this development has enjoyed strong public support. At the national level, this support has been manifested through effective forest governance and long-term general incentives like the carbon tax. At the local level, support has come through a variety of municipal measures to encourage renewable energy and energy efficiency. It is often the case that national frameworks support local ambitions through investment grants and assistance in local energy planning.

Figure 1.4 Fuels for district heating in Sweden, 1970 2015 (TWh)



Source: Swedish Energy Agency (2017)

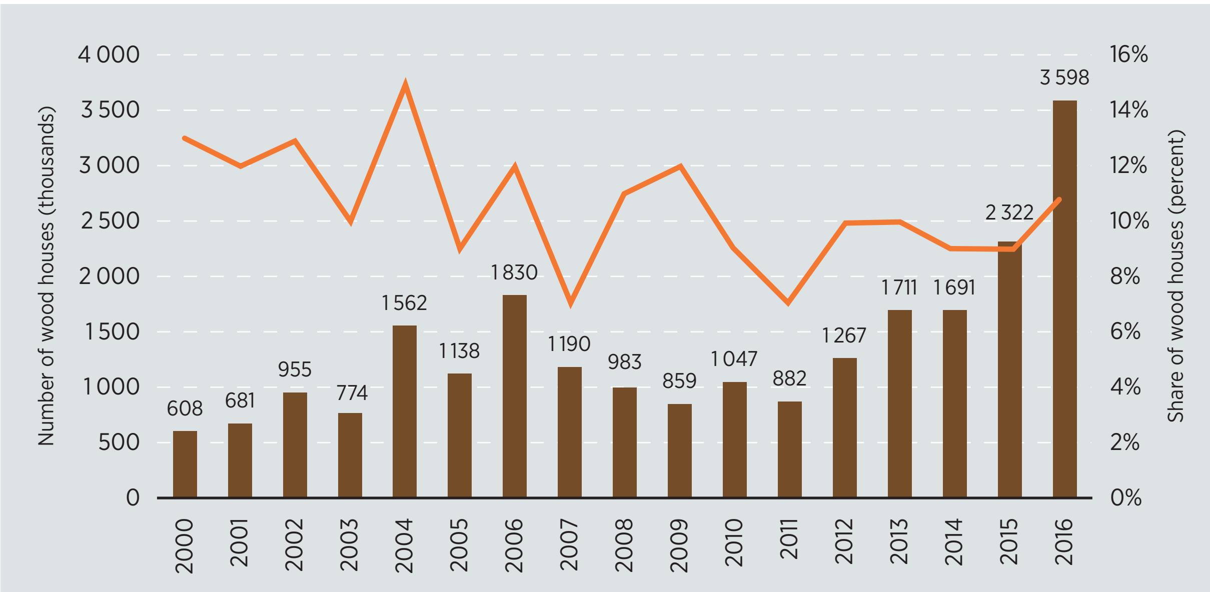
Swedish managed forestry is market based, and there are no specific incentives to promote wood production, which is pursued in a manner consistent with environmental goals. All forests, including private lands, are open to the public through the traditional law of free access. About half of the forest area is owned by 300 000 private owners, usually with relatively small holdings. The main driver for forestry is the owners' need for income.

There are also no specific policies or supports to promote the use of wood in buildings. However, single-family houses are usually wooden, and there has been growing interest in the use of wood for larger buildings. The Swedish government has also included greater use of wood for construction in its bioeconomy strategy. Changes in Swedish building codes in the 1990s made it easier to build multi-storey buildings with wooden frames, and in recent years the share of wood has increased for new apartment buildings.

The carbon tax encourages efficient and low-carbon energy for residential heating, giving bio-based heating a major market advantage over heating oil, which has become prohibitively expensive. Cement, steel and aluminium industries are not subject to the tax but are part of the EU ETS, which at present imposes a much lower carbon emissions cost. However, this value could rise over time and discourage the use of such carbon-intensive building materials in favour of wood.

As a complement to the carbon tax, the government provides incentives for action at the local level. Sweden has 290 municipalities, which play a leading role in local planning as the owners of public buildings and investors in district heating networks. Most municipalities have local utilities that own the local heat and CHP plants. The government has supported local actions primarily with money for investments in production plants and infrastructure.

Figure 1.5 Multi-storey houses in Sweden built with wood, 2000-2016



Source: Inriktning för träbyggande, Swedish government, Ministry of Industry (2018)

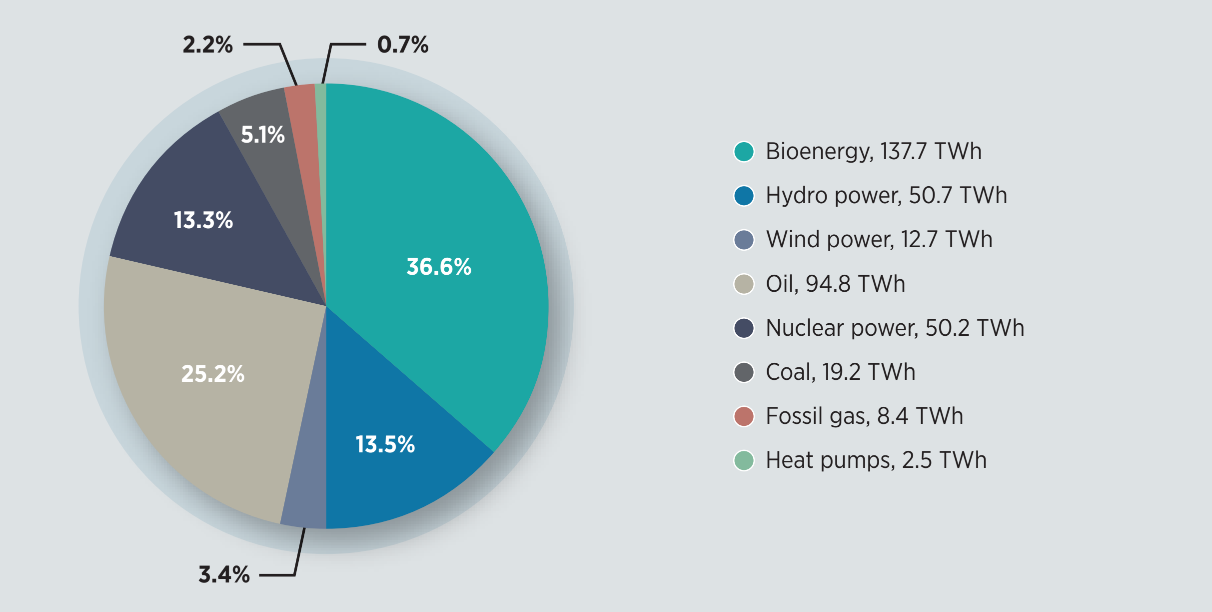
The number of apartments in multi-storey buildings built with wood (green bars) has been growing, but the percentage share of wood construction (orange line) has not.

The result – more than one-third bioenergy

The result of these policies is that Sweden uses bioenergy to meet much of its energy needs, leads the EU in deployment of renewable energy, and has reduced both greenhouse gas emissions and dependence on imported oil. Bioenergy provided 37% of final energy use in Sweden in 2016. Renewable energy of all types – including hydro power, wind power and ambient air to heat pumps – provided a total of 54%.

Sweden uses bioenergy to meet more than one-third of its energy needs

Figure 1.6 Sweden's energy use, 2016



Source: Svebio, based on data from Statistics Sweden and Swedish Energy Authority (2017)

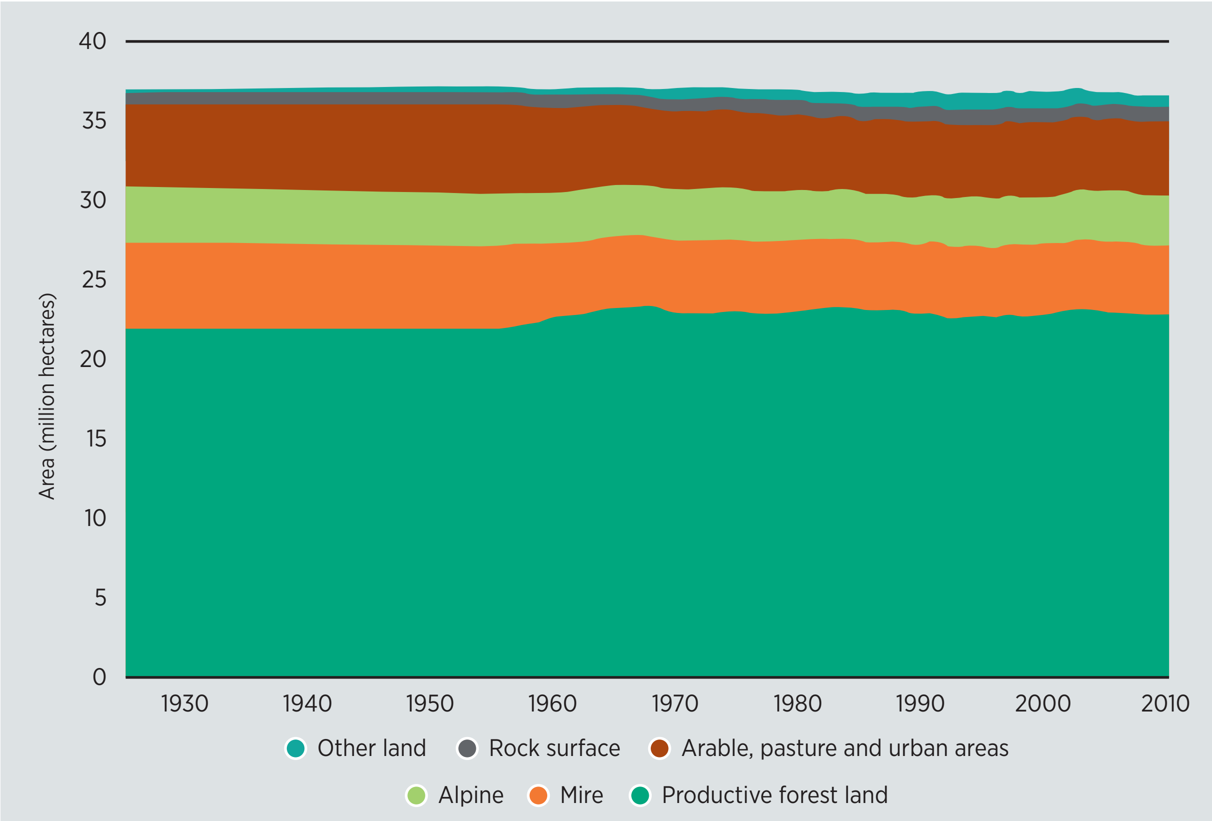
2 SWEDISH WOOD SUPPLY CHAINS AND TECHNOLOGY

Biomass for energy use in Sweden is an integral part of wood harvests from Swedish forests. Most wood used for energy is an economic residual of wood grown in managed forests for lumber, pulp and paper. The volume of such energy wood mainly depends on factors like the volume of standing stock (living wood) in forests, the annual growth in this standing stock, the share of the annual growth that is harvested, and the share of residues that can be collected from harvesting, like treetops and branches, and from lumber processing in the forest industries.

The total forest area in Sweden has been nearly constant for the last century, as shown in Figure 2.1, varying only in a narrow range around 23 million hectares (Mha) productive forests. Yet over the same period, as shown in Figure 2.2, the standing stock (volume of living wood) in Swedish forests has almost doubled (as shown by the increasing blue bars), and so have the yearly growth (red points) and fellings (green points). Note that the statistics measure cubic metres (m^3) of stemwood. This is, by tradition, the way foresters measure forest resources.

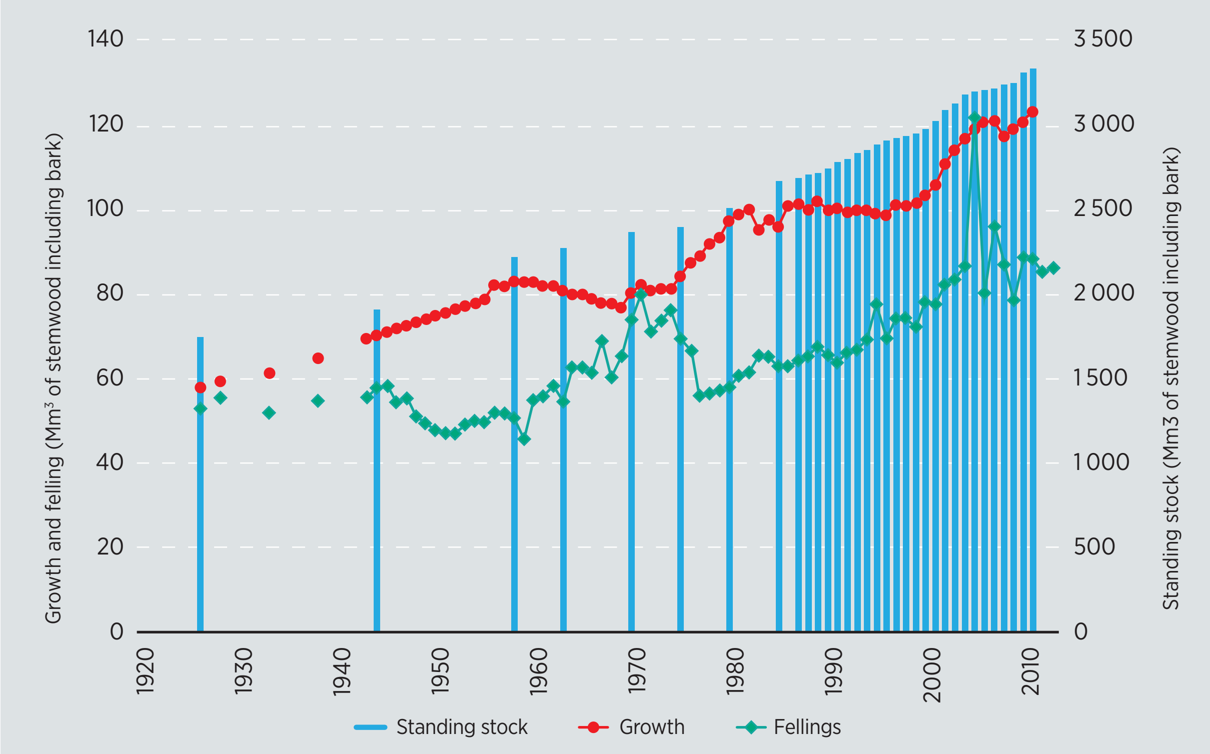
What can explain this extraordinary doubling of Swedish forest mass and output? Some less-productive farmland has been converted to forest, while urban development and road construction have taken a similar amount of forestland away from productive use. There is no reason to suppose that the new lands added to forest are on average more productive than the old lands taken away. It follows that the increase in standing stock and growth increment must be

Figure 2.1 Land area in Sweden by land use class, 1923-2012



Source: SLU analysis of Swedish Forest Inventory (2018)

Figure 2.2 Growth, harvest and standing stock in Swedish forests



Source: Swedish Forest Inventory (2018)

mainly due to other factors, such as changes in forest management and the quality of the forest stands and perhaps longer vegetation periods resulting from climate change.

According to Swedish forest law, all forests with a growth rate of more than one cubic metre per year are considered as productive managed forests, unless they are legally protected and set aside for natural conservation. This means that almost all forests in Sweden are available for forestry and subject to forest management. Areas with lower growth rates that are not available for forest production tend to be on very rocky ground or on wet and marshy peatlands.

The legally protected areas are national parks and conservation reserves. Forest owners also set aside voluntarily protected areas. In management plans and practices, parts of the forests along lakes and waterways, as well as “biodiversity hot-spots”, are also protected. Forests along the mountain range in northern Sweden have special protected status.

In general, the growth rates on managed forestlands are higher than on protected lands. One reason is that the net growth rate decreases in old stands. Another is that active management practices lead to higher growth. The forest owners have an interest in increasing the income from their forests, and they invest in better practices to promote growth, like better plant material, thinning, and more productive species. Young stands have a higher growth rate than older trees, and managed forests with a mix of all tree generations therefore have a higher mean growth rate than mature forests dominated by old trees with low net growth rates. (Forest carbon balances are detailed in Chapter 4.)

Explaining growth in forests

Forest growth or increment is measured at the stand level in cubic metres per hectare and at the national level as the sum of growth in all forests in millions of cubic metres. The net growth is the difference between growth and drain (fellings plus natural death), and net growth adds to the standing stock. Growth in turn depends on climate, management practices and age composition in the stands. Younger forests grow faster than older forests. The drain depends not only on forestry harvest but also on storms, forest fires and the natural decay of trees in the forest.

Development of Swedish forests since the mid-20th century

After a period of high demand following the Second World War, harvesting declined in the 1950s. More intensive forest management was applied, with poorly stocked old stands converted to "seedling areas," and clear-cutting became more common. At first both stock and net growth increased quickly, but then forests became unevenly distributed in terms of age, with high shares of both old and very young stands, and growth levelled out.

During the 1960s the forest industry expanded and harvesting increased. Many over-aged stands were taken down, and clear-cutting became the general practice. Around 1970, the harvest was as high as the growth, leading to public debate on the risk of over-cutting.

After the oil crisis in 1973, demand for wood fell drastically. The forest industry went through a crisis, and many factories were closed down. At the same time, many of the areas that had been harvested in the 1950s, 1960s and early 1970s now had young, fast-growing trees, and the average growth increased quickly.

From 1980 onward, the standing stock has increased steadily. The growth was faster after 2000 than during the 1990s. Fellings are again up, even higher than around 1970, but the yearly growth was also 50% higher in 2015 than in 1970. Therefore, the total harvest has remained around 70% of the total increment. Areas set aside for natural protection have expanded during the period.

The high drain in 2005 and 2007 was caused by storms. Storm Gudrun on 9 January 2005 took down 75 million cubic metres (Mm^3) of stemwood, almost equivalent to the yearly harvest level in Sweden. Storm Per on 13-14 January 2007 felled 12 Mm^3. These extraordinary storms briefly reduced the total increment of Swedish forests, but the growth soon picked up. These areas of "lost forests" were quickly replanted, and by 2015 they were once again fast-growing young stands. Almost all of the storm-felled wood was recovered and used in the wood or pulp and paper industry.

In summary, the Swedish forest inventories show that forest wood harvest and wood stock can be increased simultaneously. In fact, increased harvest is a prerequisite for the increase in growth and the long-term increase of the stock, as the fellings lead to improved and faster-growing new stands. There has been an on-going debate about the optimal level of harvesting and management practices. However, statistics show that the methods used have enabled a sustained increased in both harvest and growing stock.

Photograph 2.1 Mechanisation of Nordic forestry

Since the mid-20th century, mechanisation of Nordic forestry has boosted productivity

Photograph at left, origin unknown; right: Ponsse

No carbon debt is created in a managed forest system like Sweden's. Quite the contrary: a carbon surplus is generated each year and increasing carbon assets are created. These carbon assets, the total standing stock, have doubled at the same time as the harvest has almost doubled in volume.

Swedish forest inventory

How is so much known about growth and stock in forests? The Swedish Forest Inventory (*Riksskogstaxeringen*) has tracked the status of Swedish forests since 1923. Every year, 12 000 sample areas and 95 000 trees are measured in a combined system of random and permanent sample plots. Each plot is 10 square metres, and each permanent plot is revisited every five years. Every other visit, at ten-year intervals, the soil status is also analysed. The trees and other vegetation are measured in detail, and all facts are entered into the database, from which yearly statistics are compiled. The sample areas are evenly spread over the whole country, and they include all kinds of land use. About half of the sample areas are on productive forestland. The data are considered to be highly accurate for key indicators of sustainable forest management such as growth rate, standing stock, species composition, dead wood and soil carbon.

Current use of biomass in Sweden

The current use of biomass from Swedish forests in 2015 is shown in Figure 2.3, which indicates flows of wood, wood products and bioenergy uses in energy terms. As already noted, only around 70% of the wood growth each year is cut down. And of the wood cut, nearly half – consisting of forest residues such as branches, tops and stumps – is left to decompose in the forest (blue arrows). Only a small portion of such residues is currently used for energy (orange "slash" arrow). The lower, wider part of the tree stems (trunks) is used as saw wood and delivered to sawmills (lower dark green arrow). The upper parts of the stems, up to a diameter of 10 or 15 cm, are used as pulpwood and delivered to pulp mills (upper dark green arrow). Roughly half of the stemwood ends up as residue from lumber production. Such processing residue is then used for energy, either directly at sawmills or upon delivery to pulp mills and heat and power plants.

Figure 2.3 shows the production of wood in the forests (yearly growth) and flow of wood and wood products, as well as bioenergy, all expressed in energy terms. The numbers are from 2015, when numbers are available, and otherwise are based on average numbers obtained through different sources.

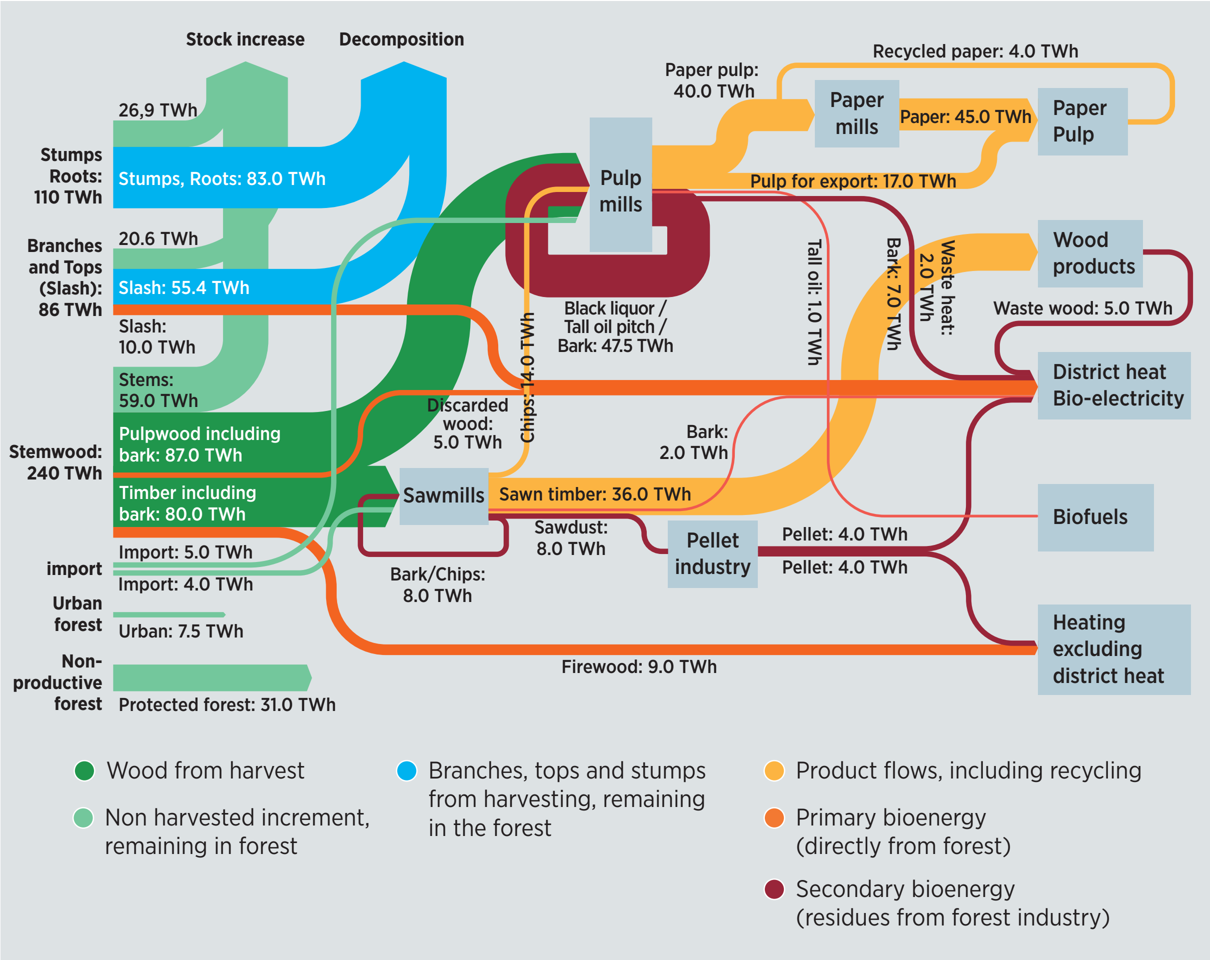
The total annual growth in productive managed forest is around 436 TWh. Of this growth, about 329 TWh or 75% is felled, while 25% is left intact, adding to forest stock.

From the fellings, 191 TWh of wood is supplied to the Swedish economy. This is mostly composed of pulpwood (87 TWh) and saw logs (80 TWh), shown by dark green arrows. Some 24 TWh of other wood is also supplied as primary forest fuels (including 10 TWh of slash from tree tops and branches, 5 TWh of discarded wood, and 9 TWh of firewood), shown by orange arrows.

The rest of the fellings, with an energy content of 138 TWh, are left in the forest after harvest. They will eventually decompose and release CO_2 into the atmosphere. This includes 83 TWh of stumps and 55 TWh of slash, shown in blue. A larger share of the fellings could be collected, improving carbon balances, as explained in later chapters.

Out of the total fellings of stemwood, with an energy value of 181 TWh, just under half (90 TWh) is used as energy. Energy use in the forest industry amounts to 56 TWh (including 48 TWh in pulp mills and 8 TWh in sawmills, shown in red loops). Energy use in the rest of the economy amounts to 34 TWh including 20 TWh for district heating, 13 TWh for other heating and 1 TWh tall oil for biodiesel fuel, shown in red and orange arrows. (Apart from stemwood, some 10 TWh of slash is also used for district heating.)

Figure 2.3 Biomass and energy flows from Swedish forest



Source: Svebio analysis of data from Statistics Sweden (SCB), Swedish Energy Agency (SEA), Swedish Forest Industries (Skogsindustrierna), Swedish Forest Inventory, SLU, Swedish Pellets Council (Pelletsförbundet) and others (2018)

The other half of the stemwood ends up as renewable material products. Long-lived products (sawn timber) account for 36 TWh, or 20% of the stemwood. Short-lived products (pulp, paper, cardboard, tissue) account for 57 TWh, or 31% of the stemwood. (Total output of energy and products slightly exceeds domestic inputs due to imports.)

The figure is simplified in several ways:

- It does not separate domestic use and export of wood, paper and pulp.
- Some of the sawn wood is used in the domestic woodworking industry, and there is a flow of dry shavings from this industry to pellet production. However, these flows are relatively small and are not shown in the figure.
- The figure does not show the particleboard industry separately. It is relatively small in Sweden compared to the pellet industry.
- “Residential and other heat” includes small-scale heating with firewood and pellets, as well as use in industries apart from the forest and wood industry, greenhouses, farms and hotels. Besides pellets and firewood, this includes woodchips and other unrefined wood fuels from different sources.
- In addition to the growth on productive forestland, there is growth on protected land (national parks and nature reserves) and in urban areas.

Primary biomass fuels directly from the forest

Primary forest biomass used for energy purposes is of three main types:

- **Slash:** This includes residues harvested from final felling (mainly tops and branches, but also small trees and bushes) and from thinning (mainly small trees and bushes, but also tops and branches, when some of the trees can be used as pulpwood).
- **Stumps:** These are uprooted from the final felling.
- **Discarded wood:** This includes discarded trunks unsuitable for industry, like rotten or sprinted stems, or species that industries do not buy.

Actual use of the different types varies greatly by time and place, depending on demand, price level and distance to heat plants. Some of this biomass needs to stay in the forest for environmental reasons, as explained in the following chapter on sustainability.

The supply chains and methods have been developed over the years, based not only on

Photograph 2.2 Slash collection at roadside

Photograph: Svebio

Photograph 2.3 Mobile biomass chipper

Photograph: Svebio

practical improvements made by entrepreneurs, forest companies, transport companies and utilities, but also on extensive research and development programmes funded by governments. The business, research and policy focus has been on cutting costs, improving fuel quality and reducing environmental impacts.

The slash is collected and forwarded in a separate operation after logs and pulpwood have been recovered from the harvesting site. The slash is then stacked at the roadside close to the site, covered with paper to keep out rain, and dried for at least one summer season. The water content is reduced from roughly 50% in fresh slash to around 30% in the sun-dried material. Stumps, if collected, are up-rooted with a digger and similarly forwarded to a roadside and piled to dry for at least one summer.

When the biomass is needed as fuel, a mobile chipper will chip the dried slash at the roadside, to be transported to the heat plant. The chipper can either be separate from the transport truck or be mounted onto the truck. Stumps have to be crushed, as they may contain stones that damage the chipper. It is important to minimise the content of non-combustible material like soil and stones, as this otherwise increases ash volumes and reduces the technical lifetime of equipment because of wear and tear.

The chipped or crushed biomass is transported in standard-sized containers on trucks – usually three containers in one transport. When delivered to the heat plant, the truckload is weighed, and samples are taken to determine the moisture content in the delivered biomass. The fuel supplier is then paid per megawatt hour of energy content of the fuel, not by weight or volume, as the heat value varies greatly with the moisture content.

Most forest fuels are delivered to heat plants within a radius of 70-100 km. Local supply chains are thus still predominant. However, more and more biomass fuel is transported long-distance by ship and train. The fuel is reloaded at terminals spread out around the country along rail lines and in ports. It makes sense to use railroad and shipping networks as much as possible because they use much less energy and cost much less per tonne-kilometre (t-km). According to an analysis by IEA Bioenergy, the amount of energy used to transport 1 t-km of wood by truck could serve to transport 7 t-km by rail or 75 t-km by ship (Thrän *et al.*, 2017). The large new Fortum/Värtan biomass CHP plant in Stockholm, for example, sources fuel by ship or rail from throughout the Baltic region.

Photograph 2.4 Chipping of discarded wood

Photograph: Svebio

Photograph 2.5 Bark residue for energy at pulp and saw mills

Photograph: Svebio

Secondary biomass from forest industries

Around half of the stemwood volume (saw wood and pulp wood) harvested from forests becomes biomass for energy use during the industrial process. When a log is sawn into planks, about half of the wood will become planks, while the rest remains as processing residue. One obvious reason for this is that a tree trunk is round, whereas planks are square. Another is that sawing produces large volumes of sawdust. A third reason is the bark surrounding the stem, which has to be removed. Finally, some wood is discarded for reasons related to quality. The sawdust is mainly used for pellet production. The other residues are used internally for wood dryers or sold as fuel to heat plants.

In the *chemical* pulp industry, only the cellulosic fibres remain in the pulp, and these fibres make up around 50% of the wood. The rest of the wood becomes residues, where hemi-cellulose and lignin are the major components. About 2-3% is fatty substances, which can be extracted as crude tall oil and used for chemical products, biodiesel and heating fuel. The rest of the residues end up in the black liquor, which provides an energy source for the process. In the *mechanical* pulp industry, most of the wood remains in the pulp, and the plants use electricity as their energy source. From these plants there is much less secondary residue.

Cascading in practical use

"The forest product system" is an intricate maze, from harvest in the forest through refining, recycling, final use of products and energy use all along the supply chains. The term "cascading" is often used to define a hierarchy where material use is prioritised ahead of energy use. The most valuable primary wood product is lumber, which can be used in the construction of buildings and in durable products like furniture. A less valuable but also important primary wood use is for pulp and paper. Reuse and recycling are higher in the hierarchy than using the biomass for energy. As shown above, biomass for energy can be recovered at all steps of the supply chain:

- primary biomass fuels, mainly from harvesting and thinning residues and discarded and low-value wood, with a very limited amount from stemwood used in fireplaces
- secondary biomass fuels from sawmills, pulp mills and the wood-working industry, like bark, sawdust, chips, black liquor and tall oil
- tertiary post-consumer biomass, like paper in municipal household waste, recovered wood and sewage sludge.

The choice between material or energy use is today made by market actors, depending on price and availability. Two examples of this are:

- Stemwood of low value can be used either in the pulp industry or by heat plants. In a situation with very high demand for pulp, the pulp mills may decide to buy more low-value wood. During a very cold winter, heat plants may be eager to find extra fuel and so be willing to pay even for relatively good wood. In general, rotten, splinted, fire-damaged, and crooked wood, and wood of certain species, are discarded by the industry. Even over-sized logs can be difficult to handle.
- Sawdust and other residues can be used both for panelboard and pellet production. The Swedish model has been to impose a carbon tax on fossil fuels, avoid direct subsidies and let the market actors decide on the use of the feedstock. Highly efficient panelboard factories are able and willing to pay market prices for their raw material.

The result of this model is "cascading in practice". The wood is used first for high-value products like sawn wood and medium-value products like pulp for paper and cardboard. The lower-value by-products, residues and waste from lumber and pulp industries are the portion of wood that is primarily used for energy. There is no governmental regulation of this allocation, which is decided and enforced by the market.

Photograph 2.6 Discarded wood as a major energy source

Photograph: Svebio

The alternative would be an administrative system to guarantee the principle of cascading. Sweden had such a regulation for a short period in the late 1980s, under which heat plants had to get a governmental permit to use woodchips or sawdust (the Wood Fibre Law). This regulation was not considered efficient and was abandoned around 1990.

For a forest owner delivering wood, lumber for sawn wood is the major source of income. As a rule of thumb, the forest owner gets 70% of the income from sawn wood, 28% from pulpwood and just 2% from energy wood (slash and discarded wood). Lumber is thus the main driver for the market and harvesting levels. As shown in Figure 2.4, market prices in Sweden for lumber at the forest roadside are typically over five times the market prices for energy wood, while pulp prices are three times those for energy wood. (For heat plants, prices are closer since transport and handling costs are higher for residues than for stemwood, but this does not affect market incentives to foresters.)

Figure 2.4 Relative market prices of lumber, pulp and energy wood from spruce

Note: Prices paid to a forest owner at roadside in middle Sweden (SEK/MWh)

Source: Svebio (2018

Bioenergy use in Sweden's forest industry

The forest industry, including pulp mills, sawmills and woodworks, is a major user of forest fuels. Almost all of these fuels are by-products and residues from within the industry. The pulp mills are particularly large energy users. But to an increasing degree these factories are self-sufficient with regard to fuels. This is certainly true for the chemical mills, whereas factories producing mechanical pulp need large inputs of electricity. Figure 2.5 shows changes in fuel use since 2000.

In absolute terms, the use of fossil fuels (oil, propane and natural gas) in Swedish forest industries declined nearly fourfold from 7.6 TWh in 2005 to 2.1 TWh in 2015, with reduced use of oil in mesa ovens and other fossil fuels in pulp mills. Bioenergy use, meanwhile, remained stable at around 50 TWh per annum, of which more than 40 TWh came from black liquor used in recovery boilers at chemical pulp mills. In sawmills and woodworking, fuel use was almost entirely from biomass during the whole period.

Bio-combinate plant at Södra Cell Värö

Recent developments at Södra Cell Värö illustrate both cascading in practice and reduced fossil fuel use in the modern forest industry. Värö is one of Sweden's largest forest industry sites, part of a co-operative called Södra owned by 51 000 forest owners in southern Sweden. Värö's pulp mill, on the west coast south of Gothenburg, produces 700 000 tonnes of paper pulp per annum, mainly for export. Värö also has a sawmill (Sweden's largest) and a pellet factory. The site can be seen as a bio-combinate producing a number of products from wood supplied by the owners: paper pulp, sawn wood, wood pellets, dried bark and other biomass fuels, tall oil for biodiesel production, green electricity, and district heating. Since it opened in the 1970s, the plant has completely transformed its energy use (Södra, 2017).

- *Oil surplus:* In the 1970s, the plant used 200 litres of fossil oil to produce 1 tonne of pulp. That number has now been reduced to 7 litres, and at the same time the plant

Figure 2.5 Fuel use in Swedish forest industries

Source: Svebio (2018), based on numbers from Statistics Sweden produces 20 litres of tall oil for every tonne of pulp produced.

- *Power surplus:* In the 1970s, the plant needed 7 gigawatt hours (GWh) of electricity per month from the grid. Now, in contrast, the plant can sell 25 GWh per month of green surplus electricity back to the grid.
- *Heat surplus:* The plant supplies nearby towns with heat for district heating.

Other energy products from the plant are dried bark, sold to heat plants, wood pellets from the sawmill and tall oil used for biodiesel production. The total energy exported from the site is typically around 1.6 TWh per year. In the future, methanol may also be recovered from the process, as well as lignin from the black liquor.

Tertiary biomass – post-consumer biomass

If recycling, waste handling and energy recovery are handled in an optimal way, very little harvested forest carbon is released to the atmosphere as CO_2 without first being used in products or for energy. After use and possible recycling, wood becomes recovered waste wood that can be used for energy. It is sorted and then chipped or crushed. If the wood is contaminated by paints, wallpaper or other materials, as when it comes from old furniture or the demolition of buildings, it has to be handled as waste and burned in plants with special permits to ensure sufficient scrubbing of the flue gases. However, clean scrap wood from construction sites can be chipped and used just like regular wood. With a well-developed waste handling system, all waste and demolition wood will be available for energy recovery. In Sweden, taking combustible biogenic waste to landfills has been prohibited since 2005.

Photograph 2.7 Piles of bark and sawdust at Värö

Photograph: Svebio

Paper products end up in municipal household waste and other waste streams, and can be used in CHP plants to generate heat and electricity. But new paper and cardboard are first recycled an average of seven times before their fibres become unusable. Tissue and toilet paper can enter streams of sewage sludge that is used to produce biogas.

Very little harvested forest carbon is released to the atmosphere as CO_2 without first being used in products or for energy

Landscaping wood and other marginal wood streams

Recent research has shown energy potential of 5 to 10 TWh per year in Sweden from landscaping wood, bushes and trees on marginal lands and conservation areas such as:

- parks, gardens and other green areas in cities and towns (urban areas make up 3% of Sweden's total land area; almost as much as farmland)
- along roads, railroads and agricultural fields
- abandoned farmland and under power lines (most power lines go through forests)
- natural landscapes like banks of lakes and streams and portions of open pasture.

Photograph 2.8 Landscaping wood: Energy wood harvest alongside fields

Photograph: Svebio

3 SUSTAINABILITY IN MANAGED PRODUCTIVE FORESTS

While developing technology and markets for forest biomass, Sweden has conducted in-depth research of related sustainability issues. It started with the Vattenfall project, which was carried out by the Swedish University of Agricultural Sciences (SLU) from 1990 through 1998. It continues today through an extensive research programme funded and led by the Swedish Energy Agency (SEA). Important sustainability issues studied include:

- soil and water quality and impact
- nutrient balance and ash recycling
- biodiversity issues and natural conservation
- carbon balance and life-cycle assessment.

The research has mainly focused on slash harvesting at the final felling stage and energy wood recovery at the thinning stage, but recently it has also focused on the effects of stump harvesting. The research results have been published in scientific papers and reports and synthesis reports from the SEA. It has been a basis for recommendations and regulations by the Swedish Forestry Board to foresters and forest entrepreneurs.

Environmental objectives in Sweden

Environmental policy is based on a set of targets adopted by the parliament. There are 16 overall objectives, each with specific sub-targets. On a global level, these objectives are related to the Sustainable Development Goals (SDGs) formulated by United Nations. The Swedish objectives were adopted in 1997 and later amended (Swedish Environmental Protection Agency, 2008).

The most relevant objectives for bioenergy from forests are:

1. *Reduced climate impact.* Sweden must contribute to the global targets adopted by the United Nations Framework Convention on Climate Change and formulated in the Paris Agreement in such a way that biodiversity is preserved, food production is assured and other SDGs are not jeopardised.
2. *Natural acidification only.* The acidifying effects of deposition and land use must not exceed the limits that can be tolerated by land and water. Sweden has been greatly affected by acid rain mainly due to emissions in other parts of Europe.
3. *Zero eutrophication.* Nutrient levels in soil and water must not adversely affect human health, the conditions for biodiversity or the possibility of varied use of land and water. This objective aims in part to protect the Baltic Sea.
4. *Sustainable forests*. The value of forests for biological production must be protected, and biodiversity, cultural heritage and recreational assets must be safeguarded.
5. *A non-toxic environment*. The occurrence of synthetic or extracted substances in the environment must not represent a threat to human health or biodiversity.

The fulfilment of these objectives is regularly evaluated, and measures are taken to ensure that they can be reached. Research concerning biomass for energy is also based on these targets. The idea is that these objectives can be fulfilled in managed forestry throughout the country. At the same time, forest areas are set aside as national parks and other protected areas for conservation.

The latest Swedish forestry legislation, adopted in 1993, is based on two parallel goals: a production objective and an environmental objective. The production objective is that the forests and forestland shall be utilised efficiently and responsibly to provide a sustainably positive yield, which is thus a long-term goal for productive use of the forest. The environmental objective is to secure biodiversity and genetic variation while providing the necessary conditions for plant and animal species that naturally belong in the forests to survive under natural conditions and in viable populations (Swedish Forest Law, 1993).

Forest productivity, nutrients and ash recycling

There has been concern that the removal of forest residues could reduce the rate of growth in the following tree generation, as the slash (branches, twigs, needles and leaves) contains more nutrients than stemwood. Over 80% of Swedish boreal forest consists of just two natural coniferous species, Norway spruce and Scots pine. Research has found that complete removal of forest residues affects yields for spruce stands but not for pine stands. Partial removal presumably has less impact on yields, particularly if it is confined to branches and twigs that are not readily incorporated in the soil. The negative growth effect, when it occurs, appears to be temporary and not a permanent decrease in site and stand productivity. Indeed, it may be largely compensated by the increased plant survival rates and quicker establishment of new stands that removal of felling residues promotes.

The main reason for growth reduction is that leaves and needles contain more nitrogen than stemwood, and nitrogen is an important nutrient in boreal forests. In general, southern Sweden has a nitrogen surplus, due to deposition of atmospheric nitrogen (acid rains), whereas northern Sweden has a deficit. It follows that an important strategy for countering growth reduction can be the use of fertiliser. However, fertiliser use in Sweden is limited to roughly 30 000 ha in any given year out of 23 Mha of managed forest – less than one-seventh of 1% of the forest area.

An obvious strategy to compensate for the loss of nutrients is to recycle wood ashes from biomass-fuelled heat plants or CHP plants. The ashes contain

Photograph 3.1 Ash recycling

Around 50,000 tonnes of clean wood ash is spread each year in Sweden, primarily in the southern provinces where the soil is affected by acidification.

Photograph: Svebio

Photograph 3.2 Slash from thinning

Slash from thinning is only harvested to a limited degree in Sweden today, mainly due to higher cost per unit of wood harvested than slash from final felling.

Photograph: Svebio

all major nutrients in the wood except nitrogen, which is lost in combustion, and the ash has low acidity. The nitrogen can often be supplied by combining ash recycling with compensatory fertiliser.

The benefits from ash recycling vary greatly between different soils and stands. Ash recycling is highly recommended when the soil is prone to acidification, such as in parts of southern Sweden affected by acid rains. On peat soil, the growth effect can be very positive due to the addition of phosphorus and potassium. In other cases, however, ash recycling has very limited or no positive effect or can even be detrimental to growth as on certain meagre soils in northern Sweden. It is therefore important to select areas that respond positively to ash recycling.

Ash recycling is promoted by the Swedish Forest Agency, and the ambition is that in future all clean ashes should be brought back to forests. They do not need to be recycled to all areas where harvest of forest residues has taken place. There are clear criteria for recyclable ashes, to ensure against spreading pollutants like heavy metals. The technology for ash recycling has been developed by researchers and entrepreneurs, to have the best effect at the lowest cost. There is no legal requirement to recycle the ashes, but about a third of ash from biomass combustion is recycled today, and the volumes increase year by year. The development is held back by the availability of clean ash, by the cost, and by uncertainty from forest owners concerning the benefits.

Removal of slash from thinning may have a similar effect as removal of slash from final fellings, with some growth reduction within 15-20 years after thinning, according to research carried out in Finland (Helmisaari, *et al.*, 2011). Due to incentives, there is more energy use of slash from thinning operations in Finland than in Sweden. Compensation fertilisation may be needed in this case. It could be combined with ash recycling.

Another strategy to avoid nutrient loss is to leave the slash on the ground over a year to allow needles to fall off. However, in this case, machinery has to come back to the site, and the planting of new trees may be delayed.

When harvesting stumps, there is no risk of productivity loss. The reason is that stumps contain fewer nutrients than branches and twigs. The harvest also leads to scarification of the ground, which promotes growth and makes planting new trees easier.

Water quality and soil impact

In general, forest fuel extraction is not seen as a problem for leakage of nutrients and eutrophication of streams and lakes. In theory, the opposite should be the case, as removal of nutrient-rich material from the forest reduces the nitrogen load. Experimental studies show that slash extraction and ash recycling have only a very limited effect on nitrogen leakage if they are carried out according to the recommendations from the Swedish Forest Agency.

The harvesting of forest residues leads to more machinery moving on the harvesting sites, which disturbs the soil and increases the risks of soil damage, especially when the ground is wet. Soil disturbance can cause increased leakage of nutrients and the transit of mercury to water streams. Much of this mercury originates from coal-fired power plants in other European countries that is transported to the forests by wind and deposited by rain. The risk is typically mitigated by avoiding deep tracks from heavy machinery. Deep tracks can be avoided by bedding the driveways with slash, which reduces the net harvest of slash, and by using low-pressure tires.

For a discussion of bioenergy impacts on soil carbon, see Chapter 4.

Photograph 3.3 Tracks from heavy machinery in forest operations

Using heavy machinery in wet areas can cause major soil damage. Often, slash is used to bed the tracks to avoid this kind of damage.

Photograph: Svebio

Photograph 3.4 Coarse wood left at forest harvest site to promote biodiversity

Leaving a certain amount of coarse dead wood at harvesting sites is essential for many species, like beetles and birds.

Photograph: Svebio

Biodiversity

Issues related to biodiversity usually concern forestry practices in general, like clear-cutting or thinning, rather than relating specifically to the extraction of biomass for energy. A set of rules and recommendations has been developed by the Swedish Forest Agency to safeguard against biodiversity losses in forestry. They are similar to recommendations put forward in Forest Europe. These are the most important:

- Leave a certain amount of coarse dead wood at the harvesting site. This can consist of both dead trees and "high stumps", old trees that are cut off at a few metres and left to dry and rot. Coarse dead wood is valuable to a wide range of species, especially beetles and other insects.
- Leave trees as protective shields along lakes and streams.
- Avoid wet and swampy areas.
- Leave old broad-leaf trees and trees of less common or rare species like oak, beech, rowanberry, alder and others. Some of these species are very valuable to birds and red-listed (endangered) wood-living species. Aspen trees are also valuable, even if they are common. Bushes carrying berries are also important to save.
- Locate biodiversity "hot-spots" and avoid harvest on these sites.

Tops and branches from spruce and pine are of lesser value for biodiversity. They do not have the same value as coarse wood, and they do not offer any more protection than the surrounding forest. Very few species depend on the slash as habitat. In any case, some of the slash, usually 20% to 25%, is left at the site. However, when the slash is stored at roadsides in big piles, waiting to be chipped and transported to the heat plant, there is a risk that these piles can become "traps" for certain species, such as, red-listed beetles that lay eggs in the piles. The general conclusion is that harvesting of residues from fellings has caused very limited biodiversity risks, but that a certain share should be left on the sites.

The harvesting of stumps for energy is a more contentious issue. To further deepen the knowledge about the environmental effects of stump extraction, the SLU, with support from the SEA, conducted an extensive research project on this issue from 2007 to 2015.

Stumps make up a large share of the dead wood in the forest and on harvesting sites, and they are important habitats for many species. Beetles and mice live in and around decaying stumps, and they are fodder for birds and mammals. The stumps also continue to store carbon over several decades as they gradually decompose. All of this is true, but at the same time billions of stumps are "produced" every year in Swedish forestry. They are valuable if used as fuel, and they could potentially substitute for large volumes of fossil fuels.

Research does not support the argument that all stumps need to be left in the forest, although almost no stumps are harvested in Sweden at present. The most conservative studies indicate that environmental effects would be very limited with stump harvest of up to 20%, above which certain red-listed species, including some types of beetles, could be affected. Other studies indicate that the share of stumps harvested could be higher without significant risk to biodiversity (Persson, 2017; Swedish Energy Agency, 2018b).

There are many reasons why the total stump volume cannot be harvested. When the ground is full of stones and rocks, stump harvest is difficult and un-economic, and the fuel will be contaminated with stones. On small clear cut areas, stump harvest is not economically viable either. On the remaining areas, a certain share of stumps must be left on the sites to ensure a minimum volume of coarse dead wood. There is no clear threshold determining what percentage biodiversity impact is not acceptable. When researchers or governmental authorities state that 20% could be harvested in a sustainable fashion, it is a rough but conservative and scientifically founded estimate (de Jong *et al.*, 2017).

Photograph 3.5 Stump left in the forest after felling

Stumps contain large volumes of biomass and are therefore attractive as a source of energy. At the same time, they have value for biodiversity.

Photograph: Svebio

Effects on birds

In response to concerns raised by non-governmental organisations (BirdLife Europe and Central Asia and Transport & Environment, 2016), the SEA funded a special study on birds and bioenergy. It found that risks to birds in forests mainly relate to modern forestry practices in general, rather than to specific practices associated with bioenergy use (Swedish Energy Agency, 2018c).

Recent bird inventories show that the numbers of forest birds and species have increased since 1990, with the current forestry policy in place. Meanwhile, the numbers of birds and species in the agricultural landscape have declined (Green, 2017). A reasonable inference is that forest birds respond positively to the environmental considerations taken in forestry, whereas changes in farming – fewer grazing animals, larger fields and less diversified farming – have had negative effects on many bird species.

Factors that could have a negative impact on bird populations include loss of old trees and dead wood. Woodpeckers are among the species most affected by loss of dead wood. Therefore, the forestry guidelines include requirements to save coarse dead wood and make high stumps at felling. Also, certain bird species prefer dense young stands that give good protection. Thinning can be negative to these birds.

Administrative practice for environmental compliance

Swedish forest law is primarily based on voluntary action by forest owners and advice from the governmental Forest Service. Most forest owners have forestry plans for their properties that define how their forest is to be used and map the different stands of trees according to their current status, including species composition, age classes, need for thinning and other management measures. From year to year, owners have to decide on different measures in the forest, like pre-commercial and commercial thinning and final cuts of mature stands. They also identify areas of conservation value and set aside voluntarily protected areas. The ambitions may vary, depending on the size of the property and the owner's own engagement.

One-quarter of Swedish forestland is owned by forest companies. Another quarter is owned by the state, municipalities or the Swedish church. The rest, about half of the forestland, is owned by 300 000 private individuals. Many of these are farmers living near the forest. Others are individuals or families in towns and cities who have inherited land from their parents or grandparents. Many of the private forest owners belong to forest owner co-operatives, which take care of forest operations and aid their members in forest management. These co-operatives also own sawmills, and even several large pulp mills, but most of the industries are owned by large forestry companies.

At least six weeks before cutting trees on their property, forest owners have to file a report with the Forest Service, noting whether residues will be harvested for energy. This requirement applies if the planned felling is at least 0.5 ha in size. The local forest inspector at the Forest Service determines if the planned felling is lawful and if there are objects of natural value on the site. The inspector can issue instructions and advice, but if the forest owner does not receive a negative response within six weeks, the felling can go ahead as planned. There is no other formal permit. There are, however, general requirements that always have to be fulfilled. These concern all the issues listed above, like leaving coarse dead wood and certain trees and species of value.

For a final felling, there is also a general requirement in the forestry law that measures to restock the site be completed within three years of harvest, though it may take a few years longer for new forest to be established. This can be done by planting, seeding or natural regeneration. Planting is the general practice with spruce, which offers an opportunity to plant extra good new trees. Natural regeneration is often done with pine. A number of good straight trees are left at the site to spread seeds. These trees can later be harvested. The requirement to regenerate after harvest was written into the law in 1905, as a response to the practice at the time by some forest companies to cut forests without ensuring regrowth.

Photograph 3.6 Regeneration according to the law since 1905

After wood is harvested, the forest law requires the forest to be restocked through planting, seeding or natural regeneration.

Photograph: Svebio

The Forest Service can make an inspection after a few years to ensure that the forest law has been followed, that environmental considerations have been taken and that new forest has been established. It is highly unusual for a forest owner to be fined for not following the law. The Forest Service instead primarily works with advice and education to improve foresters' practice.

Summary of Swedish forest sustainability practice

In conclusion:

- Substantial amounts of harvesting residues from final fellings and thinning operations can be recovered without compromising environmental objectives.
- A certain amount of coarse dead wood needs to be left at the sites, as well as certain tree species and trees along water (lakes and streams).
- To protect the soil, slash should not be taken from dry, steep or very wet sites.
- To compensate for soil nutrient loss, ash recycling is recommended.
- Slash – tops, branches, bushes and small trees – can be collected, but a certain amount needs to be left at the site, typically around 20% to 25%. To avoid soil damage, slash can be used to reinforce tracks for machinery.
- At a national level, a harvesting rate of 50% of all slash is probably a practical maximum, when considering both economic and ecological restrictions.
- Stumps can be harvested on at least 20% of the final felling area with limited negative effects on biodiversity.
- In future, it may be possible to increase slash and stump harvest rates by developing better harvesting techniques and compensatory strategies.

4 CARBON BALANCE IN A MANAGED FOREST SYSTEM

In a managed forest system with balance between growth and harvest, there is in principle no net loss of carbon. In fact, as shown in Chapter 2, it is possible to increase the standing stock of biomass, and carbon, in the forests, and at the same time increase harvests. Carbon debt is not created; instead, carbon assets are built up that can be used for renewable materials and energy.

The forest practice in Nordic boreal forestry is today based on creating even-aged stands of pine or spruce that are harvested with clear-cutting when they have reached a certain age. The time period from regrowth (planting or natural seeding) to final harvest is called a rotation. A typical rotation in southern Sweden is 70 to 90 years and in northern Sweden, 120 to 150 years. During this period, the stand is also thinned two or three times to allow better room for the best stems to develop and grow high-quality timber.

A typical managed forest rotation is illustrated in Figure 4.1. After clear-cutting and harvest of saw timber, pulp wood and energy wood (slash), the area is regenerated with new trees. This can be done either by planting or by leaving some good-quality trees for natural seeding. Spruce stands are usually replanted. For pine, natural seeding is also a common method. Much natural vegetation, birches and other broad-leaf species also start growing at the site, resulting in a mixed young stand.

After a few years, the forester makes a first thinning, clearing away some of the birches and new small trees with a hand-held brush-saw. The number of growing stems is reduced the first time, but none of this biomass is harvested as it has little economic value. A second thinning is done after another couple of decades, this time with machinery. At this time, the stems are big enough to produce pulpwood, and energy wood may also be

Figure 4.1 Carbon-neutral cycle of wood growth and harvest

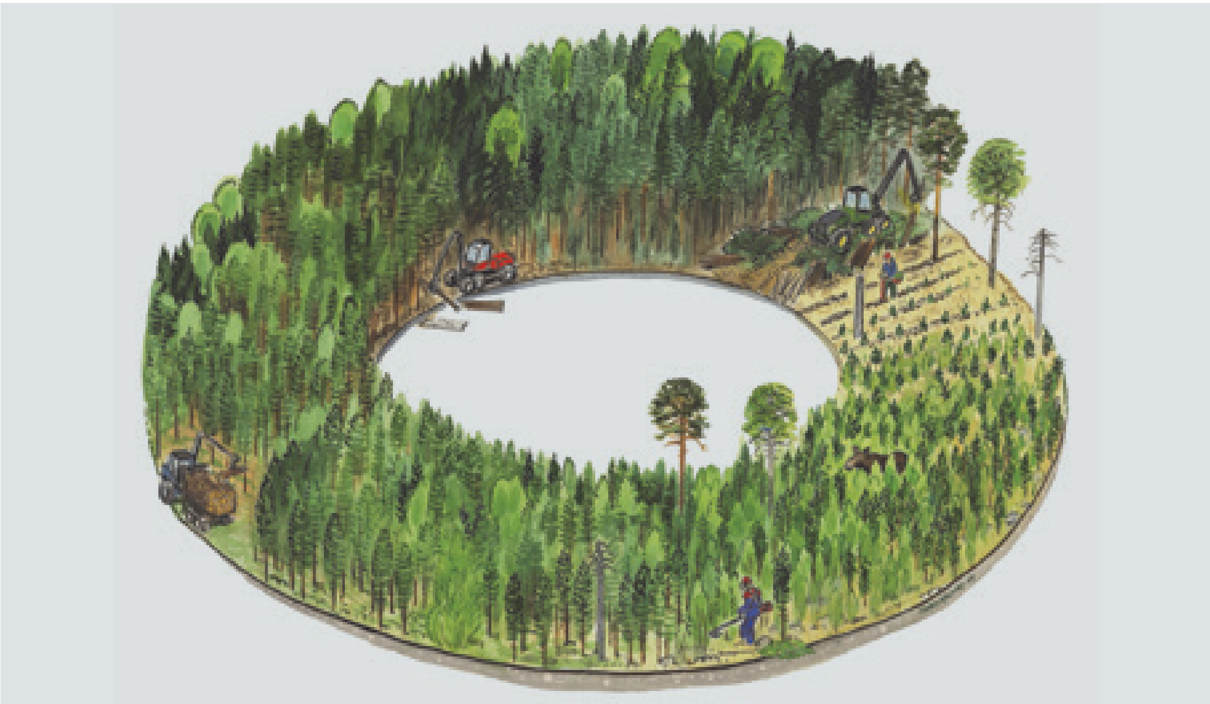


Illustration: Sveaskog

recovered. A third thinning will produce both saw timber and pulpwood. A certain number of stems per hectare will be left in the stand to mature to the preferred age of final cut. After the final harvest, the cycle can start over again.

The illustration can be seen as the development of a single stand, or a picture of the whole forest landscape, composed of a series of stands. If the illustration is conceived of as a circle with as many segments as the rotation period in years, it would be possible to harvest one segment every year. Assuming that the rotation is 100 years and that 1/100 of the circle is harvested every year, and that all trees in the circle grow every year, this yearly growth adds up to the same volume as the harvested 1/100 portion. If each segment is 1 ha in area and stemwood grows 5 m^3/ha/year, both growth and harvest of stemwood each year will be 500 m^3.

In reality, the growth is somewhat greater than the harvest since the forester is constantly trying to improve the growth rate in each new rotation, and the 99 growing segments will grow better than the previous generation did. This requires surmounting challenges like pests and drought. These are represented in the illustration by a moose eating pine shoots and damaging young trees, reducing their growth and quality.

The carbon balance is the same in a system with selective cutting instead of final felling. Selective cutting means that trees are harvested as they reach maturity in mixed-age stands; there is no clear-cutting. There are trees of all ages in all parts of the circle, and the harvest of 1/100 of the volume takes place in different parts of the circle each year.

Total productivity is at least 20% lower with selective cutting than with final felling. The main reason for this is that trees must be spaced wider apart to allow new trees to grow up. Forests with selective cutting will gradually come to have a higher share of spruce, which grows better in the shadow of other trees, and a lower share of pine (Espmark, 2017). Despite lower growth, selective cutting has other advantages, especially for recreational values and biodiversity, and can be a good choice for forests near cities.

Growth and harvest can be directly expressed in carbon. One cubic metre (m^3) of wood is equivalent to 0.2 tonnes (t) of carbon. Stemwood harvest is 100 t of carbon when the growing stock of the stand is 500 m^3 at the time of final felling, and uptake of carbon in the system is the same. With balance between carbon uptake and removal, apart from possible carbon emissions associated with fossil fuels used for wood harvest and transport, products from the managed forest system are carbon neutral.

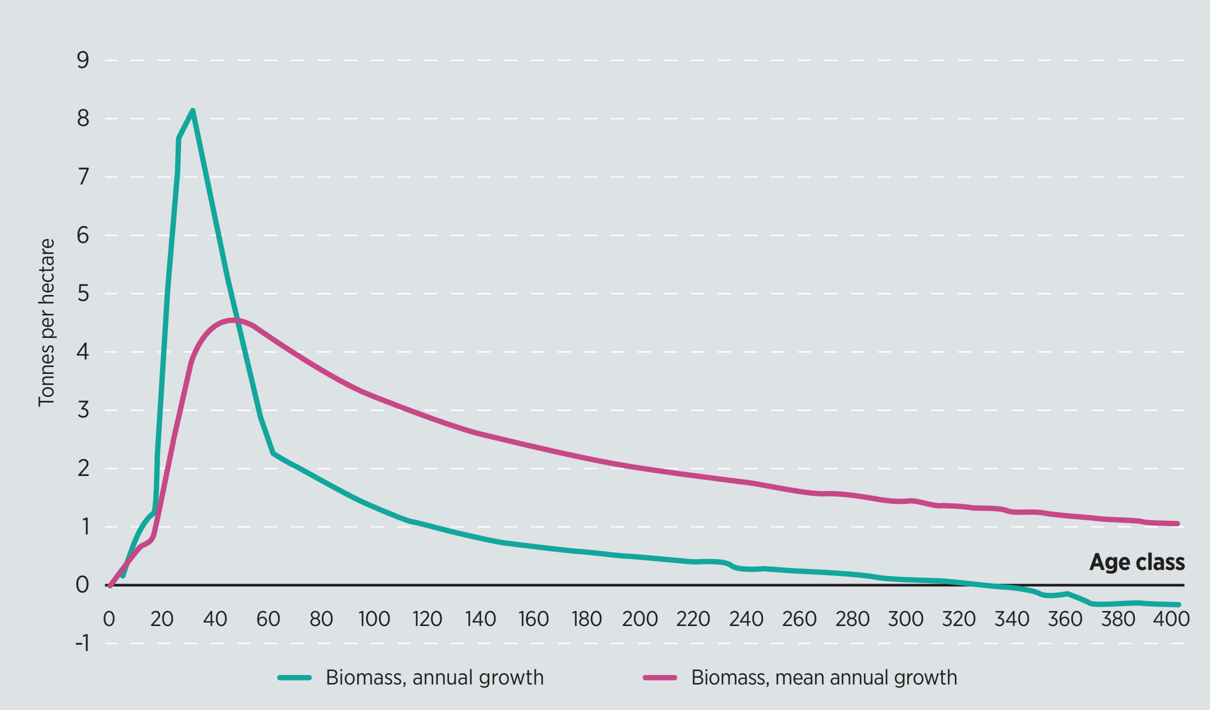
Growth and carbon uptake in a stand of trees over time

A tree or stand of trees has a life cycle, with different rates of growth and carbon uptake at different ages. Growth rates are different in each part of the circle. Figure 4.2 shows the growth pattern, year by year, for spruce in the middle latitudes of Sweden, in tonnes per hectare of dry wood (Hektor *et al.*, 2016). It takes a few years for new plants to develop, but the growth rate shown in blue rises quickly as young trees mature and peaks when trees are 20 to 40 years of age. After that, net growth decreases as trees start shedding twigs and branches and approach their maximum height. For each age on the x-axis, the red line shows the average yearly growth for the tree or stand up to that age; this has a later peak than the current yearly growth, shown in blue.

If trees are left to grow older, the net growth decreases gradually down to zero growth, and the average total growth follows. In this case, trees over 300 years of age have no net growth, but instead have more decay and loss of biomass than new growth.

For a forester or forest owner, a decision must be made regarding when to harvest the trees. In this case, the growth when the tree is 120 years old is only one-eighth of the maximum growth of the same tree when it is 40 years old. By harvesting at an optimal time in the growth cycle, the forester can keep the average growth rate high. Keeping over-aged forest un-harvested leads to a reduced average growth rate and lower total growth. This is particularly true if yield-enhancing strategies such

Figure 4.2 Growth pattern of spruce in Sweden



Source: Hektor et al. (2016)

Growth is expressed in tonnes per hectare. The blue line shows the growth in each age class per year. The red line shows the mean growth up to that age. At 200 years of age, the trees in the age class grow by 0.5 tonnes per year, and the mean growth has been 2 tonnes per year for the stand. After 300 years, growth is negative.

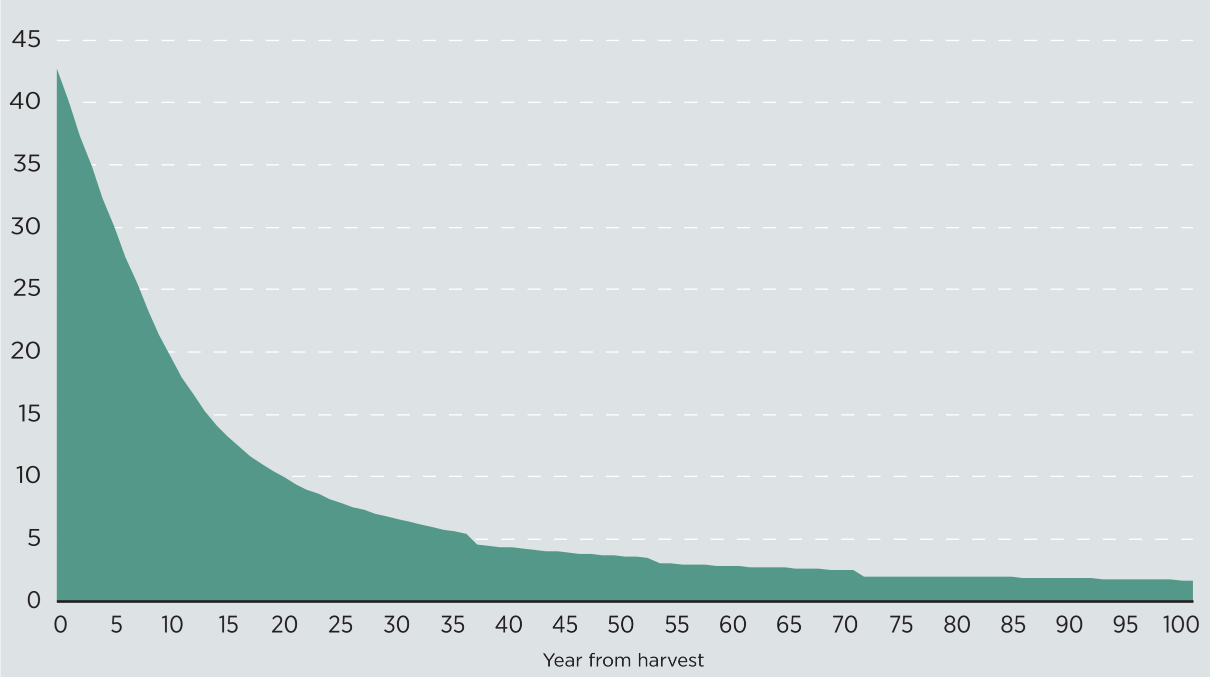
as faster-growing seed and controlled application of fertiliser are applied to the newest stands when they are harvested and replanted.

Biomass can be directly translated into carbon content. One tonne of oven-dry wood is equivalent to 0.5 t of carbon. So carbon uptake in the stand peaks at 4 t/ha when trees are 30 to 40 years old and gradually declines to less than 0.5 t/ha when they reach the age of 120. Keeping over-aged forest leads to reduced total carbon uptake.

The general picture presented above concerns the living biomass in the stemwood above ground. In the forest inventories, only growing stock of stemwood is measured, but the standing volume of growing stock can be easily converted into estimates of the entire amount of woody biomass above and below ground, including branches, roots, and leaves or needles. This is done by applying generally accepted values (called expansion factors) for shares of biomass in different parts of a tree.

For a calculation of the total carbon content in the forest, the carbon in the dead wood, soil and litter must be considered. Branches, twigs, leaves and needles fall to the ground and decay or add to the soil carbon pool. Researchers have developed decay functions based on scientific measurements. These are shown for slash and stumps in figures 4.3 and 4.4. Leaves, needles and thin twigs decompose quickly, whereas coarse wood and stumps may take decades to decompose. There is an initial loss of carbon in the soil after the felling, but an addition of dead and decaying material. Later on, the soil carbon builds up gradually as the trees grow and shed material.

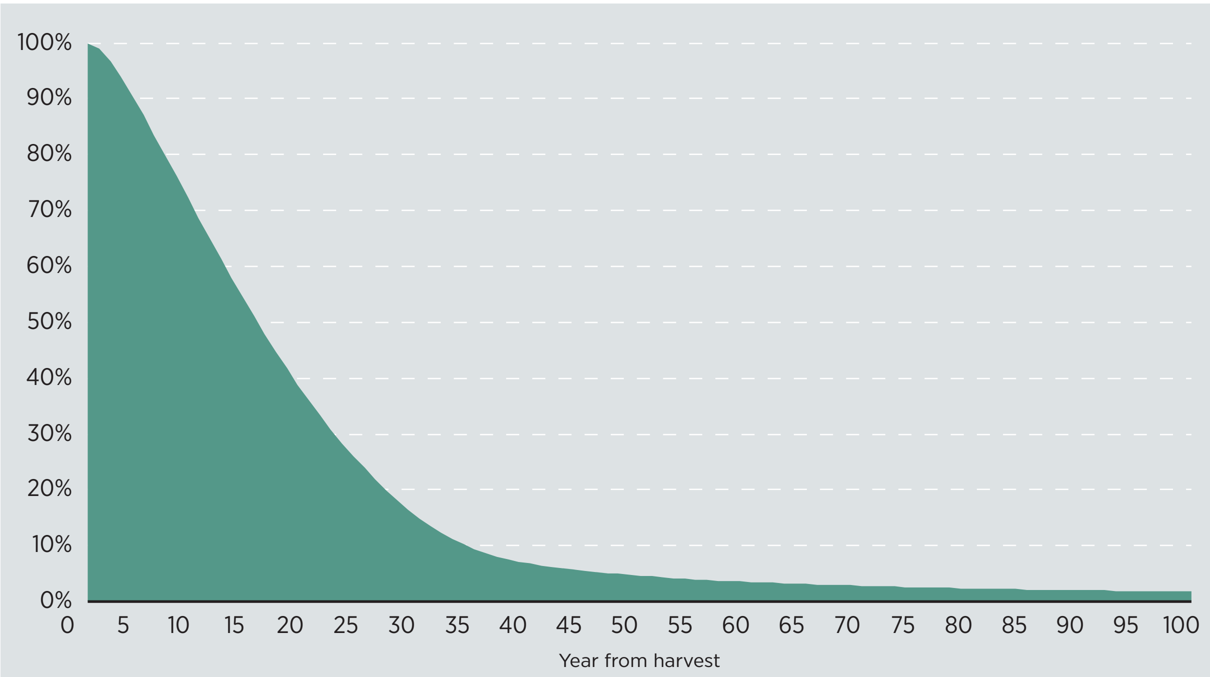
Figure 4.3 Decomposition of slash



Source: SLU

The chart shows the decomposition of slash (tonnes per hectare) over a 100-year period. After 10 years, half the slash has decomposed. After 50 years, less than one-tenth of the biomass and carbon remains.

Figure 4.4 Decomposition of stumps



Source: SLU

The chart shows the decomposition of stumps as a percentage of original biomass volume over a 100-year period. Decomposition is slower in the beginning as for slash, but after 50 years, less than 5% of the volume remains.

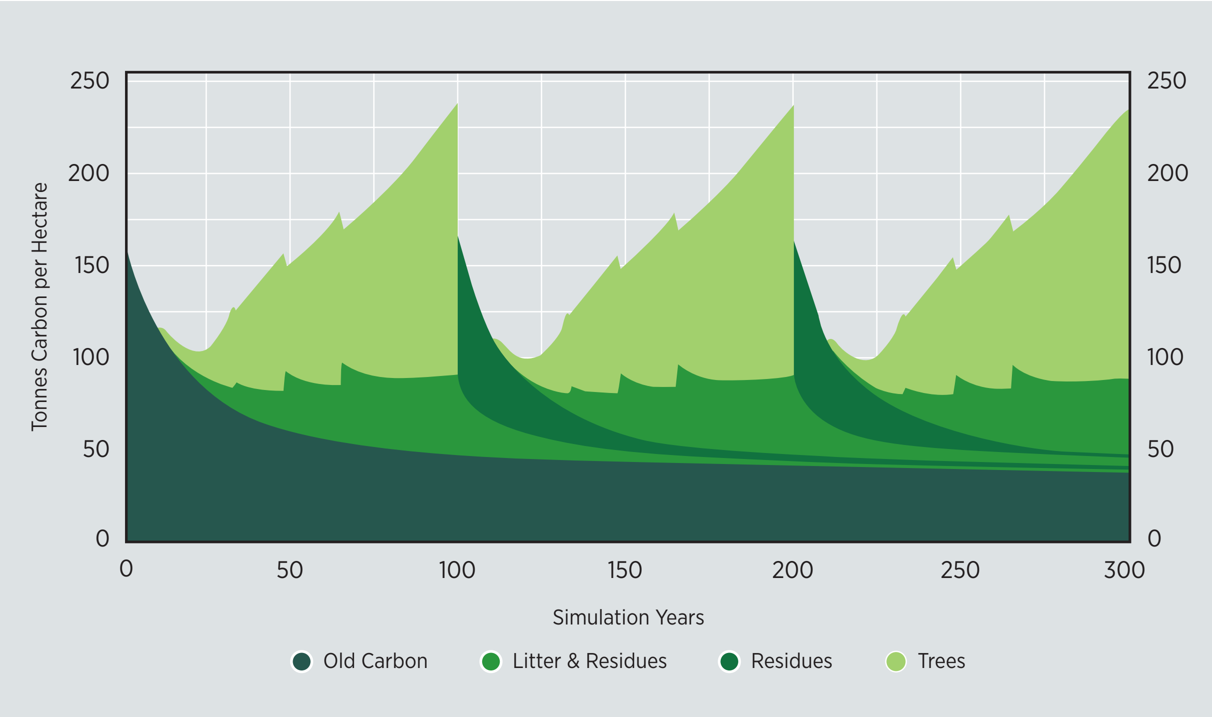
The total carbon balance in a managed forest system has been studied by a group of Swedish researchers (Eliasson *et al.*, 2013). Figure 4.5 shows the development of a single stand of forest with 100-year rotations, typical for southern Sweden (Växjö, 57° N). The chart starts with growth after felling and ends with the full growth of the third rotation after 300 years. The carbon stored in the forest fluctuates greatly over the years in a single stand. This is a theoretical model where the whole stand is cut after 100 years, so harvest equals 100% of growth in each rotation. Only stem harvest is shown; Figure 4.7 shows carbon flows when residues are also harvested.

The pool of "old carbon" at the outset includes the residues from the recent felling as well as the long-term pool of carbon in the soil. New volumes of residue are added to the soil carbon pool after each final felling, and it is possible to see how litter and residues are constantly added and decomposed. Almost all of these added residues are decomposed over time, but a small fraction is eventually added to the long-term soil carbon pool. Decomposition is a natural process assisted by insects and microorganisms. In this process, almost all of the carbon is eventually released as CO_2 through cellular breathing, but a small portion enters long-lived carbon structures that add to the soil carbon pool.

The living biomass in the trees (both above and below ground) is the light green on top. The growth of three generations of trees (rotations) is shown. There are three fellings, and all the residues are added to the litter pool. About half of the biomass from the final felling ends up as residues (tops, branches, stumps and roots), and they are not harvested. Half of the biomass is harvested stemwood. Note the large volume of litter and residues during the lifetime of the trees: needles, leaves, dead twigs and branches.

The total carbon pool in the stand fluctuates between 110 and 230 tonnes of carbon during the rotation cycle. Carbon content declines after the harvest but rises again at the end of the rotation. Looking at the single stand, it is possible to talk about a "carbon debt" created at the time of harvest, which takes a generation to fully pay back. However, much of the harvested wood will go to produce lumber that displaces more carbon-intensive cement in buildings, and much

Figure 4.5 Simulated volumes of ecosystem carbon in a stand of managed forest



Source: Eliasson et al. (2013)

of the residues will generate heat or power that displaces the use of carbon-intensive fossil fuels. The chart does not show these added values in the carbon product. In addition, the picture for the whole forest landscape is totally different from the picture of the single stand. As stands are planted in succession, the carbon pool at forest level is stable.

Carbon content of the whole forest

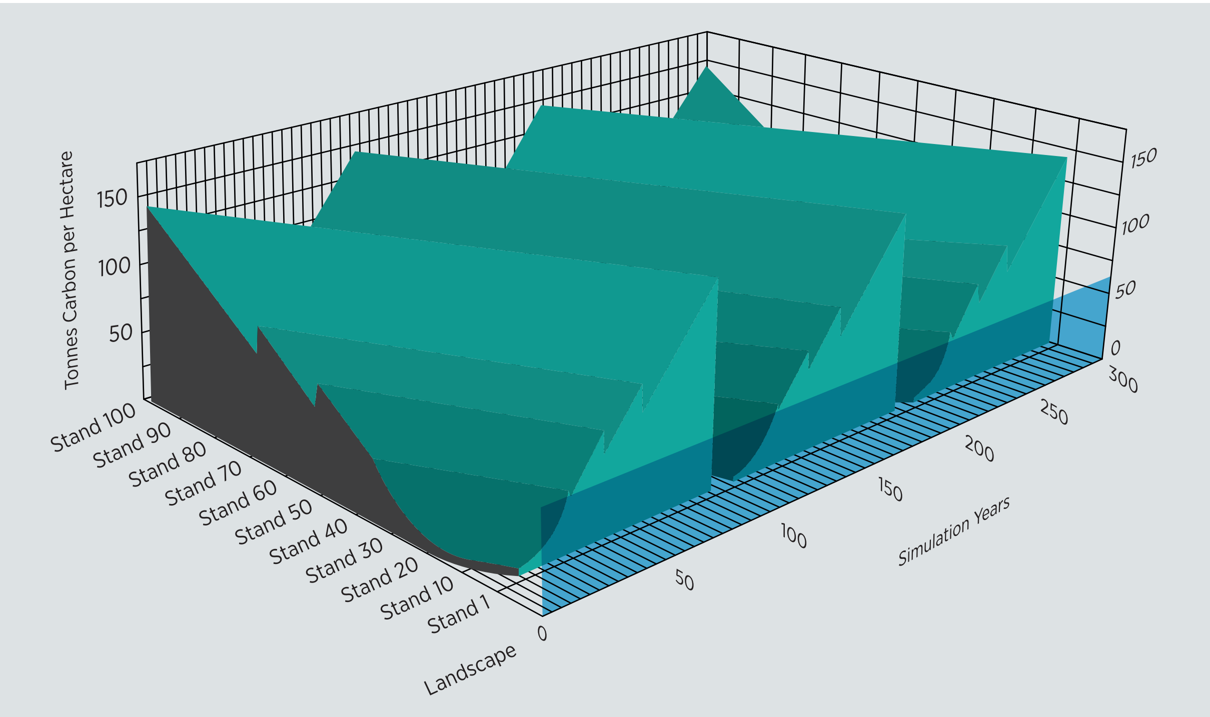
To examine the carbon pool in the forest as a whole, Eliasson and his research team looked on a landscape level with 100 even-aged stands in 100 consecutive age classes, where 1/100 of the forest is harvested each year. The youngest stand is age 0 (bare ground); the second, new plants (1 year old); the next, 2 years old; and so on, up to the stand harvested (100 years old).

This three-dimensional illustration shown in Figure 4.6 shows the development on a landscape level over 300 years. Each year, there are 100 stands where each is one year older than the other. A system is generated in which the total carbon pool is identical from year to year. The total growth and the fellings are the same each year. The average carbon pool per hectare each year is shown as the straight line at the front of the chart. Thus, the average level is the same as for a single stand over a period of 100 years.

Carbon balances with harvest of wood and residue

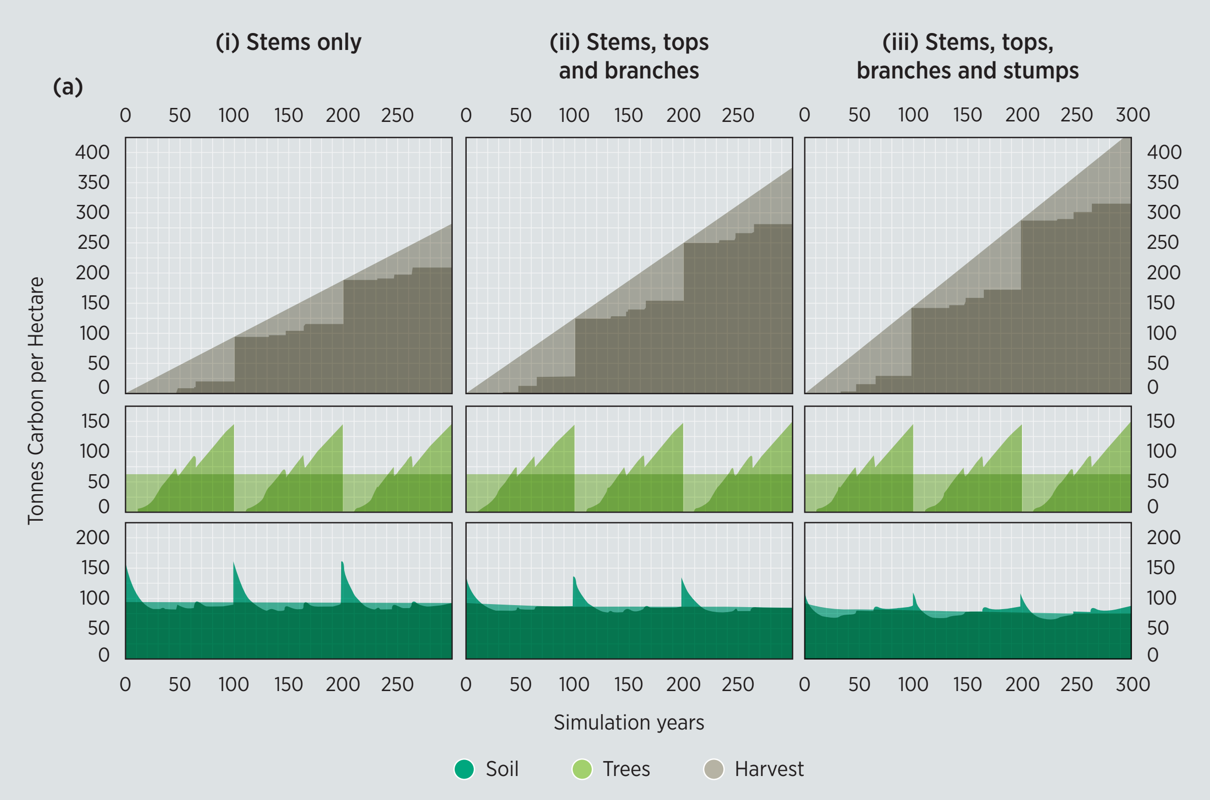
To complete the picture of the carbon effect of the forest, the harvested carbon must be included. The harvested biomass can be used for material (wood products) and energy. In both cases the biomass can substitute for fossil fuels and reduce carbon emissions. The removal of residues also affects soil carbon. So the same researchers looked at harvest volumes and analysed how the harvest affected the carbon pools in the forest.

Figure 4.6 Simulated volumes of ecosystem carbon in a managed forest landscape



Source: Eliasson et al. (2013)

Figure 4.7 Simulated ebb and flow of carbon in harvested wood, trees and soil



Source: Eliasson et al. (2013)

They studied three cases (the results seen above from left to right):

- Case i: Only the stems are harvested and all the logging residues (tree tops and branches) are left in the forest. This used to be the standard case in Swedish forestry, before biomass for energy was harvested in the forests.
- Case ii: 80% of the tops and branches are harvested in addition to the stems. This case reflects the situation in many parts of Sweden today.
- Case iii: 80% of the tops and branches and 50% of the stumps are harvested in addition to the stems. This could be a future practice when demand for bioenergy increases, while still protecting biodiversity. (Note: this level of harvesting forest residues is higher than that assumed in Chapter 3).

The total harvest of biomass is shown in the upper charts, in brown. Over three rotation periods, the harvest is 275 t of carbon per hectare when only the stems are harvested, 350 t when logging residues are also harvested, and 425 t when both logging residues and half of the stumps are also harvested.

The average carbon volume in the standing trees (light green, middle charts) remains the same in all three cases from rotation to rotation, since all three cases nurture trees and later cut them down to harvest the stems. However, the carbon pool in soil, including residues, litter, slash, stumps and roots (bottom charts, grey), varies between the three cases. In all cases, soil carbon is lost during the first part of the rotation but recovers at the end of the rotation. However, soil carbon losses are higher when slash and stumps are harvested and removed. That is because the soil carbon pool in these models includes the slash and stumps. This also means that there is less non-decomposed material from slash and stumps. When the trees get older, they shed needles, twigs and branches, which also add to the soil carbon pool. Compared

to the large volumes of harvested carbon, these carbon losses in soil are mostly temporary and therefore minor in the long run.

The straight lines in these charts show the harvest volumes (brown) and the carbon pools (green and grey) per hectare on a landscape level (100 stands harvested in 100 consecutive years). The figure shows there is no loss over time in the carbon pools of trees and soil. The amount of harvested carbon increases at a steady pace in the system, as harvesting takes place every year of one stand out of 100.

Dynamics of fostering growth in forest carbon storage

The calculations described so far are based on a model used in analysing Swedish forestry (the Q-model), which is static. Using another model, the COUP model, Eliasson and team could show increasing carbon pools and increasing potential for wood production over time, as a result of increased growth of wood in the forest system. This confirms what has actually happened; development in the forests is dynamic. As noted earlier, Swedish forest harvests have increased by 1% per year since the Second World War. This is largely because substantially less than the full increment of forest growth has been harvested each year. But it is also because of a steady increase in productivity caused by improved forestry methods and more fast-growing young trees. A more accurate calculation should include a factor for this gradual increase in harvests. With higher production, the carbon content in trees and soil will increase from rotation to rotation. More growth automatically produces more litter and more slash.

Avoided carbon emissions from substitution of wood for fossil fuels

Outside the forest, the use of wood for energy can displace carbon-intensive fossil fuels. Historically, most energy wood has been used for district heating and industrial process heat, while smaller shares have been used for electricity generation in CHP plants and for small-scale residential heating (firewood and pellets). Lately, a smaller amount has been converted to liquid fuels for transport.

As shown in Figure 4.8 (from Werner, 2017), district heating (in red) has expanded at a steady pace in Sweden from the 1960s onward. Initially, district heating was almost entirely fuelled by oil (as shown in Figure 1.4). However, with support from the carbon tax (introduced in 1991), district heating is now largely supplied by efficient combustion of wood. Increased wood-based district heating has thus mainly displaced heating by fuel oil (in grey), and today supplies more than half of the heat market in Sweden.

Reduced oil use for heating started with the oil crises of 1973 and 1979. At the end of the 1960s, cheap oil had captured more than 80% of the Swedish heating market, even substituting for a lot of firewood use (dark red). During the 1970s and 1980s, 12 nuclear reactors were started, and electric heating became common in single homes. In recent years, much electric heating has been switched to more efficient heat pumps. Heating with oil has been continually reduced, recently mainly in single homes, which today use almost no oil boilers but rely on a mix of wood furnaces, boilers and stoves.

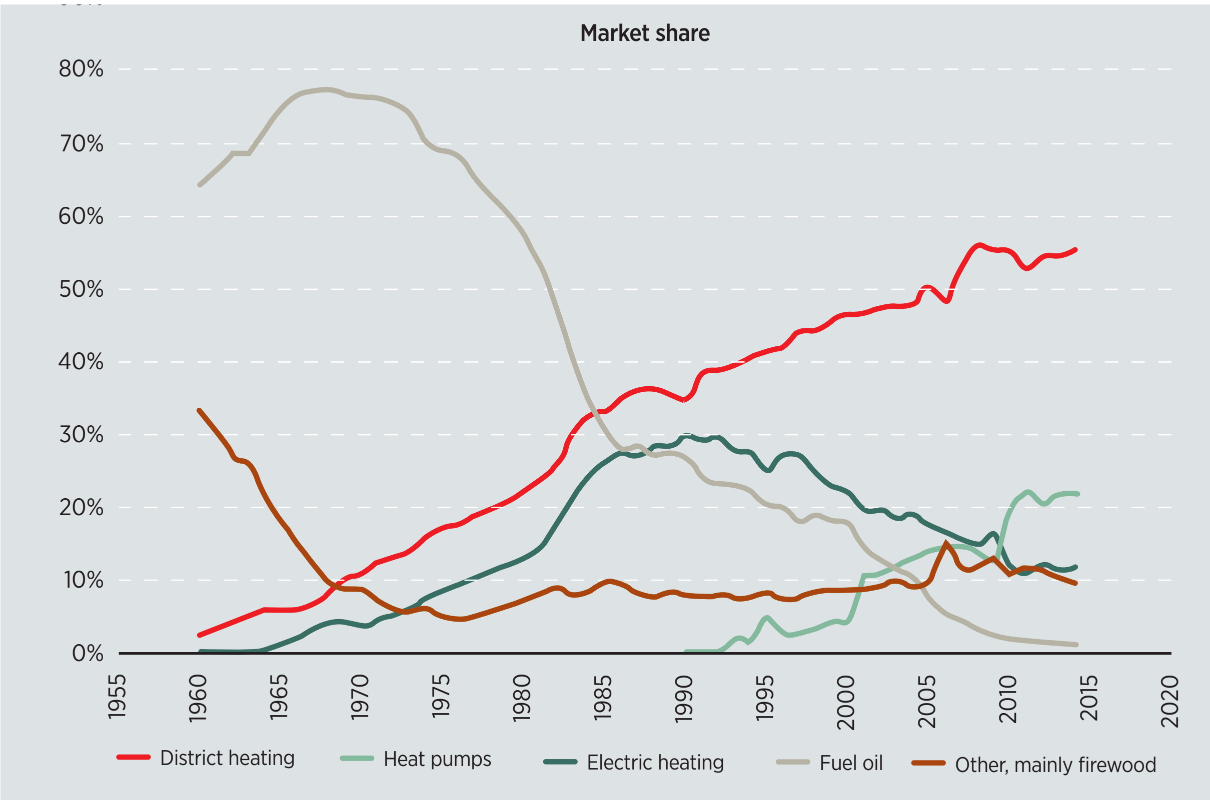
The implication is that historically, there was a significant substitution for direct fuel oil use in buildings by district heating and electricity from 1970 to 1985, with the district heating still almost entirely based on fossil fuels and electricity based on nuclear power. After 1985, district heating shifted away from fossil fuels and increasingly relied on wood fuels. For small-scale heating, a combination of heat pumps, modern wood heating (pellets) and district heating reduced fossil fuel use to a minimum.

Today, almost half of the end use of heat is bioenergy-based: 65% of district heating (0.65 x 55% = 36% of total heat use), 10% as small-scale direct combustion of biomass, and 7% of electricity (0.07 x 34% = 2.5% of total heat use): in total, 48.5%. The rest is mainly provided by hydro and nuclear power and district heating based on municipal waste and waste heat.

This is a radical change from 1970, when 77% of heat was supplied by oil boilers, and the 10% supplied by district heating was also almost entirely based on oil. Today the direct use of oil is 1% and the fossil fuel share of district heating is less than 10%. As a consequence, carbon emissions from the heating sector have decreased greatly.

Looking forward, the potential for further carbon reductions through displacement of fossil fuel combustion for heating is limited. However, there is large potential for carbon reductions through displacement of petroleum-based transport fuels. That assumes continued progress in technologies for conversion of wood to biofuel for road vehicles and jet fuel for aviation. A number of projects are under way in Sweden.

Figure 4.8 Heat supply shares to residential and service buildings in Sweden



Source: Werner (2017)

Benefits from using wood products

The use of forest products has a long history in the Nordic countries (primarily Sweden, Finland, and Norway), where products like tar and charcoal were big exports long before sawn wood, paper and cardboard – the dominant products in the current forest industry. Today, the forest industry looks increasingly to chemicals, plastics, composites, textiles and even pharmaceuticals. The industry is developing what is often labelled "bioeconomy". In principle, everything that can be made from fossil black carbon can be made from renewable green carbon.

When used as a substitute for fossil raw material in making various products, wood and other biomass products have climate benefits. This is obvious for biomass for energy and biofuels, but just as important for other bio-based products. In addition to the direct substitution effect (reduced use of fossil materials and fossil fuels), there is also a positive climate effect from the storage of carbon in the products, for a period of time. The climate benefit from this temporary storage of carbon can be calculated, and the pool of wood products is also included in the reporting under the Paris Agreement.

Following the Intergovernmental Panel on Climate Change (IPCC) guidelines for wood products in use, the "half life" is 30 years for solid wood products, with reduction (decay) of 2.3% per year, but the half-life for paper products is just 2 years. When researchers study patterns of carbon storage in wood, they make more refined calculations with different lifetimes for different kinds of products. One Swedish study assumes an "average service life" of 80 years for wood used in building construction, 30 years for wood used in building interiors such as furniture, and 10 years for other wood products. Wood used for energy, in contrast, is considered to release its carbon instantly.

Traditionally, wood has only been used for small, one- or two-storey buildings, but architects and builders in the Nordic countries are increasingly also using wood for higher and larger buildings. The biggest climate benefits come from the substitution of fossil-intensive or fossil-based products – like steel, aluminium and cement used in construction – and plastics and other fossil-based materials.

There is a lot of uncertainty surrounding substitution of materials, as the results of calculations depend to a large extent on assumptions and system

Photograph 4.1 Building in wood for climate benefit

Photograph: Interior from Metla-Talo (Forest House) in Joensuu, Finland (photo Svebio) boundaries. When building a house of wood instead of brick or concrete, it is easy to calculate the fossil energy input into brick production or cement production with current practices. What is not always taken into account are the benefits from by-products and residues from the wood supply chain. In addition, questions surround whether the use of wood for construction will be less valuable for the climate if in the future cement can be produced with less fossil energy input. Another issue to consider is that although steel is an energy-intensive material, it can eventually be recycled.

A meta-analysis (Sathre and O'Connor, 2010) compared 21 scientific studies of the substitution benefit of using wood as construction material. On average, the studies find a substitution benefit of 1.9 t of CO_2 emissions reduction per cubic metre of wood used in buildings. This would be roughly equivalent to 1.1 tonne carbon (tC) per oven dried tonne. Many of these studies look at the use of wood in specific cases where the alternative clearly would be a product like concrete, aluminium or steel. However, the studies vary considerably in their focus. They focus on either whole apartment buildings or individual building components like floors, windows, beams or doors. The estimated substitution benefit increased considerably when all wood residues were assumed to be used for energy, and all other wood was assumed to be recovered for energy use (instead of taken to a landfill) when its initial use was complete (for example, after buildings are demolished or furniture or plywood discarded).

Another study (Gustavsson *et al.*, 2006) specifically assesses the carbon displacement factor for building materials in Swedish building. The study compares net CO_2 emissions from the construction of concrete-framed buildings with those from a wood-framed building known as Wälludden in Växjo, Sweden. It takes account of emissions from fossil fuel used to make building materials and from chemical reactions required to produce cement.

- The overall carbon balance is estimated at -41.4 tC for a wood-framed building and 25.8 tC for a concrete-framed building.
- Dividing by wood material input of 98 oven-dry tonnes (odt) for a wood-framed building and 70 odt for a concrete-framed building, the carbon balance per odt of wood used in construction is -0.42 tC/odt for a wood-framed building and 0.37 tC/odt for a concrete-framed building. The overall carbon displacement factor can then be calculated as the difference between these two values, or 0.79 tC/odt of wood used in construction.
- Excluding the portion that relates to 0.02 tC from substituting logging residues for fossil fuels, the net substitution effect is 0.77 tC/odt of wood used in construction, including 0.44 tC from material production, 0.26 tC from cement processing residues, and 0.07 tC from substituting wood wastes and processing residues for fossil fuels.
- Multiplying by the 44/12 ratio of carbon dioxide to carbon molecular weight, this equates to 2.8 tCO_2/odt of wood.
- Dividing by 5.33 MWh/odt-wood per the net calorific value (NCV) of wood energy content, this converts to a net CO_2 displacement factor of 0.53 tCO_2/MWh or 0.53 $MtCO_2$ /TWh.

All of these studies focus on substitution effects from wood use. None of them considers substitution effects for paper. This may be relevant for newsprint and many other types of paper. However, for packaging and other paper products, other alternatives have higher carbon footprints, like plastics and metals. Paper can substitute for plastic in many applications, such as paper instead of plastic bags or paper packaging instead of plastic containers. Paper and cardboard can be recycled several times and finally end up as fuel from municipal solid waste. In addition, unlike plastic, paper products are biodegradable.

When solid wood products reach the end of their useful lifetime, they can and should be used for energy, to produce heat, electricity or refined fuels. They usually have lost very little of their energy value. To some extent, used wood can be recycled for new products, but there may be a risk of contamination. A well-developed system for recovery of used wood for energy is essential. What used to be landfills and dumps have today become recycling centres where all combustible products can be recovered.

In summary, wood-based products can have multiple positive impacts on climate. They can substitute for fossil feedstock (oil, gas and coal) as raw material. They can substitute for products with high carbon footprints like steel, aluminium and cement. When no longer functional, they can be used as biogenic fuel and substitute for fossil fuels in heating and power plants. They also temporarily store the biogenic carbon while in use.

Climate benefits of the whole wood and energy system

The total climate effect from both carbon storage and substitution can be shown in principle in a single graph. The total climate benefits depend on a number of factors:

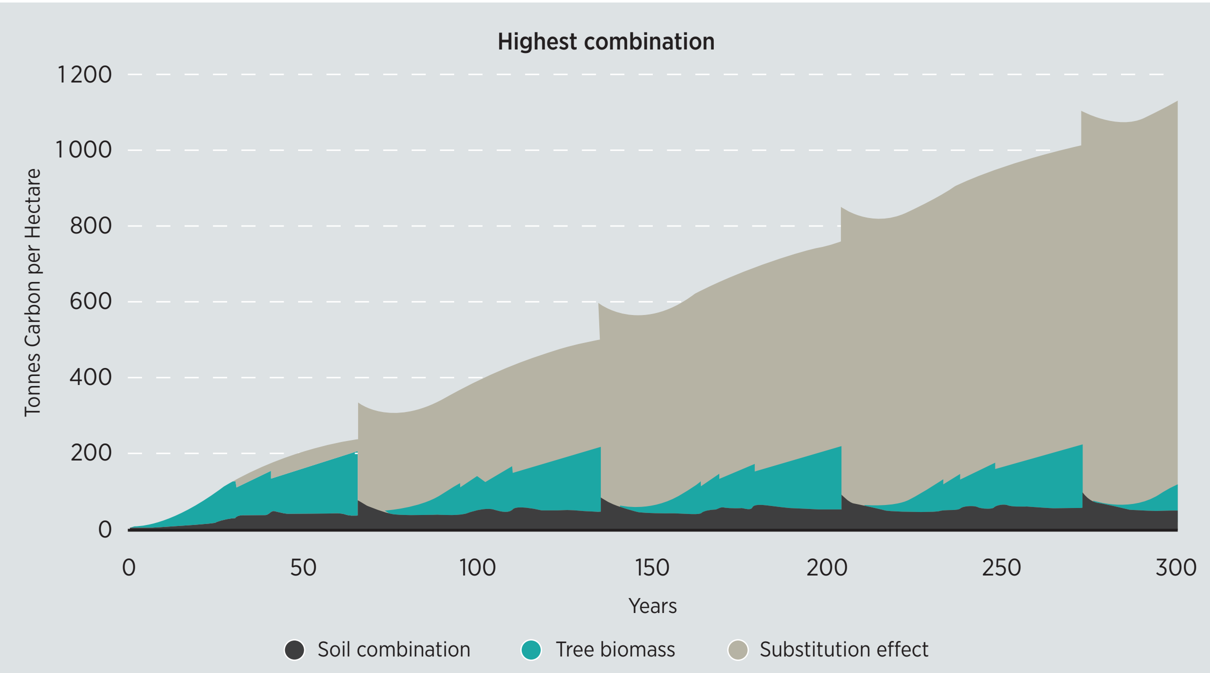
- the forest growth rate
- the harvest levels of industrial wood and biomass for fuels
- the use of harvested wood to substitute for carbon-intensive products
- the energy use of biomass and the fossil fuels for which it substitutes.

Researchers from the Swedish University of Agricultural Sciences (SLU), Mid Sweden University and Purdue University in the United States modelled the total climate effect under alternative assumptions about forest management practices and wood substitution (Eriksson *et al.*, 2007). The following two charts show the results for two alternatives, with maximum climate benefits and minimum climate benefits.

The conditions for the “maximum benefit case” are that the forest is fertilised, which gives faster growth and shorter rotations (70 years); that all slash and stumps are harvested; that the wood is used mainly as construction material; and that the biomass fuel is used to substitute for coal.

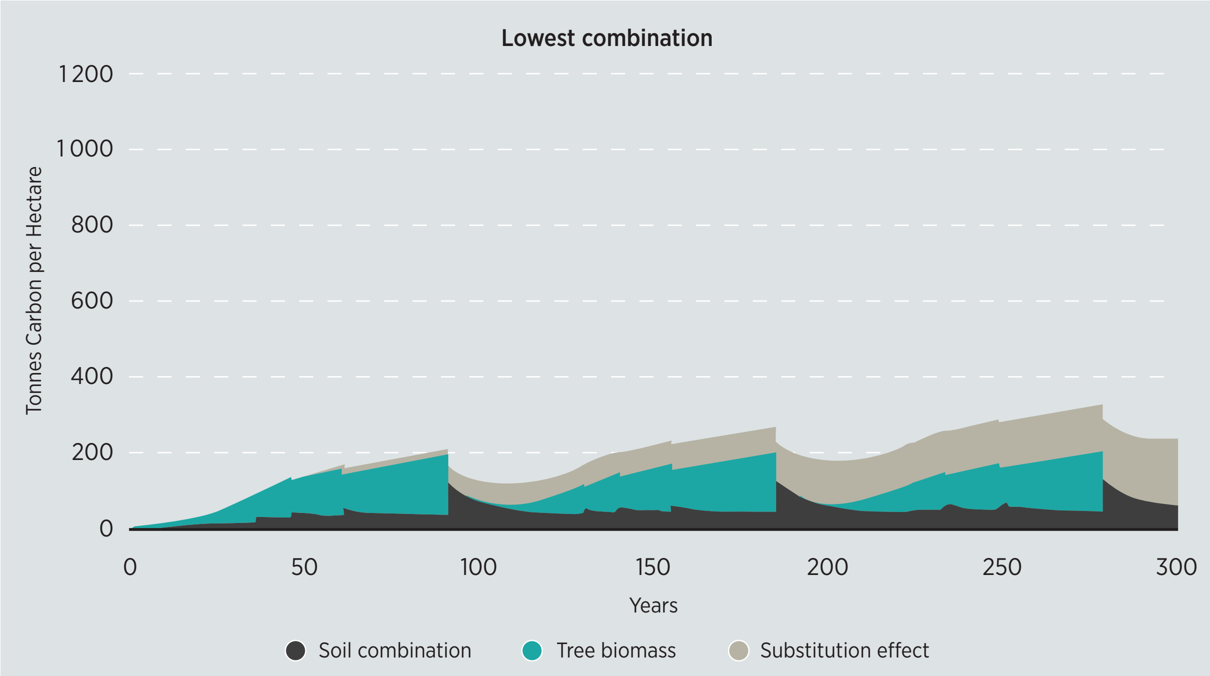
The conditions for the “minimum benefit case” are that the forest is not fertilised, but is managed with traditional 90-year rotations; that no slash or stumps are harvested for energy; that the wood is

Figure 4.9 Maximum carbon benefits scenario



Source: Eriksson et al. (2007)

Figure 4.10 Minimum carbon benefits scenario



Source: Eriksson et al. (2007)

used only for biofuels production with relatively low efficiency; and that the substitution is for natural gas.

The examples show that the climate benefits can be optimised by "doing right", and that the total climate benefits can be very high in the long run. A general conclusion is also that substitution gives much higher climate benefits than carbon storage in the forests if the wood products and fuels are used wisely.

Researchers at the Swedish University of Agricultural Sciences have similarly looked at the climate benefits of the whole forestry system, from forestry practice to end use of products and bioenergy. The study is a modelling exercise for the Future Forests project (Lundmark *et al.*, 2014). The analysis covers effects, both in Sweden and globally, caused by the use of wood products from Sweden. The researchers analysed:

- the carbon stock and carbon stock changes in the forest ecosystem
- the carbon stock in long-lived wood products
- fossil emissions from forest management, logistics and wood product processing and the paper and pulp industry
- substitution effects through avoidance of the production and disposal of other non-wood material, usually with a higher carbon footprint
- substitution of fossil fuels by using wood fuels and residues.

The conclusion was that Swedish forestry using current practices absorbs around 60 Mt of CO_2 per year. This more than balances the 53 Mt CO_2-equivalent (Mt CO_2-eq) of greenhouse gas emissions from all other sectors in Sweden in 2016. The CO_2 uptake amounts to 466 kilograms (kg)/m^3 of harvested biomass. In a scenario with increased growth, this average uptake could increase to 546 kg/m^3, and the marginal uptake from each additional unit of harvest could reach 719 kg/m^3 if the extra wood harvested were mainly used for material and energy substitution. Higher harvest levels could then boost the total uptake of CO_2 from Swedish forests to over 100 Mt per year.

The calculation includes both carbon build-up in the forests and climate effects from the use of wood products and biomass for energy. For wood products, both substitution and storage effects are included. For bioenergy, the substitution of fossil fuels is counted. However, no substitution effect is considered for paper products, and substitution factors for wood products are more conservative than in some other studies (Sathre, 2007).

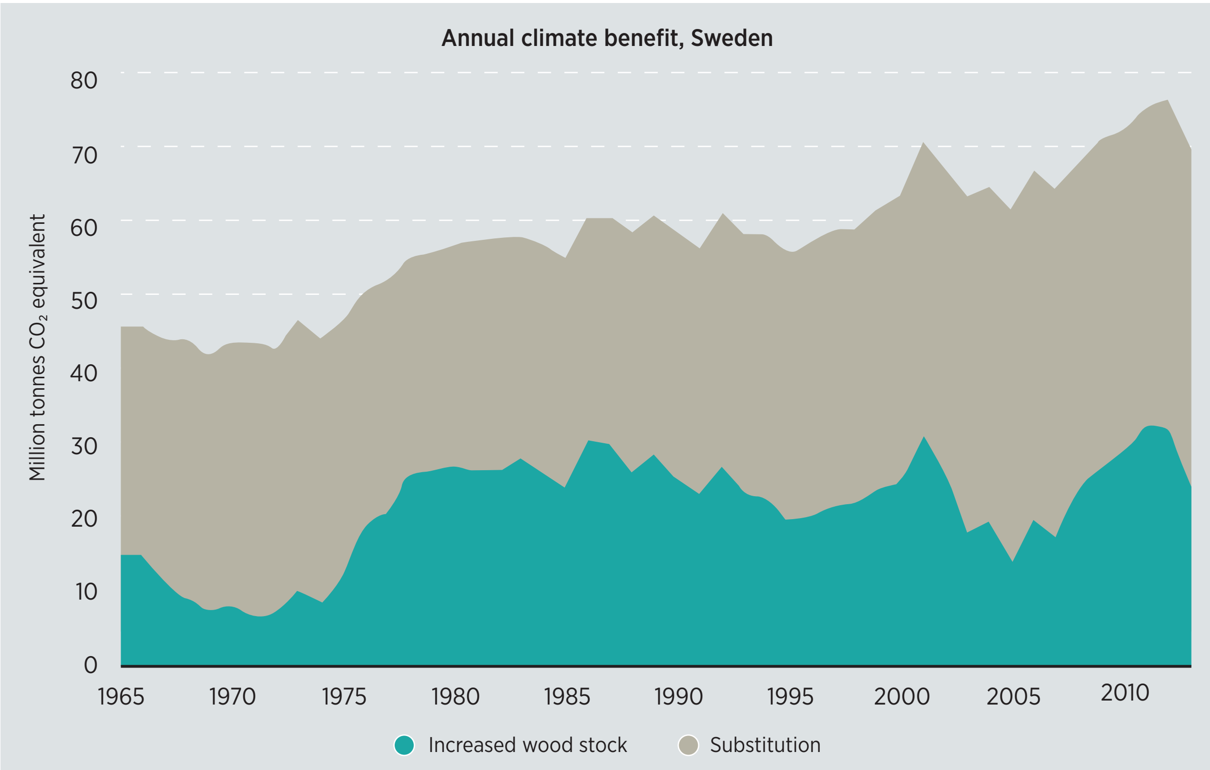
With a climate effect of around 500 kg CO_2 per m^3, one could argue that it is better to let the carbon stay in the forest, as biomass contains carbon corresponding to 700-900 kg of CO_2 per m^3. About this, Sathre comments that:

> Focusing solely on increasing carbon stocks in this way is, however, a limited climate mitigation strategy, since it is not possible to store unlimited quantities of carbon in the forest. If this method were to be applied, timber reserves in Sweden would initially increase, but would eventually reach a new equilibrium between growth and natural attrition. When this balance is reached, the "uncultivated forest landscape" would, in principle, be CO_2 neutral, i.e., it neither sequesters nor releases carbon to any significant extent.

In that case, Sathre further points out, no harvest would take place, and the current consumption level of forest-based products would have to be satisfied with other, more energy- and fossil fuel-intensive materials and fossil energy. Unlike these other materials, sustainably managed forest wood can be supplied perpetually on a renewable basis. Moreover, if harvests ceased, the risk for disturbance from hard winds, forest fires and insects would increase.

The numbers from the Swedish study have been used to calculate the climate benefits from Swedish and Nordic forestry over the last 50 years. Figure 4.11 shows how this benefit has increased and how the share of substitution has increased over time, due to increased use of bioenergy. In the Swedish context, substitution is more important for the climate than storage of carbon in the forests.

Figure 4.11 Climate benefits of Swedish forestry, 1965-2013



Source: Nordic Forest Research (2017)

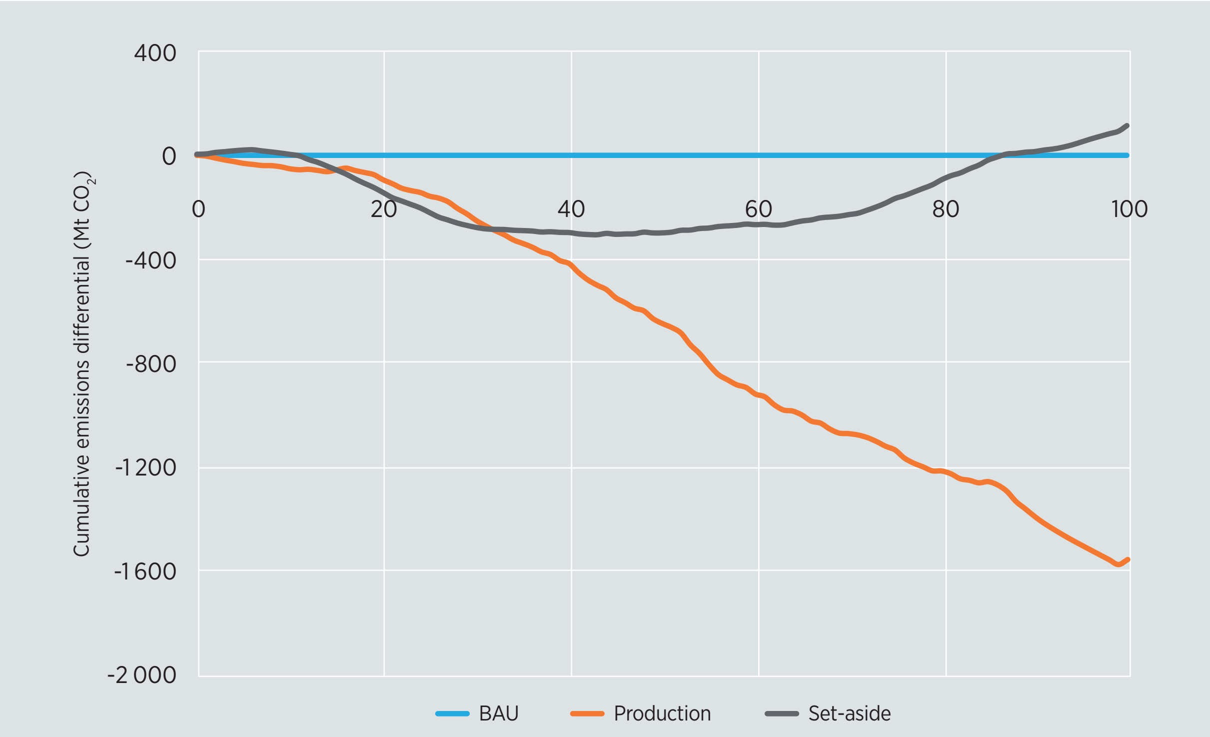
Active forest management to boost carbon uptake

It seems intuitive that carbon uptake will be greater if the forest is just left alone, rather than actively managed for extraction of wood and energy. Indeed, the stock of wood and carbon in the forest is apt to be greater for some period of time. But the overall carbon uptake can be greater with active management, assuming there is substantial displacement of carbon emissions from fossil fuels and from building materials.

The balances are explored in depth for the Swedish case by a group of researchers from Linnaeus University and the Swedish University of Agricultural Sciences (Gustavsson *et al.*, 2017). They compare a "business-as-usual" case with a "production" scenario and a "set-aside" case. The business-as-usual case assumes that harvest equals growth, which is more aggressive than the actual Swedish harvest, which has varied between 70% and 85% of growth over the last decade. The production scenario introduces faster-growing pine species to enhance yields, substituting *Pinus contorta* for the prevalent *Pinus sylvestris* on half of the area planted each year. It also doubles the number of planted hectares that are fertilised, further boosting yields. The set-aside case doubles the amount of protected area to simulate the impact of leaving the forest alone.

They found that cumulative change in *carbon stock* after a century is nearly twice as great in the set-aside case as in the production scenario (400 MtC vs. 230 MtC). But they also find that *net carbon uptake* increases steadily in the production scenario towards 1 600 $MtCO_2$ after 100 years, while it levels off in the set-aside case after 30 years and is wiped out by century's end. This is shown in Figure 4.12, where negative numbers mean carbon uptake and lower emissions. The figure compares the production case in orange and the set aside case in grey with business as usual in blue. The climate benefit from saving trees in the set aside case is temporary, while the benefit from boosting productivity in the production case is continuously increasing.

Figure 4.12 Cumulative emissions differential in Swedish set-aside and production scenarios



Note: BAU = business-as-usual
Based on: Gustavsson et al. (2017)

In the production scenario, as the authors explain,

> Net ecosystem exchange, composed of living tree biomass change, soil carbon stock change, and harvested biomass, becomes more negative under more intensive management, as more CO_2 is removed from the atmosphere and exported from the forest ecosystem as harvested biomass. This carbon is subsequently released back into the atmosphere when the biomass is utilized in bioenergy systems, which results in a corresponding avoided emission from fossil fuels….[and] greater stemwood harvest…leads to reduced emissions from cement and other non-wood building materials.

Carbon losses from natural disturbances

How secure is storage of carbon in forests over the very long term? Natural boreal forests are regularly affected by massive disturbances like forest fires, storm damage and insect infestations. Forest fires occur regularly in the summer season in Siberia and Canada, as well as in the western United States. A massive storm in Sweden in 2005 destroyed great swaths of forest landscape. Canadian forests have undergone massive attacks by insects in recent years, like mountain pine beetles in British Columbia. Similar attacks have taken place on Engelmann spruce in the US Rocky Mountains. Hundreds of thousands of hectares of forest have died in a short time.

Managed forests in Sweden and other Nordic countries are less affected by such natural disturbances. One reason is that the forests on average are younger and less susceptible to these attacks. Forest fires spread more easily in old forests because they have a lot of undergrowth and dead trees. In managed forestry, there are systems in place to detect and fight forest fires, and roads used to transport harvested wood from the forest also give better access to fire fighters.

One or two years per decade are dry years in Sweden with enhanced risk for forest fires. A large forest fire occurred in 2014, when 14 000 ha burned in Västmanland in central Sweden. Such a big fire had not occurred in the previous 100 years. A couple of hundred years ago, well before modern forestry practices, around 1% of the Swedish forest area burned every year. Today, it is unusual for forest fires in any given year to affect more than a few hundred hectares.

The historic incidence of forest fires was studied by Granström and Niklasson (2008) in a large 5 000 ha forest area in central Sweden called Rossen in Hälsingland. By analysing and dating charred old trees and stumps, they found that at least 67 forest fires had occurred over the roughly 6-century period between the years 1235 and 1845. From 1430 through 1781, forest fires occurred an average of every seven years; nine were large, the last one in 1781. Since the mid 19th century, when forest harvesting began in the area, no forest fires have occurred there.

In the hot and dry summer of 2018, though, forest fires again hit Sweden hard, burning around 25 000 ha at a number of sites. With climate change, forest fires may occur more often.

There is also no way to stop big storms. The winter storm Gudrun in 2005 in one night felled 75 Mm^3 of wood in southern Sweden, almost equivalent to one year's normal harvest in Swedish forestry. The areas affected by this hurricane are among the most productive in Sweden, and many small-scale forest owners lost their whole forest – stands of trees built up over a couple of generations.

Thanks to good infrastructure, good planning, and resources mobilised from the whole country, forest owners and the forest industry managed to recover almost all the wood. This was risky and difficult, and several lives were lost – more than during the storm itself.

Within a few years, all of the areas where the forest had been "harvested" by the storm were planted with new forest, and today these areas have young stands, which in the coming years will grow very fast and take up a great deal of carbon. The carbon loss in the storm will be reversed, and this area in southern Sweden will once again be a major carbon sink.

Photograph 4.2 Before Storm Gudrun levelled a spruce forest in southern Sweden (2005)

Before the storm...

Photograph: Vida Energy/Anders Gerestrand

Photograph 4.3 After Storm Gudrun levelled spruce forest in southern Sweden (2005)

After the storm.

Photograph: Vida Energy/Anders Gerestrand

5 ENHANCING BIOENERGY SUPPLY AND CARBON UPTAKE FROM SWEDISH FORESTS

Although bioenergy extraction from and carbon uptake in Swedish forests are already high, there is considerable potential to increase them. There are three ways of doing so physically, which may be evaluated in terms of their environmental and economic sustainability:

1. increase the use of wood products and residues collected from wood harvested
2. increase the share of annual forest growth increment that is harvested
3. boost the annual forest growth through improved forest management.

1. ***Increased use of lumber and residues within the current harvest level*** would increase the use of lumber and other wood products to displace cement and other carbon-intensive materials in buildings and would also increase the use of residues to displace carbon emissions from fossil fuels. *Greater use of lumber and other wood products in buildings* would not provide more energy, but it would yield 2 t of avoided carbon dioxide emissions for every tonne of wood used (see Chapter 4). This could mean using a greater share of sawn timber for buildings rather than other products, or converting pulp or residues to composite materials suitable for construction. *Greater use of residues to displace fossil fuels* would reduce the amounts of stumps and "slash" (tree branches and tops and small trees from thinning) that are left in the forest to decompose. Instead of simply decaying in the forest and releasing carbon to the atmosphere over time, residues can be combusted for energy so that the carbon dioxide released is compensated to a large extent by immediate displacement of carbon emissions from fossil fuels.

2. ***Increased harvest level as share of current forest growth*** would initially reduce net additions to forest wood stock while increasing flows of biomass to the economy. Available amounts of stemwood, slash and stump would increase in proportion to harvest, as the physical structure of trees harvested would remain the same. Other things being equal, flows to sawmills and pulp mills would grow in proportion as well, and so would various products and residues. There would remain a choice to use a greater or lesser share of the stemwood and residues to displace building materials and fossil fuel combustion. Increased harvest would typically come from older stands with relatively low growth rates. Larger areas would be converted from old stands to young replanted stands, with higher growth rates in these areas after about a decade. Growth in the young stands could be further enhanced through the introduction of higher-yielding varieties and other management practices to raise productivity. The increased growth rates in replanted stands would tend to moderate the initial reduction in annual additions to forest wood stock over time.

3. ***Increased forest growth*** would potentially increase all forest wood flows, including both net additions to forest wood stock and use of harvested biomass in the economy. If the rate of growth were boosted sufficiently, it could allow for an increased amount of wood to be harvested each year while still allowing some extra biomass to accumulate in the forest. For example, research shows that the application of fertiliser to forest stands in certain areas can more than double the growth rate. Climate change and continuous improvements in forest management should boost forest growth in the coming decades.

Increasing use of lumber and residues within the current harvest level

The largest component of forest residues collected for energy use is ***slash*** (tops and branches) from final fellings and thinning. Yet only about 15% of the slash is collected in Sweden at present, and almost no ***stumps*** are extracted since other types of biomass are more abundant and cheaper to collect. But as explained in Chapter 3, at least 50% of the slash and 20% of the stumps could be collected on a sustainable basis. As shown in Table 5.1, this could increase collection of logging residue nearly five-fold, from 10 TWh to 50 TWh. If it were possible to collect 70% of slash and 30% of stumps sustainably, comprising roughly half of all logging residues, the collection of logging residues could increase to 71 TWh.

Roughly 60% of the sawn wood produced in Sweden is used for building material either domestically or in export markets. GeoPartner AG reports (Hofer *et al.*, 2008) that of 5.38 million cubic metres (Mm^3) produced in a year, 34% is used for construction (exterior walls, pillars, ceilings, insulation, roofing and underground engineering) and 26% for interior works other than furniture (such as walls and ceiling coverings, staircases, flooring, facades and doorframes).

Table 5.1 compares the actual wood flows in Sweden in 2015 with the flows that might occur assuming enhanced use of residues to displace fossil fuels.

- To highlight the impact of more wood and residue use, most factors are unvaried:
  - Forest growth increment is the same (436 TWh).
  - Share of growth cut is the same (329 TWh or 75%).
  - Distribution of cut among different components of tree wood is the same.
    - Stemwood is 55% of the cut (181 TWh)
    - Slash (tops and branches) is 20% of the cut (66 TWh)
    - Stumps (and roots) are 25% of the cut (82 TWh)
  - Distribution of stemwood products is the same.
    - Pulpwood is 48% of the stemwood (87 TWh)
    - Saw logs are 44% of the stemwood (80 TWh)
    - Firewood is 5% of the stemwood (9 TWh)
    - Discarded wood is 3% of the stemwood (5 TWh)
- To show the impact of greater use of residues for energy, the share of slash collected is assumed to increase from 15% (10 TWh) to 50% (33 TWh), and the share of stumps collected is assumed to increase from 0% (0 TWh) to 20% (17 TWh).

Figure 5.1 shows the impact of increased residue collection on primary energy use.

- With both current and enhanced residue collection, there are identical amounts of residues from pulpwood and timber processing, firewood and discarded wood:
  - About 20 TWh of processing residues and discarded wood are used for district heating (DH), assumed to be about 100% efficient (theoretically, levels above 100% are possible, by conventional engineering definitions of heat value).
  - About 60 TWh of processing residues are used for process heat in pulpwood and sawmills, and 9 TWh of firewood is used; these wood flows are taken to be used in modern wood furnaces with 87% conversion efficiency.
- Enhanced residue collection leads to much more energy from slash and stumps:
  - Primary energy from slash increases from 10 TWh to 33 TWh.
  - Primary energy from stumps increases from 0 TWh to 17 TWh.
  - Primary energy from logging residues thus expands nearly five-fold to 50 TWh.

Table 5.1 Wood flows in Sweden with current and enhanced use of residues (2015)

Wood flow element	Current residue shares	Enhanced residue use
Forest biomass growth in 2015	**436 TWh**	**436 TWh**
(Left in forest growing)	107 TWh	107 TWh
Cut (75% of growth increment)	**329 TWh**	**329 TWh**
Stemwood (55% of cut)	**181 TWh**	**181 TWh**
▪ Pulpwood (including bark)	87 TWh	87 TWh
· use for energy (DH)*	9 TWh	9 TWh
· use for energy (mills, other)	48 TWh	48 TWh
· use for energy (biofuel)	1 TWh	1 TWh
▪ Saw logs (including bark)	**80 TWh**	**80 TWh**
· sawnwood in construction	**22 TWh (60% of sawnwood)**	**22 TWh (60% of sawnwood)**
· other sawnwood use	14 TWh (40% of sawnwood)	14 TWh (40% of sawnwood)
· use for energy (DH)	6 TWh	6 TWh
· use for energy (mills, other)	12 TWh	12 TWh
▪ Firewood	9 TWh	9 TWh
▪ Discarded wood (DH)	5 TWh	5 TWh
Slash (20% of cut)	**66 TWh**	**66 TWh**
▪ Use for energy (DH)	**10 TWh (15% of slash)**	**33 TWh (50% of slash)**
▪ Left in forest rotting	56 TWh	33 TWh
Stumps (25% of cut)	**82 TWh**	**82 TWh**
▪ Use for energy (DH)	**0 TWh (0% of stumps)**	**17 TWh (20% of stumps)**
▪ Left in forest rotting	82 TWh	66 TWh
Total bioenergy use	**99 TWh**	**139 TWh**

Note: Energy uses are shaded in pink.

** DH = district heating*

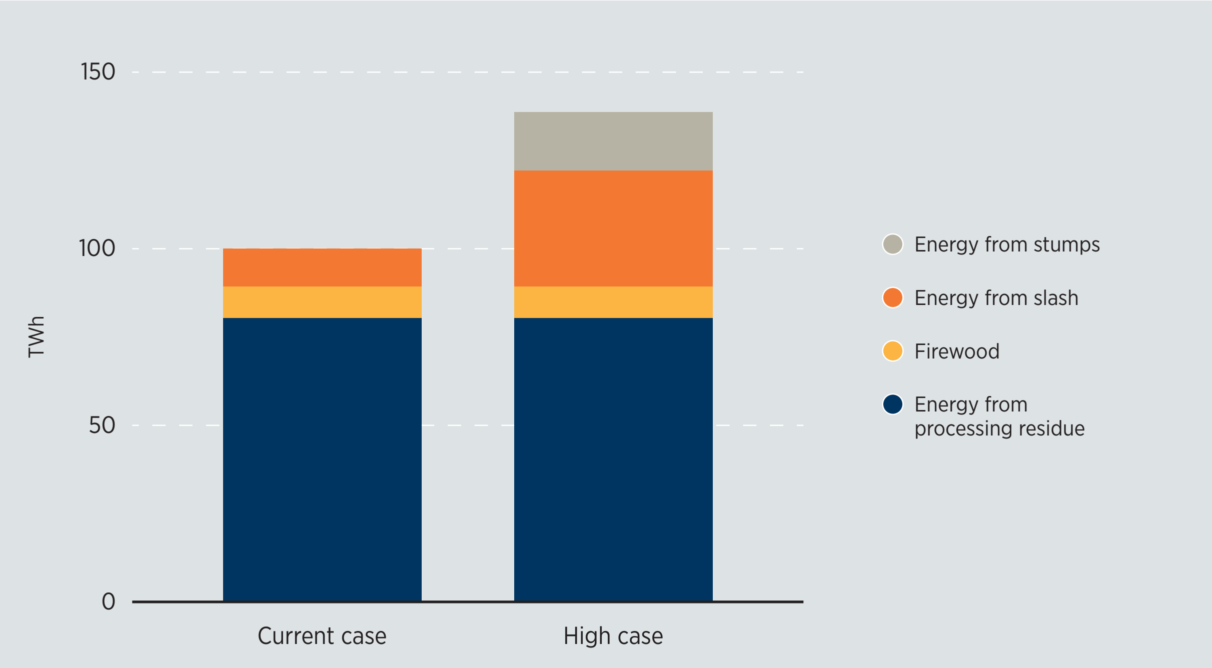
Source: IRENA and Svebio analysis of Swedish forest data

- Total primary energy extraction increases around 40%, from 99 TWh to 139 TWh.
- By comparison, Pål Börjesson at Lund University has estimated that Swedish forestry could theoretically provide 24 TWh to 42 TWh of additional biomass residues for energy today and 36 TWh to 74 TWh by 2050. He estimates an ecological potential for stump harvest of 30 TWh by 2050, but an economic potential of only 5 to 7 TWh.

Figure 5.2 shows the impact of wood use on carbon uptake.

- With both current and enhanced wood use, all wood mass cut is assumed to turn to carbon dioxide eventually, leaving the same amount of carbon stored in the forest:
    - Residues left in the forest would decay to carbon dioxide gradually. About half the biomass decomposes after 10 years for slash and 15 years for stumps.
    - Wood used in buildings would remain intact for at least several decades, but might later be recycled for other uses and eventually combusted for energy.
    - Residues and other wood combusted for energy would emit carbon dioxide immediately, though the emissions would be largely offset by displacing emissions from fossil fuel combustion, as explained below.
    - The 436 TWh of wood added to the forest equates to uptake of 150 $MtCO_2$, the 329 TWh of wood cut from the forest equates to emission of 113 $MtCO_2$, and the 107 TWh of wood remaining equates to net uptake of 37 $MtCO_2$.
- Wood use in buildings provides a substantial carbon credit:
    - Approximately 2.8 t of carbon dioxide emissions are avoided for every tonne of wood used in buildings, as described in the previous chapter.
    - Each tonne of wood mass contains about 5.33 MWh of primary energy, so that every million tonnes of wood contain about 5.33 TWh of energy.
    - Using 60% of sawn timber for buildings, 22 TWh or 4.1 Mt of wood displaces some 11.5 Mt of CO_2 emissions from manufacture of other building materials.

Figure 5.1 Annual energy from enhanced wood residue use (75% of forest growth cut)

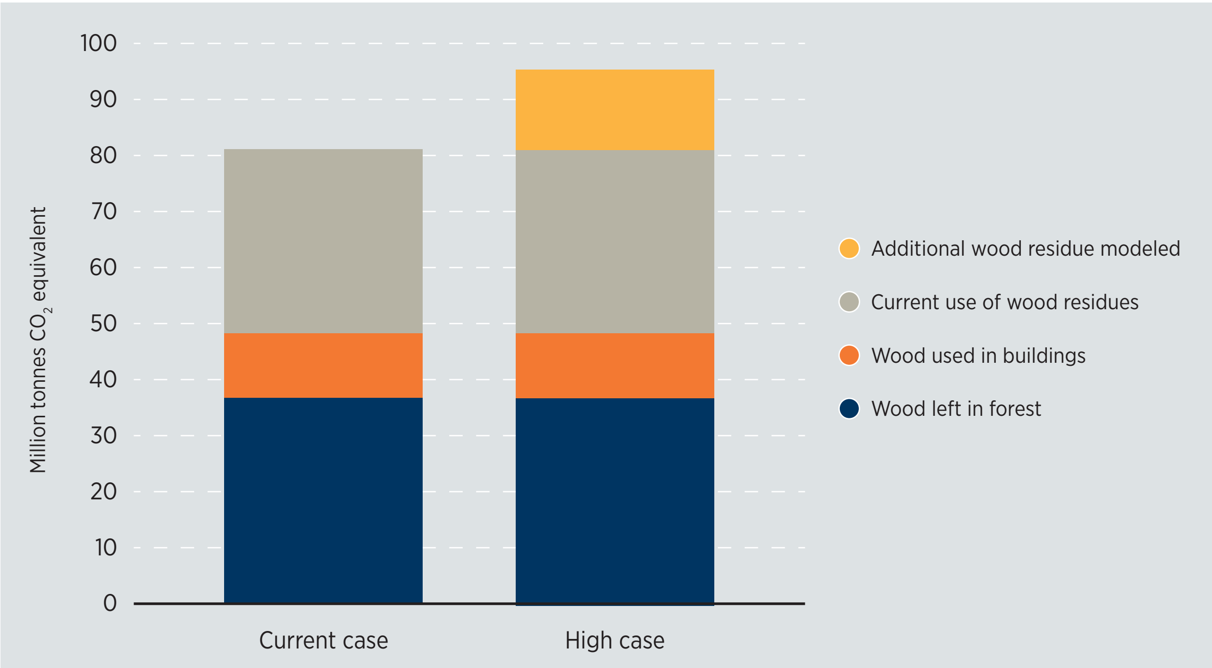


Source: IRENA and Svebio analysis of Swedish forest data

- Further emissions could be displaced by using a greater share of sawn wood in buildings or developing high-strength building materials from residues.
- Additional CO_2 could be stored for years or decades in waste wood or paper.

- Fossil fuel displacement provides a further carbon credit:
  - Fuel oil contains about 0.079 tC or 0.29 tCO_2 per MWh of primary energy.
  - If fuel oil is combusted at 80% efficiency, 0.36 tCO_2 are thus emitted per MWh of final energy generated, or 0.36 $MtCO_2$ per TWh of final energy generated.
  - Then assuming 69 TWh of wood processing residues and firewood are used in modern wood furnaces at 87% efficiency, they would generate 60 TWh of heat, displacing roughly 22 $MtCO_2$ (60 TWh x 0.36 $MtCO_2$/TWh = 21.6 $MtCO_2$).
  - And assuming 20 TWh of wood processing residues and discarded wood are used in district heating plants at 100% efficiency, they would generate 20 TWh of heat, displacing roughly 7 $MtCO_2$ (20 TWh x 0.36 $MtCO_2$/TWh = 7.2 $MtCO_2$).
  - Further assuming logging residues are also used for district heating at 100% efficiency, amounting to 10 TWh with current residue extraction and 49 TWh with enhanced residue extraction, additional emissions from fuel oil are avoided – about 4 $MtCO_2$ currently and 18 $MtCO_2$ with enhanced extraction.
  - Fossil jet fuel contains 0.32 tCO_2 per MWh of primary energy, so 1 TWh of residues converted to bio jet fuel with 38% efficiency would yield 0.38 TWh of bio jet fuel, displacing 0.12 $MtCO_2$ (0.38 TWh x 0.32 $MtCO_2$/TWh = 0.12 $MtCO_2$).
  - Total avoided emissions from fossil fuel displacement would then amount to 33 $MtCO_2$ with current residue use and 47 $MtCO_2$ with enhanced residue use.
- In all, net carbon uptake in an initial year would rise from around 81 $MtCO_2$ with current wood use to 95 $MtCO_2$ with enhanced wood use, an increase of one-sixth.

Figure 5.2 Annual carbon uptake in Swedish forestry (75% of forest growth cut)



Source: IRENA and Svebio analysis of Swedish forest data

Harvesting a greater share of the forest wood increment

What would be the impact on energy use and carbon uptake of harvesting a greater share of the forest wood increment each year? Suppose that 100% of Sweden's annual forest growth were harvested instead of 75%, still allowing a constant accumulation of carbon in the forest wood stock, with no net increase or decrease in forest wood stock over time. Wood flows then become as shown in Table 5.2 in the initial year, one-third more than in Table 5.1.

- Primary energy input in the initial year grows to 132 TWh with current wood use and 184 TWh with greater use of wood for construction and fossil fuel displacement.
- Carbon uptake in the initial year declines from 81 $MtCO_2$ to 61 $MtCO_2$ with current wood use patterns and from 95 $MtCO_2$ to 80 $MtCO_2$ with enhanced use of wood.
  - Mass left in the forest from the year's growth declines from 37 $MtCO_2$ to zero.
  - If all extra sawn wood production is used for construction, with other uses constant, carbon uptake from wood use grows from 12 $MtCO_2$ to 18 $MtCO_2$.
  - Fossil fuel displacement grows from 33 $MtCO_2$ to 43 $MtCO_2$ with current residue use rates and from 47 $MtCO_2$ to 62 $MtCO_2$ with enhanced residue use.

The analysis shows that total fellings, residue harvest rate and building share of wood use have major impacts on energy extraction and carbon balances. As Sweden is not a planned economy, most of the forests and buildings are privately owned. Decisions on both total fellings and residue recovery are dispersed among numerous forestry companies and hundreds of thousands of small-scale forestry owners, based on government regulation, advice and market prices. Decisions on wood use in buildings are taken by thousands of builders and architects, as informed by the preferences of millions of renters and owners.

Temporal trade-offs of increasing wood removals as share of forest growth

It should be sustainable, with respect to wood energy use and forest carbon uptake, to harvest up to the full amount of forest growth each year. By definition, the forest would not be decreasing in volume, so the annual energy extraction and carbon uptake would also not diminish. In fact, enhanced replacement of older, slower-growing trees with younger, faster-growing trees, perhaps combined with focused fertilisation to boost wood yields, could allow growth to continue. However, there are temporal trade-offs involved in increasing the share that is harvested. A greater harvest share would raise the amount of energy taken from the forest initially, but it would allow less wood to accumulate in the forest over time. So taking too high a share could lead to a reduced amount of forest growth available for harvest.

The trade-off in energy terms is illustrated in Figure 5.3. In simplified terms, forest mass and extractable energy are growing around 1% per annum at present, with fellings comprising 75% of growth. This is shown by green lines, the solid one representing base case energy extraction, starting at 99 TWh in 2015, the dashed one showing high case energy extraction with enhanced use of residues, starting at 139 TWh. If the entire forest growth were felled each year, the volume of forest would remain constant.

This is shown by red lines, the solid one representing primary energy available at current logging residue use rates, starting and remaining at 132 TWh, the dashed one showing primary energy available with enhanced residue use, starting and remaining at 184 TWh. After around three decades, the green and red lines cross. Afterwards, potential energy extraction is greater at today's 75% felling rate than it would be if the felling rate were increased to 100%. (In reality, the orange lines would have an upward slope, since replacing more old trees with new ones would enhance wood growth on the land cleared, so the lines would take longer to cross.)

Table 5.2 Hypothetical wood flows in Sweden with all forest growth harvested (2015)

Wood flow element	Current residue shares	Enhanced residue use
Forest biomass growth in 2015	**436 TWh**	**436 TWh**
(Left in forest growing)	0 TWh	0 TWh
Cut (100% of growth increment)	**436 TWh**	**436 TWh**
Stemwood (55% of cut)	**240 TWh**	**240 TWh**
▪ Pulpwood (including bark)	115 TWh	115 TWh
· use for energy (DH)*	12 TWh	12 TWh
· use for energy (mills, other)	63 TWh	63 TWh
· use for energy (biofuel)	1 TWh	1 TWh
▪ Saw logs (including bark)	**106 TWh**	**106 TWh**
· sawnwood in construction	**22 TWh (60% of sawnwood)**	**22 TWh (60% of sawnwood)**
· other sawnwood use	14 TWh (29% of sawnwood)	14 TWh (29% of sawnwood)
· use for energy (DH)	8 TWh	8 TWh
· use for energy (mills, other)	16 TWh	16 TWh
▪ Firewood (other energy use)	12 TWh	12 TWh
▪ Discarded wood (DH)	7 TWh	7 TWh
Slash (20% of cut)	**87 TWh**	**87 TWh**
▪ Use for energy (DH)	**13 TWh (15% of slash)**	**44 TWh (50% of slash)**
▪ Left in forest rotting	74 TWh	43 TWh
Stumps (25% of cut)	**109 TWh**	**109 TWh**
▪ Use for energy (DH)	**0 TWh (0% of stumps)**	**22 TWh (20% of stumps)**
▪ Left in forest rotting	109 TWh	87 TWh
Total bioenergy use	**132 TWh**	**184 TWh**

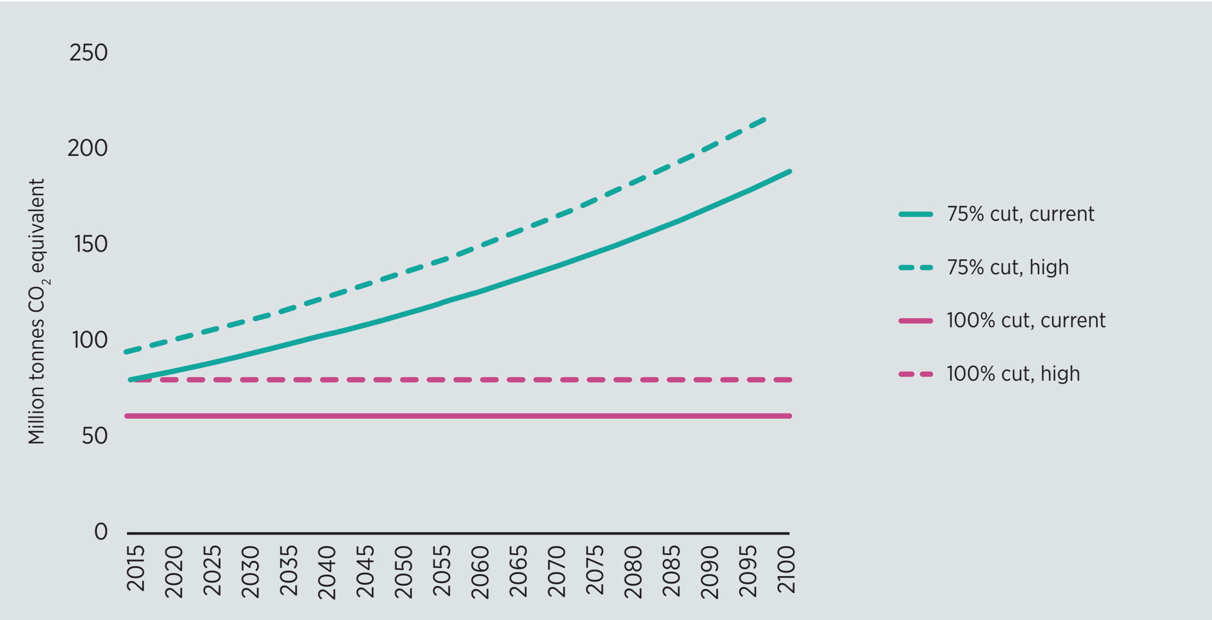
Note: Energy uses are shaded in pink.
** DH = district heating*
Source: IRENA and Svebio analysis of Swedish forest data

The trade-off in carbon terms is illustrated in Figure 5.4. With forest mass and extractable energy growing 1% per annum and 75% of forest growth felled, as at present, shown in green, carbon uptake in forests starts at 81 Mt CO_2-eq in 2015 with base case energy extraction and 95 Mt CO_2-eq with enhanced use of residues. With the entire forest growth felled each year, shown in red, carbon uptake starts and remains at 61 Mt CO_2-eq at current residue use rates and 80 Mt CO_2-eq with enhanced residue use. (The red lines would actually have an upward slope, even though all forest growth is extracted each year, since enhanced energy extraction from faster replacement of old trees with new ones would make available additional wood for displacement of construction materials and fossil fuels.)

Figure 5.3 Primary energy from forests with different harvest rates and wood use

Source: IRENA and Svebio analysis of Swedish forest data

Figure 5.4 Carbon uptake from forests with different harvest rates and wood use



Source: IRENA and Svebio analysis of Swedish forest data

Enhancing growth in the forest wood increment

Since the Second World War, the increment in the Swedish forests has increased by an average of 1% per year. This is mainly due to better forest management with a resulting increase in forest wood density; the forest area has only increased marginally. Better management has brought improvements in plant material, training, planning and forestry methods based on research and "learning by doing". There is no sign that forest growth will stop or be reversed, though the rate of growth might well decline due to an increasing share of older, slow-growing stands. Indeed, higher temperatures from climate change are expected to boost growth by prolonging the growing season.

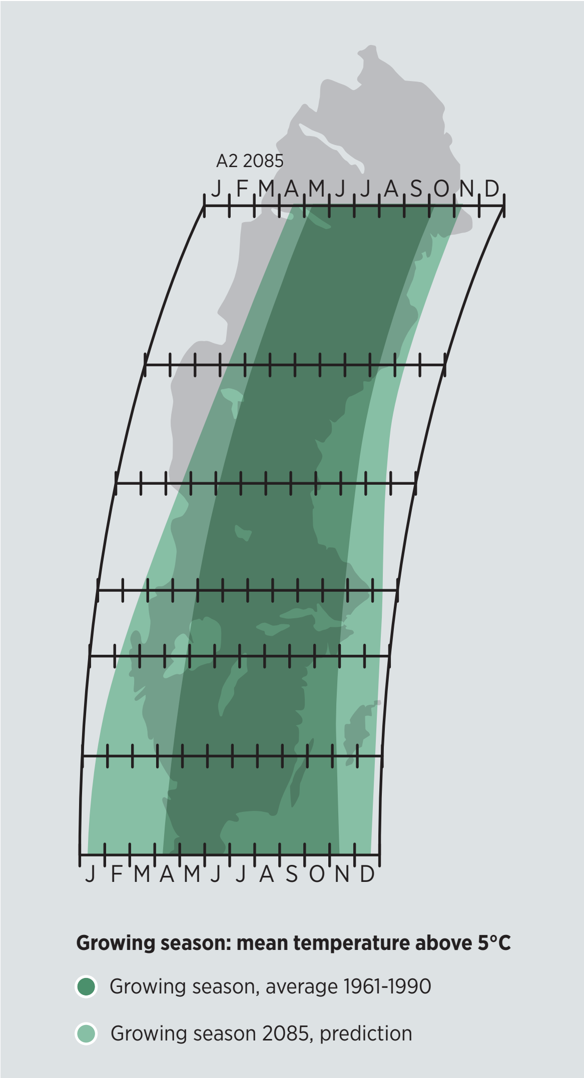
Figure 5.5 shows how climate change might lengthen the growing season in Sweden. The growing season is defined as the period when the mean temperature is more than 5°C. The dark green area shows the growing season in the last four decades of the 20th century at different latitudes. The light green area shows the projected growing season in 2085. Both the longer vegetation period and higher mean temperatures will increase forest growth. There may also be greater losses from storms and fires as rising temperatures make them more intense.

Lundmark *et al.* (2014), in their analysis of the climate benefits of Swedish forests, show that in a baseline scenario the harvest of stemwood increases 12% by 2035 compared to 2005. But in an "increased growth scenario" the stemwood harvest could increase 56% by 2035. This would represent a 39% boost over the 2035 baseline. Apportioned over a 30-year period, such a boost would amount to 1.3% per annum on an uncompounded basis. In this context, a 1% annual increase in the annual growth increment appears quite reasonable and even conservative.

Some forest researchers suggest a strategy in which the foresters use more intensive methods than today, using developed plant material and increased use of forest fertilisation. The growth levels could then increase substantially compared to traditional forestry. These fast-growing plantations would probably use spruce on selected good soils. Another alternative is fast-growing poplars using earlier abandoned farmland.

An experiment by SLU at a spruce stand Flakaliden, a village outside Umeå in northern Sweden, shows that fertilisation can cause the growth rate to double. Nitrogen fertiliser was applied to maximise growth with the restriction that there would be no increase of runoff to surrounding streams. From the time that fertiliser was first applied in 1987, the growth rate increased dramatically, as can be seen from the pattern of rings in the stem cross-section, in which each ring represents one year's growth.

Figure 5.5 Increased growing seasons in Sweden due to predicted climate change

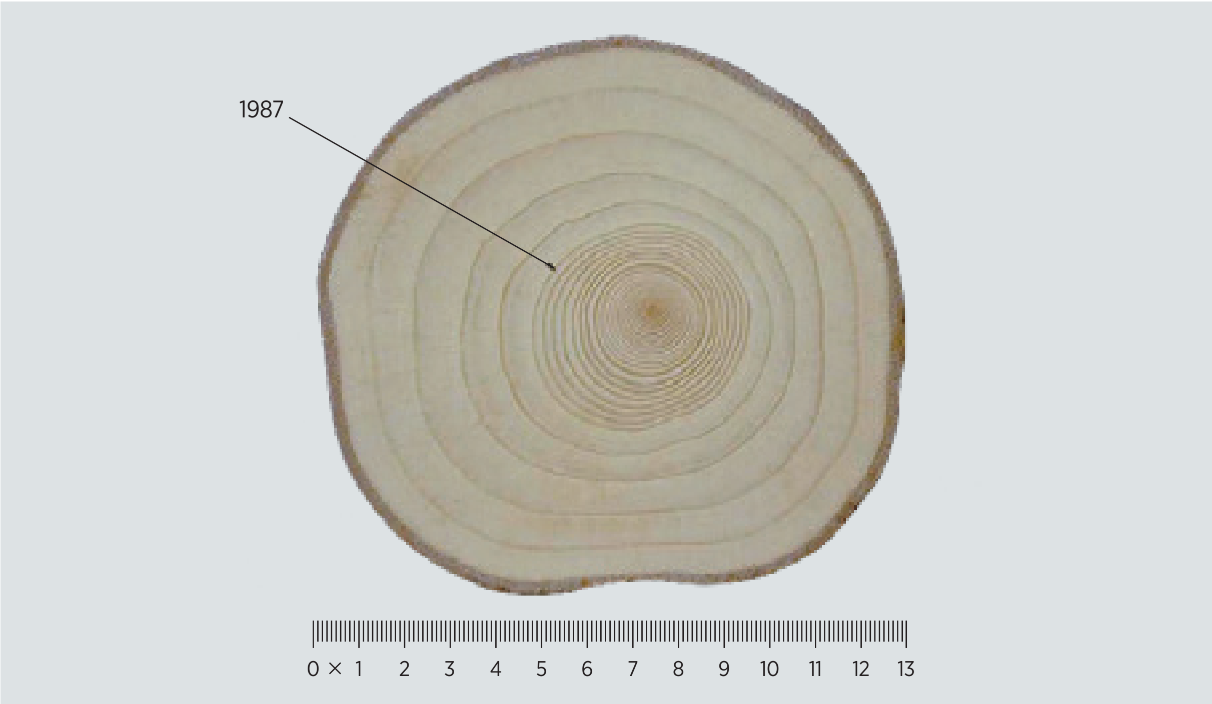


Source: Fogelfors et al. (2008)

If 5% of Swedish forest area could be used for such plantations, it would increase the overall forest growth by 5%. In the highest case assessed above, this would be the equivalent of a further 9 TWh of wood energy per annum (5% of 184 TWh). It would take a full forest rotation until this potential could be utilised fully.

The lesson learned from Nordic forestry is that it is possible to find a balanced solution in which the harvesting level over time is somewhat lower than growth, with year-by-year increasing harvests combined with a continuous increase in the carbon stock.

Figure 5.6 Fertiliser speeding growth of spruce (stem shown in cross-section)



Source: SLU

6 EUROPEAN POTENTIAL FOR FOREST BIOMASS PRODUCTION AND CARBON UPTAKE

With perspectives offered by Nordic forestry in Sweden, it is interesting to explore the broader potentials for biomass production and carbon uptake from forests in Europe.

In this chapter, these potentials are roughly estimated using two different approaches. The focus is on the 28 member states of the European Union (EU28) and their neighbours.

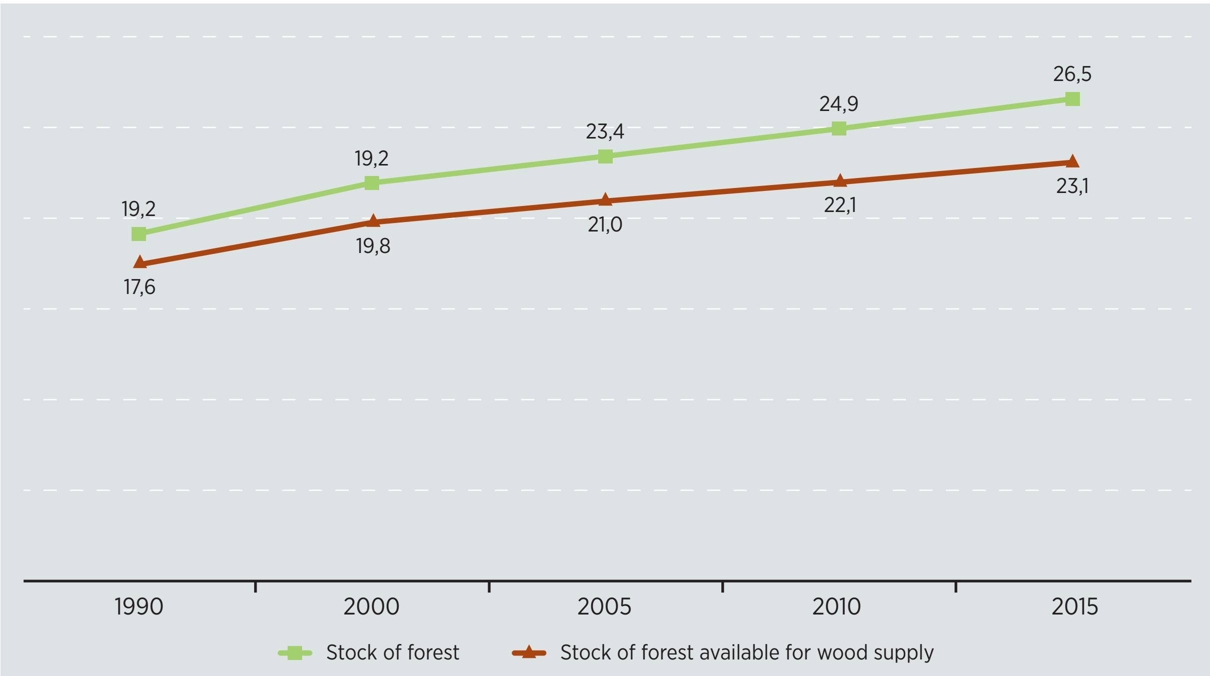
Forests in the European Union

The EU28's forest area (forests and other wooded lands) totals 181 Mha and comprises 42.6% of its total land area. Over the last 25 years, this forest area grew 5.2% or 0.2% per year (AEBIOM, 2017b, based on Eurostat). It was stable in most member states but grew 55% in Ireland, 32% in Spain, and between 10% and 25% in several others (United Kingdom, Lithuania, Hungary, Bulgaria, Croatia and Italy). The absolute increase was greatest in Spain, where the forest area grew by 4.6 Mha.

As in the Nordic countries, the standing stock in forests has been expanding throughout the EU. Between 1990 and 2010, the standing volume grew 38% from 19.2 billion m^3 to 26.5 billion m^3 while stock available for wood supply grew 31% (AEBIOM, 2017b).

For biomass harvest, the interesting number is not forest area or standing stock, but yearly forest growth. Total growth in EU28 forests available for wood supply was 784 Mm^3 in 2010 (Forest Europe, 2015). The harvest was 535 Mm^3, or 68% of the growth, so 32% of the growth was left in the forests. With a similar pattern persisting over the years, the standing stock in forests has continuously increased.

Figure 6.1 Increase of growing stock in EU forests



Source: AEBIOM (2017b)

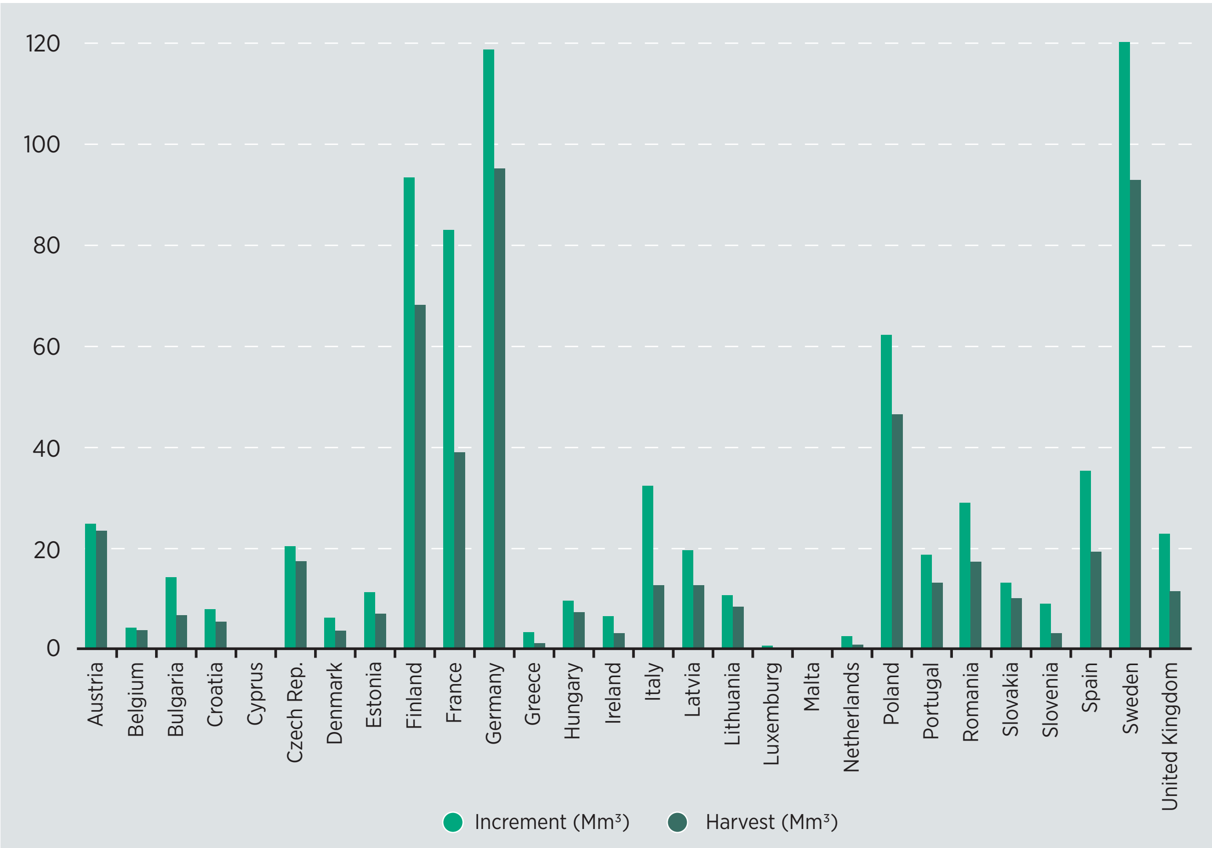
The harvesting level varies greatly by country, from 37% in Slovenia to 94% in Austria. It also varies over time due to changes in industrial wood demand and climate.

Harvesting levels could presumably increase to 100% of forest growth without causing the forests' productive capacity or carbon uptake to diminish. An even higher harvesting rate could make sense where the age composition is very unfavourable; for example, in places where forests are old and trees are growing very slowly. On the other hand, a lower harvesting level can be appropriate in recently afforested areas where younger trees predominate.

If harvest levels were increased to 100% in all EU28 countries, an extra 252 Mm^3 of stemwood would be obtained. Those countries with the greatest potential to increase the *amount* of stemwood harvest, in descending order, are France, Italy, Sweden and Finland. Those with greatest potential to increase the *share* of stemwood harvest are in southern Europe (Cyprus, Greece, Italy, Bulgaria and Spain) and Slovenia, France, Netherlands, Ireland and the United Kingdom. Bioenergy potential would also increase:

- If this stemwood were used for sawn wood and pulpwood in the same proportions as in Sweden, about half of the biomass would ends up in products, and half would be biomass *processing* residues (such as sawdust, bark, chips, black liquor and tall oil). As 1 m^3 of wood has an energy value of around 2 MWh, the total energy value of these processing residues would be 252 TWh.
- To this volume, *logging* residues from the fellings – tops, branches and possibly some stumps can be added. If an added volume of 25% of the stem volume is assumed, it would mean another 63 Mm^3, with an energy value of 126 TWh.
- Residues would thus provide 378 TWh of energy in all.

Figure 6.2 Growth and harvest of forests in EU28 countries



Sources: Forest Europe (2015), Swedish Forest Inventory

Table 6.1 Potential from 100% harvest in all EU28 countries (increase)

	Added volume	Energy value
Stemwood	252 Mm^3	504 TWh
Processing residues	126 Mm^3	252 TWh
Logging residues	63 Mm^3	126 TWh
Total residues	189 Mm^3	378 TWh
Total harvest	315 Mm^3	630 TWh

Note: "Industrial residues" are part of the stemwood volume.

Potential within the existing harvesting system

These numbers are only for the added harvesting level. There is also potential within the existing forest industry. This potential is harder to assess in the absence of a country-by-country situational analysis. Most of the processing residue from sawmills, pulp mills and woodworking industry is utilised already. However, limited amounts of logging residues are used (tops, branches, stumps and thinning material). Hence there is substantial potential to use more logging residues from existing harvesting sites.

The total harvest of stemwood (sawlogs and pulpwood, excluding fuelwood) was 345 Mm^3 in 2016 (FAOSTAT/AEBIOM statistics).[1] With one-quarter of stemwood recovered as logging residue, this would provide 86 Mm^3 of biomass with an energy content of 172 TWh. Some of this is already collected in Sweden (10 TWh), Finland (8 TWh) and Baltic countries (Estonia, Latvia and Lithuania). Some is also collected in other countries as fuelwood for heating. Absent detailed numbers on current collection of logging residues in most of Europe, it seems reasonable to suppose a net potential increase on the order of 100 to 150 TWh of energy from 50 to 75 Mm^3 of wood. How much of this can be collected depends on how much is needed for soil protection and how much it costs to remove from the forest.

Other resources

As in Sweden, the present study presumes there is potential in the EU28 from non-commercial growth like wood from landscaping and roadsides, conservation management, and urban areas. Much is probably harvested as small-scale firewood, but there may be unused potential.

In southern Europe, there is a large need for measures for fire prevention in forests and areas that are recorded as "other wood-lands" in the statistics. These measures can include harvesting of undergrowth and thinning of dense and dry stands. This report does not allocate any numbers to these resources.

Potential in the rest of Europe

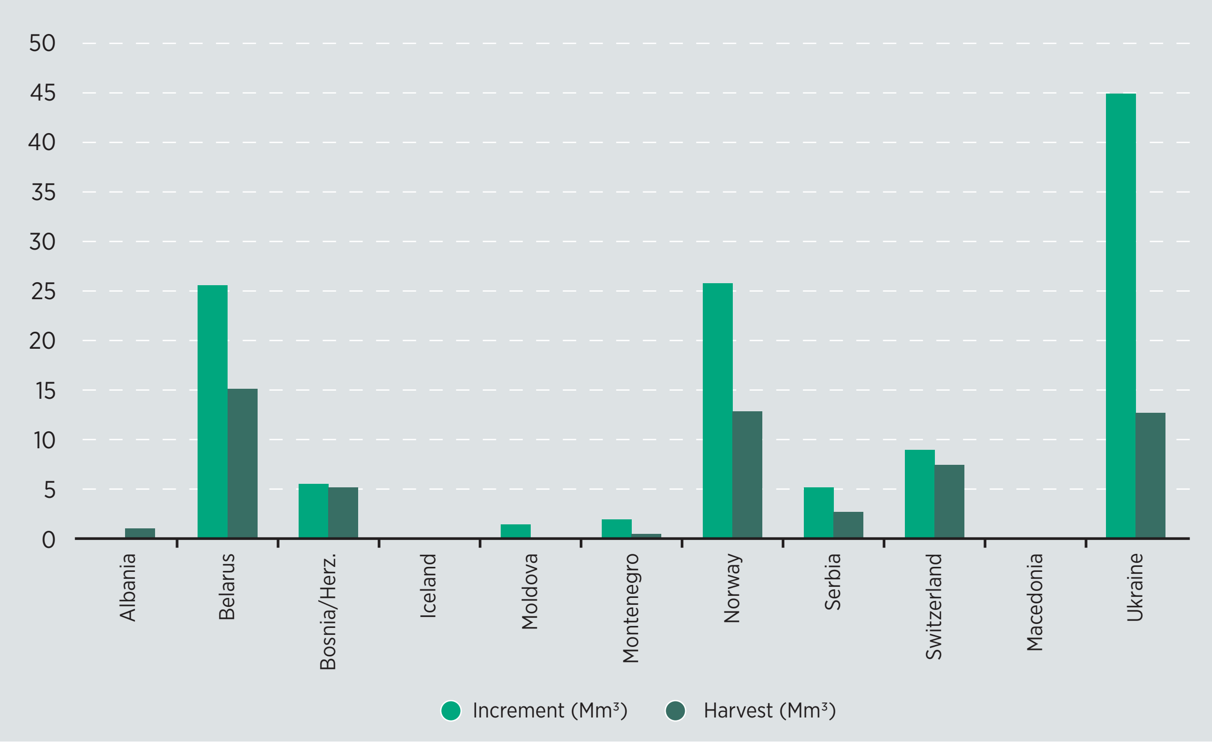
To get a full picture of the potential in Europe, the biomass resources in neighbouring countries – some of which may become EU member states in the coming years – should be considered. Figure 6.3 compares forest growth (increment) and harvest (fellings) in these countries. Together, they could obtain an additional harvest volume of 46 Mm^3 at a 90% harvest level. The bulk of this potential is in Ukraine, Norway and Belarus, but there is also notable potential in Switzerland, Bosnia and Serbia.

1. There is a difference in the forestry statistics between "fellings" and "total roundwood volumes", which explains the difference between these numbers and the numbers for harvests.

Using the same kinds of calculations as for EU28, an added bioenergy potential of 57.5 Mm^3 or 115 TWh can be found if all stemwood from increased harvests were used for energy, or 69 TWh if only the residues from this added volume were used. There is also potential to increase the collection of forest residues at current harvest levels.

Europe could obtain substantially more energy from forest residues

Figure 6.3 Potential in the rest of Europe (excluding Russia and Turkey)



Source: Forest Europe (2015)

Table 6.2 Potential from 100% harvest in the rest of Europe (excluding Russia and Turkey)

	Added volume	Energy value
Stemwood	62.0 Mm^3	124 TWh
Industrial residues	31.0 Mm^3	62 TWh
Forest residues	15.5 Mm^3	31 TWh
Total residues	46.5 Mm^3	93 TWh
Total added harvest	77.5 Mm^3	155 TWh

Note: Russia and Turkey are excluded.

Summary for Europe – EU28 and neighbouring countries

In summary, European forests have substantial potential to boost bioenergy production, including:

- 471 TWh of additional primary energy from logging and processing residues, if harvests were increased from current levels to 100% of forest growth each year
  - of which, 378 TWh in the EU28
  - and 93 TWh in neighbouring countries.
- 115 TWh or so of additional primary energy from raising the share of logging residues collected, at current levels of harvest as share of forest growth
  - of which, 100 TWh in the EU28
  - and 15 TWh in neighbouring countries.

Climate effects

The climate impacts of enhanced wood production depend on how the wood is utilised. To illustrate the likely range of impacts, this report considers two contrasting cases. In one case, the whole added stemwood volume is used for construction. In another case, stemwood is used roughly as in Sweden: half for sawn timber and half for paper production. In both cases, the residues from logging and from stemwood processing are used for energy.

In the first case, where all added stemwood volume is used for construction:

- Added stemwood in EU28 is 252 Mm^3 with 504 TWh of energy.
- About half the stemwood, or 126 Mm^3, is converted to products, while the rest becomes processing residue, and the entire product portion is sawn wood. Assuming, as in Chapter 5, that each cubic metre of wood used in buildings avoids 1.8 t of CO_2 emissions, the substitution of building material reduces emissions by 227 Mt.
- For the remaining 478 TWh of residues, including those from existing forestry, if substitution for fossil fuels reduces emissions by 0.36 Mt of CO_2 per TWh as explained in Chapter 5, displacement of fossil fuels reduces emissions by 172 Mt.
- Emissions reductions thus equal 399 Mt CO_2.

In the second case, where half of stemwood is used for construction and half for paper, emissions reductions (neglecting shorter-term carbon storage in paper) would be lower:

- Added stemwood in EU28 still amounts to 252 Mm^3.
- Half the stemwood (126 Mm^3) is still available for products, but only half of this half becomes lumber that substitutes for other building materials, reducing emissions by 113 Mt of CO_2, while the other half becomes pulp.
- Remaining residues still replace fossil fuels, reducing emissions by 172 Mt.
- Emission reductions thus equal just 285 Mt of CO_2 (about 29% less).

Adding potential from neighbouring countries would increase these figures by one-fifth.

The conclusion is that from a climate standpoint it makes sense to use the wood first as material and then as energy. In reality, the wood is used in parallel, both for products and for energy. A refinement of the knowledge of substitution effects is needed.

Other studies and calculations

AEBIOM reports a use of 91.4 Mtoe (million tonnes of oil equivalents) of solid biomass in 2015 in the EU. This is equivalent of 1064 TWh or, assuming 2 MWh of energy per cubic metre of wood, 532 Mm^3 of wood. That would be almost the same as the total harvest in EU28 forests. But not all the biomass used came from forests, so the amount must be adjusted.

- The energy content may be higher than our assumed 2 MWh/m^3 wood; at least this is true for much of the broadleaf wood. With an energy value of 2.5 MWh for wood, the volume would be reduced by 20% to 425 Mm^3.

- Not all of the solid biomass is wood from forests; some is residue from farms, landscaping, urban areas and other areas outside forests. According to Mantau (2012), this supply was around 33.4 Mm^3 in 2010.
- Imports to the EU, mainly of pellets, which are around 60 TWh or the equivalent of 24 Mm^3 to 30 Mm^3 of wood, must be taken into consideration.
- Taking into account of all these factors, the total amount of biomass fuel taken from EU forests could be adjusted downward to something like 368 Mm^3.

Mantau (2012) made a flowchart that has been used by many others to show the wood flows in Europe. His total number for wood for energy is 337 Mm^3, which would yield 674 TWh of primary energy at 2 MWh/m^3 or 842 TWh at 2.5 MWh/m^3.

Mantau's chart (Figure 6.4) includes the EU27 (Croatia had not yet joined the EU). The net increment was 1 277 Mm^3. This is the total biomass growth above ground, including not only stemwood but also stumps, branches, tops (slash) and small trees from thinning. The numbers are based on The EUwood project that was finalised in 2010 (Verkerk *et al.*, 2010).

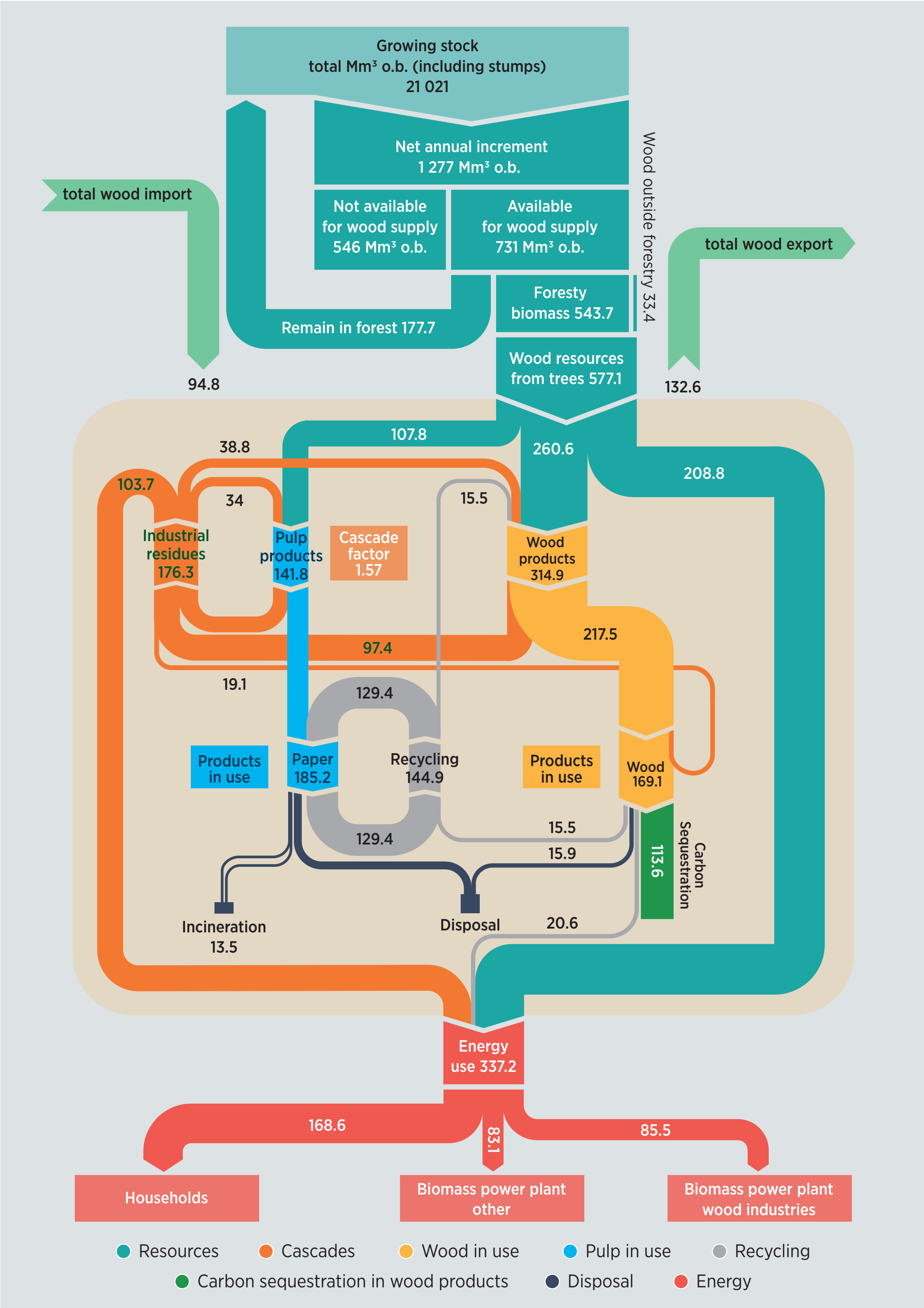
- Of the growth, 731 Mm^3 or 58% is considered "available for wood supply" (AWS). This includes stemwood, logging residues from stemwood harvest, and stumps.
    - Three-quarters of AWS (577.1 Mm^3) is harvested, including stemwood, bark, some residues and some wood from outside forests (33.4 Mm^3). Hence, just 43% of the total forest growth (75% x 58%) is utilised.
    - One-quarter of AWS is not harvested and remains in the forest.
- The other 42% of growth is considered "not available for wood supply" (NAWS). This includes trees that cannot be harvested for environmental or economic reasons, as well as residues that need to be left in the forest for soil protection.
- Unharvested forest residues and stumps are thus divided in the chart between AWS and NAWS. Their volume is large; the EUwood project found 52% of the total biomass potential lies in stems, 26% in stumps and 21% in logging residues.
- The AWS or potential harvest of 731 Mm^3 assumes "medium mobilisation" in which strict limits are placed on harvest to protect nature and the soil, and few stumps are removed. If looser restriction were applied, as in a "high mobilisation" case, the potential could grow to 898 Mm^3 of biomass (wood and harvested residues).
- About one-quarter of the wood available for wood supply "remains in forest". In Figure 6.4, the arrow up to the growing stock implies that this volume is the un-harvested part of the increment, or around 25% of the growth – similar to the situation in Sweden.
- It is not clear, however, where Mantau's chart places unharvested forest residues, which account for nearly half the available biomass; Mantau notes 21% of this lies in logging residues and 26% in stumps (Verkerk *et al.*, 2010).

Mantau found that European forests in 2010 supplied 337 Mm^3 of wood for energy (central red flow at bottom of Figure 6.4) to households and power plants, including:

- 208.8 Mm^3 of primary wood fuels (right-most green flow in Figure 6.4), of which 129.8 Mm^3 was household firewood and 39.2 Mm^3 was forest (logging) residues
- 103.7 Mm^3 of industrial (processing) residues (left-most orange flow in Figure 6.4)
- 20.6 Mm^3 of post-consumer wood waste (skinny grey thread in Figure 6.4).

If firewood is excluded, the use of forest residues and industrial residues was 207 Mm^3. At the same time, 368.4 Mm^3 of wood was supplied to the forest industry. Compared to the Swedish case, the share of biomass for energy in relation to the wood to the forest industry is much lower for the EU as a whole.

Figure 6.4 Wood flows in Europe



Note: o.b. = over bark, which means stemwood volume including bark.
Source: Mantau (2012)

Wood energy potentials may be calculated based on Mantau's chart as follows:

- With an increase of the harvesting level from 75% to 100% of the AWS, the harvest would increase by 178 Mm^3, to 731 Mm^3. This would include both stemwood, harvesting residues and stumps corresponding to the EUwood medium mobilisation level. The increase would correspond to an increased energy supply of 366 TWh, assuming that each cubic metre contains 2 MWh.
- In the high mobilisation scenario, the total harvest would be 898 Mm^3 of wood and residues, or 167 Mm^3 more than in the medium mobilisation scenario. The energy value of this added volume is 334 TWh.
- The high mobilisation scenario places a stronger emphasis on wood for energy, with fewer restrictions for the harvest of stumps and residues and better mobilisation of marginal wood. This is a result of measures to organise small-scale forest owners to increase their motivation to harvest.
- It is unclear how the EU wood report apportions stemwood and residues, but assuming that roughly half of the added volume is harvesting residues, while about half the remaining stemwood becomes processing residues, then 525 TWh of biomass for energy would be added in the high mobilisation scenario (75% of total added potential of 700 TWh, derived by adding 366 TWh from moving to 100% harvest and 334 TWh from moving to high mobilisation).

Matthews *et al.* (2015) assessed several scenarios of bioenergy potential for the European Commission to inform its Renewable Energy Directive (RED-2):

- They found EU wood potential in 2050 could reach 1 122 Mm^3, including 842 Mm^3 of stemwood and 280 Mm^3 of harvesting residues. Assuming half the stemwood ends up as final products and half (421 Mm^3) as processing residue, total residues would amount to 701 Mm^3 with 1 402 TWh of energy potential.
- But in their scenario, they limited harvest to 70% of this maximum, or 786 Mm^3 of wood including 590 Mm^3 of stemwood (of which some 295 Mm^3 would become processing residue) and 196 Mm^3 of harvesting residues, reducing energy wood potential to 491 Mm^3 or 982 TWh .

Conclusions

As shown in Table 6.3, the present study's estimate of EU-wide wood energy potential is comparable to estimates of EU-wide wood energy potential made in other studies.

It is possible to increase the use of biomass for energy from forestry in EU28 by 43% by increasing the harvest to 100% of the growth, according to the calculations in this study. This assumes that all of the industrial-quality wood goes to industry and that the current EU production of forest-based biomass for energy is 370 Mm^3. Other studies confirm that an increase of this magnitude is possible.

- If some of the added stemwood harvest is used for energy, the energy potential is greater. One possibility is to use the added saw logs for climate-friendly construction, but not to increase the production of paper pulp.
- The potential in the EU's neighbouring non-EU countries, excluding Russia and Turkey, is about 21% of the EU increase.
- This calculation does not consider the on-going acceleration of growth in many countries due to better forest management, increased forest areas and climate change. Nor does it consider how annual forest growth may increase due to a more favourable age composition when harvesting is increased. All of these factors together will increase the potential considerably.
- Finally, this calculation does not include increased volumes of recovered waste-wood and other bio-based waste flows, which would be a direct result of the increased use of wood and other wood-based products. This potential will occur over a longer period, but some of it would be available in the short term. If half of the products end up as waste for energy, paper in household waste and recovered waste wood, this will add another 100 TWh per year.

Benefits from better utilisation of biomass

In the Nordic countries, almost all biomass is used either in CHP or heat plants. Flue gas condensation is applied in most major plants. This means that energy losses are very limited; the energy efficiency is typically 90% to 95%. The plants are connected to district heating grids in larger towns and cities.

On a European level, some of the biomass is still used in stand-alone power plants. These plants employ condensing technology in which excess heat is lost, so they are just 30% to 40% efficient in their energy conversion. Substantial energy benefits would be gained if all biomass for energy were used in CHP plants, district heating/cooling plants or modern home furnaces, which are typically more than twice as efficient.

Table 6.3 Comparison of estimates of biomass potential in Europe

Source of estimate	Energy value
Current study (IRENA and Svebio) 100% harvest	1058 TWh
Mantau 75% harvest, medium mobilisation	674 TWh
Mantau 100% harvest, high mobilisation	1374 TWh
Matthews with 70% cap on use of potential	902 TWh
Matthews maximum potential	1402 TWh

7 BOREAL FOREST BIOMASS POTENTIAL IN CANADA AND RUSSIA

Canada and Russia have the largest boreal forest areas outside of western Europe. There are clear similarities in the forests of these countries and how they are managed, as well as differences:

- The forest areas are very large: hundreds of millions of hectares.
- The forest growth rate is less than half that in Sweden and Finland.
- Natural disturbances like fires and infestations lead to large losses of carbon.
- Only a limited part of the forests is actively managed; large areas are wilderness.
- Most managed forest (as well as protected forest) is publicly owned.
- The use of biomass for energy from forests is still relatively low.
- Forest management regulations and certification requirements differ substantially.

Canada and Russia each have large potential to increase the harvest of wood and to use more biomass for energy. Both countries export forest products, and mobilisation of wood for these products depends on market conditions and incentives in importing countries. However, both countries also use large amounts of fossil fuels, for which expanded domestic use of wood for energy could substitute while reducing carbon dioxide emissions. In a longer perspective, there is potential both to increase forest growth rates and to reduce forest losses, hence considerably to improve the carbon balance in forestry. However, large uncertainties remain concerning the technical, environmental and economic feasibility to achieve these objectives.

CANADA

Canada has nearly one-quarter (24%) of the world's boreal forests. As of 2005, Canadian forests had some 47.3 billion m^3 of growing stock, of which around 30 billion m^3, or 63%, were in boreal forests. Forests and wooded lands cover 397 Mha, of which 226 Mha, or 57%, are managed forests. Canada's forests are mainly publicly owned, primarily by the provinces; only 6% are privately owned. Canada's forest inventory tracks areas and stocks, but data on growth rates which are being compiled from the National Forest Inventory (NFI) are not yet publicly available.

The yearly harvest is 160 Mm^3, or an average of 0.7 m^3 per ha of managed forestland. The area harvested each year is only 0.35% of the managed forest area. The volume of wood harvested each year is just 0.34% of the total standing forest volume. Table 7.1 shows a comparison of these numbers with the Swedish numbers.

The table shows that the harvesting intensity is several times higher in Swedish forestry than in Canadian forestry. The share of forest area harvested is 3.5 times as great, and the harvested share of the total standing volume is 8 times as great. This implies a large theoretical potential to mobilise more wood in Canada for fossil-free materials and energy.

Table 7.1 Comparison of forest harvests in Sweden and Canada

	Total forest area	Annual harvest area	Harvest share of area	Total forest volume	Annual harvest volume	Harvest share of volume
Sweden	28 Mha	0.20 Mha	0.71 %	3 300 Mm^3	90 Mm^3	2.73 %
Canada	397 Mha	0.78 Mha	0.20 %	47 320 Mm^3	160 Mm^3	0.34 %

Because Canada does not report the annual forest growth increment, it has to be inferred from other numbers. Over time, the increment is equal to the drain plus change in stock. The drain is the net removals (harvest) and the losses from natural disturbances. The carbon removals refer to above-ground biomass. The drain from natural disturbances varies greatly from year to year.

It is possible to make a rough calculation for managed forestland from Canadian forestry statistics. In 2015, 164 Mt of CO_2 was removed from managed forestland and 247 Mt of CO_2 was lost due to natural disturbances. Together, the 411 Mt of CO_2 removals and losses corresponded to 561 Mm^3 of wood. On the managed forest area of 226 Mha, they would thus amount to 2.5 m^3 per ha. Reducing this by 25% to count above-ground biomass only, CO_2 removals and losses would be 1.9 m^3 per ha. Canada does not report any change in forest stock, so it is taken as zero.

A comparison with Russia and Scandinavia may help to determine whether Canada's increment of 1.9 m^3 per ha is reasonable. The mean increments per hectare for the Nordic countries are 3.1 m^3 for Norway, 4.0 m^3 for Sweden and 4.8 m^3 for Finland. The mean increment for Russia is much lower: just 1.3 m^3 per ha. A Canadian growth rate lower than the Scandinavian countries, but somewhat higher than for Russia, seems right considering that Canada has coastal provinces with higher precipitation than Russia, but similar continental forest regions. Scandinavia, on the other hand, has a more developed managed forestry system and relatively high precipitation.

However, a paper by a group of Canadian researchers (Paré *et al.*, 2016) studied ratios of net primary production (NPP) for a number of countries, based on satellite data (MODIS). They found Canada's average NPP is 13% higher than Russia's, but similar to NPPs in Nordic countries. By contrast, the above-estimated growth rate in Canada is two-fifths higher than in Russia and less than half that in Nordic countries. This would seem to imply that Russia's growth rate could be closer to Canada's than it is, while Canada's increment could be closer to Scandinavia's than it is.

If a Canadian increment of 1.9 m^3 per ha and a harvest rate of 75% as currently prevails in Sweden is assumed, this would give the following potentials for forest bioenergy:

- *Harvest levels* of stemwood would roughly double from 160 Mm^3 to 315 Mm^3. The energy content of the harvest would increase proportionately from 320 TWh to 630 TWh.
- If half of stemwood ends up as *processing residues*, as is typical in Sweden and other countries with lumber industries, this would give a bioenergy supply of 315 TWh.
- Some 170 TWh could also be recovered as *harvesting residues*, assuming that 50% of the slash and 20% of the stumps were harvested, as in the enhanced case for Sweden.
- So 485 TWh (1.35 EJ) of biomass for energy could come from Canadian managed forests.

Note that this does not include any recovery of salvage wood from areas affected by natural disturbances outside the managed forest areas. It also does not consider the existing policy of defining "annual allowable cut" as a basis for Canadian forestry and harvesting levels.

Canadian researchers have studied how much bioenergy could be recovered within the existing harvesting levels. A summary (Mansuy *et al.*, 2017) indicates the potentials shown in Table 7.2.

Apparently the overall energy potential at existing harvest levels could be as high as 1 150 TWh (3.19 EJ), including 400 TWh (1.11 EJ) from residues and 750 TWh (2.08 EJ) from salvage wood. The residue estimate is lower than the one above, perhaps since it is restricted to the current harvest level. The salvage wood potential is additional, as the estimate above does not consider it.

The biophysical constraints to forest growth suggest that Canadian forest could produce more biomass. Nevertheless, several constraints would need to be overcome.

Table 7.2 Annual Canadian forest residue and salvage wood potential

Forest feedstock	Wood mass	Wood volume	Wood energy
Processing residues	20-40 Modt	50-100 Mm^3	100-200 TWh
Harvesting residues	15-40 Modt	37-100 Mm^3	75-200 TWh
Subtotal residues	**35-80 Modt**	**87-200 Mm^3**	**175-400 TWh**
Salvage wood, insect damage	30-90 Modt	75-225 Mm^3	150-450 TWh
Salvage wood, fire damage	20-60 Modt	50-150 Mm^3	100-300 TWh
Subtotal salvage wood	**50-150 Modt**	**125-375 Mm^3**	**250-750 TWh**
Total residues and salvage wood	**85-230 Modt**	**212-575 Mm^3**	**425-1150 TWh**

Note: Modt = Million oven dried tonnes
Source: Mansuy et al. (2017)

Canadian forest is sparsely populated, so the road network does not allow optimal harvesting and thinning operations at more remote stands. Canadian forest has a greater diversity of species than Nordic forests, and several of the species have limited value for industrial use.Natural disturbances support certain forest flora and fauna, and while efforts are being made to limit the losses that result from them, it may be difficult or impossible and sometimes undesirable to stop them.

RUSSIA

Russia's forests are twice as large as Canada's, covering 809 Mha. But large forest areas have little or no forestry activity, mainly due to limited road infrastructure and long distances to industries and major transport corridors or harbours. The average increment reported to the Food and Agriculture Organization (FAO) is 1.3 m^3 per ha, with a lower increment of 1.1 m^3 per ha in coniferous forests and a higher increment of 1.7 m^3 per ha in broadleaf forests. The total increment adds up to 853 Mm^3 per year. Table 7.3 shows a comparison with Sweden.

The harvesting level in Russia is less than one-tenth of the harvesting level in Sweden, as share of the standing stock, and only one-fifth of the yearly growth, increment, is harvested. A big potential exists to increase harvesting to produce fossil-free materials like wood for construction, and to make wood-based fuels to substitute fossil fuels.

If the harvesting level were 75% of increment, as it is now in Sweden, the harvest would be 640 Mm^3, almost a four-fold increase compared to the current level. This volume contains 1 280 TWh of energy. About half of this volume could be used as energy, 640 TWh; the other half would be products (wood and paper). Another 486 TWh bioenergy could be added from harvesting residues, assuming the same harvesting rate as in Sweden. This adds up to 1 126 TWh, or 3.1 EJ. The current use of bioenergy from forests in Russia is only around 39 TWh (Paré *et al.*, 2016).

Table 7.3 Comparison of forest harvests in Sweden and Russia

	Annual forest increment	Annual harvest volume	Harvest share of increment	Total forest volume	Annual harvest volume	Harvest share of volume
Sweden	120 Mm^3	90 Mm^3	75 %	3 300 Mm^3	90 Mm^3	2.73 %
Russia	853 Mm^3	170 Mm^3	21 %	81 500 Mm^3	170 Mm^3	0.21 %

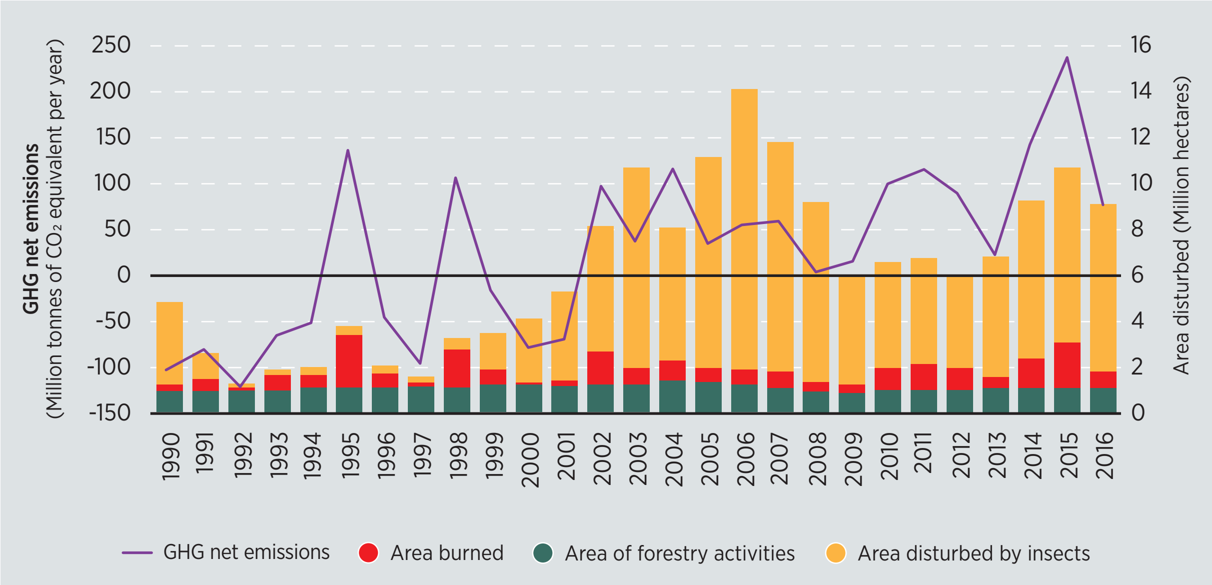
Large-scale natural disturbances

Losses from natural disturbances vary greatly over time. In Canada, the area affected by forest fires was 1.4 Mha in 2016 but varied from 0.8 Mha to 4.5 Mha per year over the preceding decade. The area affected by insects was 17.6 Mha in 2016 but varied from 6.0 Mha to 16.7 Mha over the preceding decade.

Figure 7.1 shows the fluctuations in losses from natural disturbances in *managed* Canadian forests from 1990 through 2016. In most years, insect infestations (yellow bars) affected larger areas than forest fires (red bars), and natural disturbances (fires and infestations together) took place on much larger areas than forest management (clear-cutting, in dark green). Carbon emissions (years with purple line above the x-axis) are roughly balanced by carbon sequestration (years with purple line below the x-axis). A trend of higher losses in recent years is also evident, possibly due to climate change.

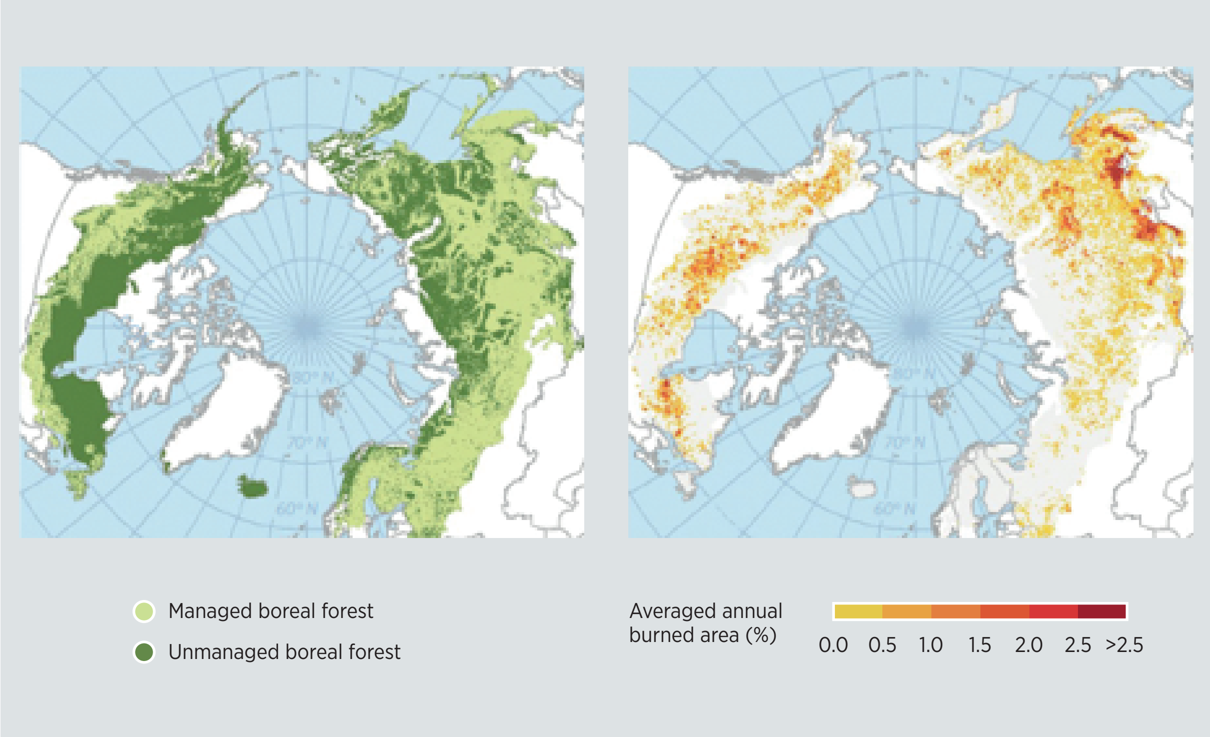
Russia also has large-scale disturbances like yearly occurring forest fires. Figure 7.2 shows the extent of boreal forests (in green), active forestry (in light green) and forest fires between 1997 and 2014 (ranging from yellow to red by share of forest burned).

Figure 7.1 Carbon emissions and removals in Canadian managed forest



The total net emissions and removals, taking into account both human activities and natural disturbances, were about 78 Mt CO_2-eq in 2016. This includes emissions from wood harvested in Canada and used in Canada and abroad.
Source: Natural Resources Canada (2018)

Figure 7.2 Boreal forest area affected by forest fires (1999-2014)



Source: Astrup et al. (2018)

Managed forests in Scandinavia are almost unaffected by forest fires, as are most of the forests in European Russia. The forests in Siberia and the Canadian wilderness, by contrast, are heavily affected by fires. In an unusually hot and dry year like 2018, when forest fires also occur more frequently in Scandinavia, the total impact is still lower due to better conditions for fighting the fires, such as roads and other infrastructure.

So for both Canada and Russia, it is reasonable to suppose that a different kind of forest management, with more harvesting and a higher share of young trees, as well as a better network of access roads in the forest to speed removals and emergency response to fires, would reduce carbon losses from forest fires. These reduced losses would improve the carbon balance of these boreal forests, on top of the increased growth and subsequent sequestration, and on top of the increased harvest and substitution benefits that greater growth would allow.

Thinning as a strategy to harvest biomass and reduce carbon loss

Thinning can be used as a strategy to make forests more resilient and at the same time produce biomass for energy. The illustration of thinning in Photograph 7.1 is from the southeastern United States, but the practice and conclusions can be similar in many types of forestry, not least in Canada and Russia. The main purpose of thinning is to improve the quality of the remaining trees and increase the production of high-quality timber. Many studies have shown that thinning also leads to increased carbon sequestration and reduced impact of wildfires, infestations and disease. The stand to the left is from a poorly managed and un-thinned stand in eastern Tennessee, while the stand to the right is a thinned and well-managed forest in Georgia. Often, the trees from thinning in this region are used for pellet production. In many regions, there is a large volume of “natural thinning” through high mortality of young trees growing in the shadow of larger trees.

Potential to boost use of residues

Research in Québec (Durochet *et al.*, 2019; Thiffault *et al.*, 2015) shows major potential to increase the harvest of currently underutilised species and trees. In Canada, a much larger share of trees than in Nordic countries is left to decompose on logging sites. In some instances, due to the lack of market for pulpwood-quality trees, stems as well as branches are left on logging sites. By not harvesting these logging residues, much carbon is lost to the atmosphere during decomposition. It may also take longer for new forest to be established than if the area had been cleared and made ready for replanting.

Coniferous tree species make up a large share of the harvest for sawmills. There is large potential to increase the harvest of low-quality trees from broadleaf species like maple, birch and aspen. The absence of a market for these trees tends to hinder the harvest of coniferous trees that are present in mixed stands (Durocher et al. 2019).

Photograph 7.1 Forest in southeastern United States before and after thinning

Source: Parrish, Dale and Kline (2017)

Photograph 7.2 Wood harvesting site in Québec where residues have been left to rot

Photograph: Evelyne Triffault, University of Laval

Figure 7.3 shows the potential to increase the harvest of different tree species in Québec (based on numbers from 2009-2013). Tan areas show the upper and lower bounds of actual fellings as a percentage of annual allowable cut in the forest, while the horizontal bars in the middle show average shares.

- Birch harvest ranges from 0% to 35% of annual growth.
- Maple harvest ranges from 20% to 65% of annual growth.
- Poplar harvest averages 25% of annual growth and ranges from 0% to 60%.
- Coniferous harvest (pine, spruce) averages 65% and ranges from 45% to 90%.

In summary:

- By using the Nordic forestry model and harvesting levels, Canada and Russia could theoretically mobilise 1.35 and 3.1 EJ, respectively, of forest biomass for energy. Russia has greater potential than Canada because it has more forest available to manage.
- In the short run, there is large potential for better use of by-products and residues at the current harvesting level, within the forest management systems already in place. Both Russia and Canada currently use low amounts of biomass from forestry.
- The higher use of wood products from these forests will also lead to increased carbon storage in wood products, as well as added volumes of post-consumer wood and paper residues that can be used for energy.
- With the Nordic forestry model, losses from natural disturbances like forest fires and infestations could be reduced in some places, cutting CO_2 emissions into the atmosphere.
- There is large potential to salvage trees from forest fires and infestations for energy.
- The limitations that would need to be overcome to enhance the biomass supply are numerous and are different from the ones experienced in Western Europe. Technical, economic, ecological and infrastructure constraints are important to consider.

Figure 7.3 Actual vs. potential harvest for major boreal tree species in Québec

Source: Thiffault, et al. (2015)

8 GLOBAL FOREST RESOURCES AND CARBON BALANCES

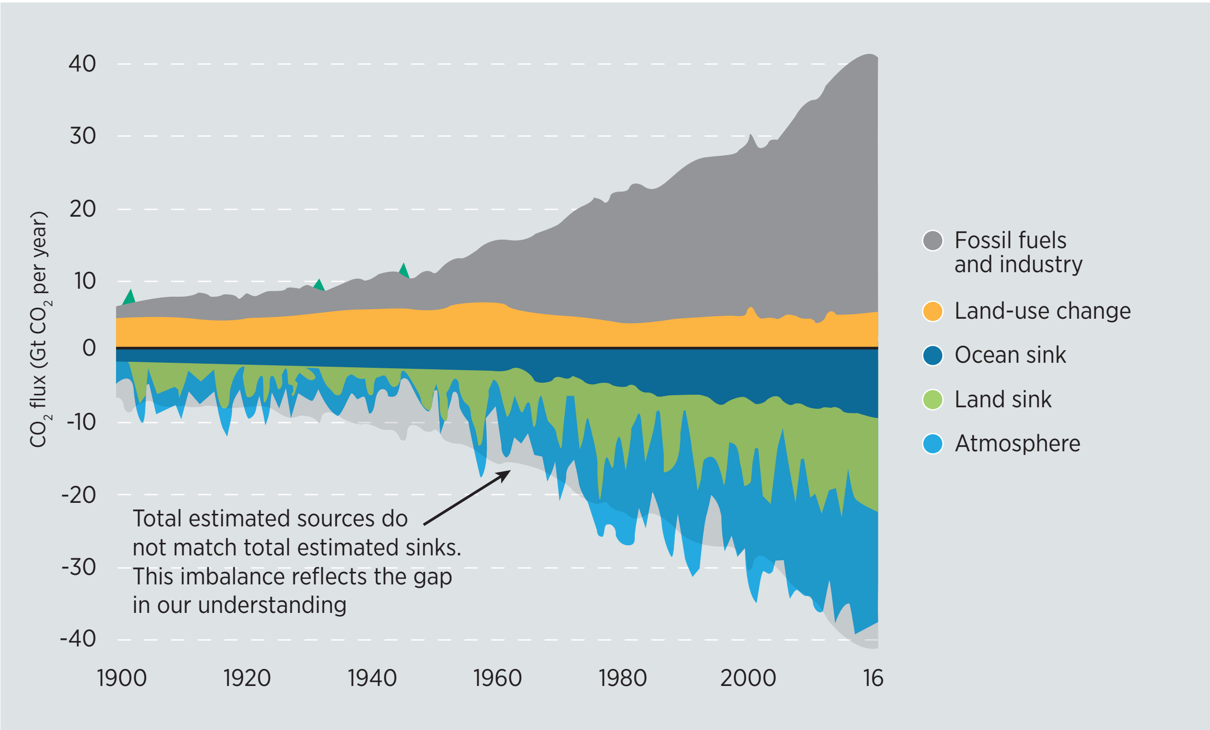
Global forest resources are increasing, despite on-going deforestation in many parts of the world. The Global Carbon Project estimates that the globe has a gross "land sink" of 11 billion tonnes (Gt) of carbon dioxide per year from growth of forests and vegetation. This is an average figure for the decade from 2007 through 2016; annual figures vary depending on weather conditions and climate phenomena like el Niño and la Niña. While deforestation caused an average loss of 4.8 Gt CO_2 per year during the same period, there was still a net gain of 6.2 Gt CO_2 per year. As shown in Figure 8.1, CO_2 gains in the land sink (in green) have been greater than CO_2 losses from land use change such as deforestation (in yellow) for the last several decades (Global Carbon Project, 2017).

Afforestation trends globally

Growth in the forest carbon pool is due to both increased biomass stock in existing forest systems and an increase in managed forest area. There is a growing volume of forests in most countries and regions, primarily in developed high-income and middle-income countries. Despite continuing deforestation in countries with high poverty rates, unsustainable forestry practices, or encroachment on forests by expanding plantations, the global trend is one of net forest accumulation, as reflected in Figure 8.1.

Research by the University of New South Wales illustrates this trend (Liu *et al.*, 2015). A new method, based on satellite-based passive microwave data, was used to measure biomass volumes globally, in all land categories. The change in carbon content was then calculated for each type of land. Table 8.1 shows the average annual change of carbon stocks

Figure 8.1 Global carbon sources and sinks



Source: Global Carbon Project (2017)

Table 8.1 Net carbon stocking and CO_2 uptake in different types of forest (2003-2012)

Type of land	Carbon stocking (Gt C/year)	CO_2 uptake (Gt CO_2/year)
Boreal forest	+ 1.04	+ 3.82
Temperate forest	+ 0.67	+ 2.46
Tropical forest	- 0.52	- 1.91
Total forest	**+ 1.19**	**+ 4.37**
Non-forestland	+ 0.63	+ 2.31
Total all land	**+ 1.82**	**+ 6.68**

Source: Liu et al. (2015)

and CO_2 uptake over the decade from 2003 to 2012. Boreal and temperate forest uptake of CO_2 together grew by 6.28 Gt yearly, out of a total net global sink of 6.68 Gt per annum. Including tropical forests, all forests globally showed a net annual CO_2 uptake of 4.37 Gt, similar in magnitude to estimates by the Global Carbon Project, though 30% lower.

A recent study, based on satellite images, shows global forest area grew by 224 Mha or 7.1% in the 35-year period from 1982 to 2016. There was a loss of area in tropical forests due to deforestation and expanding agriculture, but a total gain of area in boreal and temperate forests that was twice as great. There were particularly large forest expansions in China and the countries of the former Soviet Union. Forests expanded especially in mountain regions, as a warmer climate allowed tree cover at higher altitudes. Overall, the study found that 60% of the documented land use change was due to human activities while 40% was due to indirect drivers like climate change (Song *et al.*, 2018).

Another study, completed under FAO auspices in 2017, found that current statistics have underestimated forest area in dry regions, so that global forest area should be adjusted upward by 467 Mha or 9%. The new numbers are based on interpretation of Google Earth satellite images by persons familiar with the analysed areas (Bastin *et al.,* 2017).

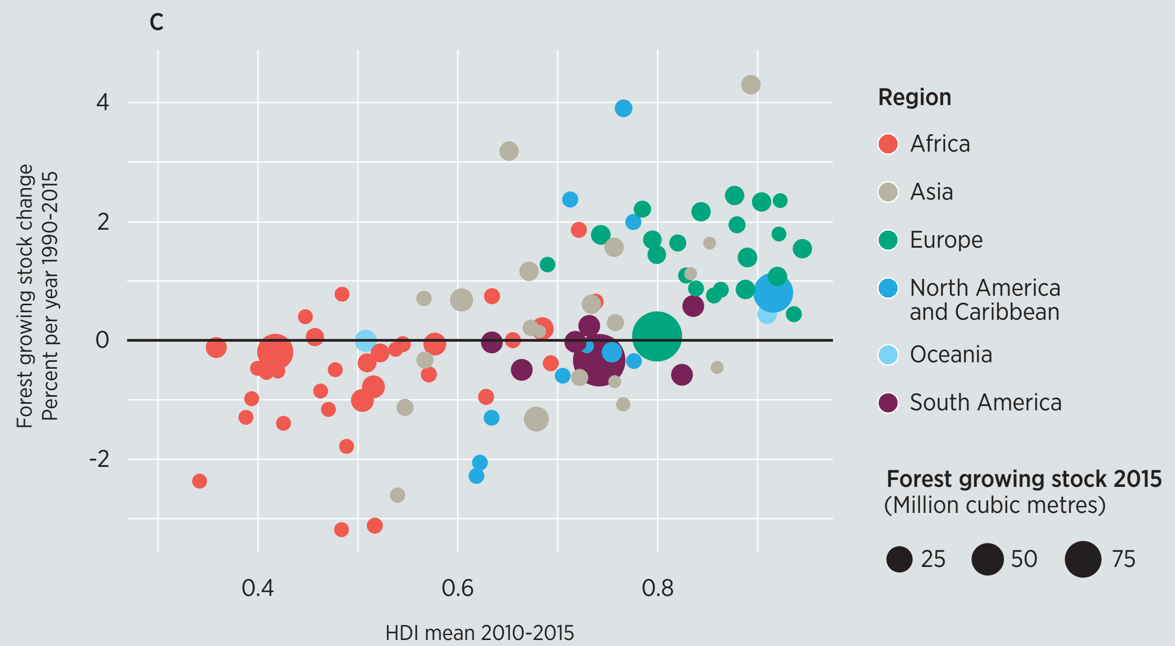
In summary, several studies show that during the last few decades, there has been more afforestation globally than deforestation, and that the forest areas may have been significantly underestimated. Yet deforestation must be taken seriously and reversed.

Forest resource management and development

There is a close relation between forest resource development and economic and human development. Pekka Kauppi at Helsinki University has shown that practically all countries above a certain income level (gross domestic product per capita) have increasing forest resources (forest areas and forest growth). The correlation is even stronger between increasing forest growing stock and countries' scores on the United Nation's Human Development Index (HDI), as shown in Figure 8.2. As countries develop, they usually switch from losing to increasing forest resources. This positive forest transition took place in many European countries before 1900, and since then it has spread throughout Europe and North America, as well as to Asian countries such as China (Kauppi *et al.*, 2018).

Forest growth results from several factors. When modern agricultural methods are applied on good farmland, marginal lands will turn to forests. Also, developed countries invest in programmes for sustainable forest management and plant forests on degraded or deforested lands.

Figure 8.2 Forest growth closely related to human development level



Each bubble represents a country. The size of the bubble shows the size of the growing stock, and the position in the chart the forest growth and HDI index.

Source: Kauppi et al. (2018)

Further, economic development tends to improve governance and strengthen the political control of land management.

At the other end of the scale, in poor countries there is pressure to use forest resources for daily needs, like firewood for cooking and deforestation for grazing animals. Unsustainable practices like slash and burn agriculture prevail. Yields are low in farming. Governance is weak, leading to unsustainable logging and the expansion of agriculture into forests. Most of these factors change in a positive direction with economic development.

Global bioenergy resource

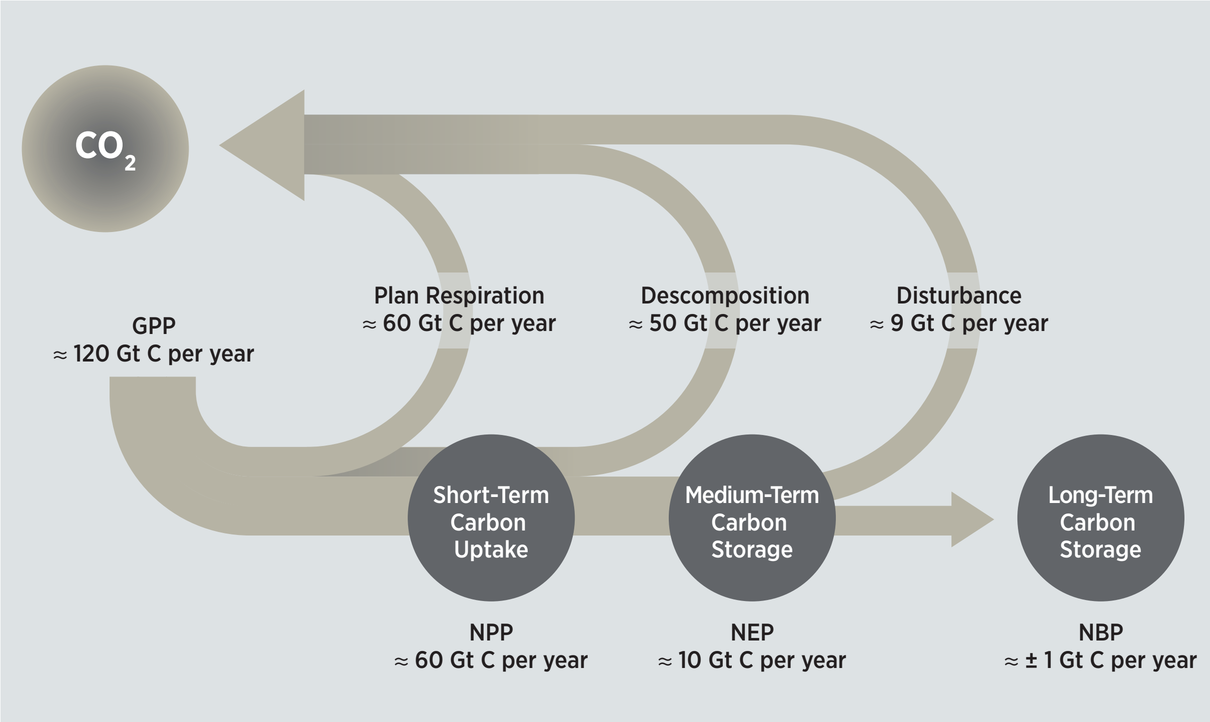
Gross primary production (GPP) of biogenic carbon by photosynthesis is around 123 Gt of carbon, or 451 Gt of CO_2. The net primary production (NPP) is around half of this – 56 Gt of carbon or 206 Gt of CO_2 on land (IPCC, 2013; Beer *et al.*, 2010). As shown in Figure 8.3, of the gross carbon production (approximately 120 Gt), almost all is recirculated through plant respiration (60 Gt), decomposition (50 Gt), or disturbances like fire and combustion (9 Gt), and only a small part is net increase of the biogenic carbon pool, measured as land sink. CO_2 is released by microorganisms, animals and humans consuming the plant matter (cellular breeding) and by natural fires, as well as bioenergy use in boilers and motors. This is all part of the natural carbon cycle.

The total above-ground biomass pool contains 450 - 650 Gt of carbon (IPCC, 2013), equivalent to 1 650 - 2 390 Gt of CO_2. With an annual land sink of 11 Gt CO_2, global biomass volume thus increases by 0.46% to 0.66% per annum.

Current global energy use is some 570 EJ, of which 80% is fossil fuels, with a growth rate of 2.2% per year (IEA, 2018). Bioenergy could replace a lot of the fossil-fuel energy use:

- Gross land sink: 11 Gt CO_2, or 3 Gt carbon, is equivalent to 84 EJ of energy.
- Net primary production (NPP): 56 Gt carbon is equivalent to 1 568 EJ of energy.
- Gross primary production (GPP): 123 Gt is equivalent to 3 444 EJ of energy.

Figure 8.3 Gross Primary Production (GPP) and Net Primary Production (NPP)



Note: C = carbon; NEP = Net Energy Production; NBP = Net Biomass Production;
Source: IPCC (2013)

The potential for bioenergy lies in using the net surplus, using as fuels the solid biomass that otherwise would decompose, and increasing production in forestry and agriculture.

The Nature Conservancy in 2017 published a study called *Natural Climate Solutions*. This showed a mitigation potential of 23.8 Gt of CO_2 per year through land management measures, of which 11.3 Gt could be achieved through measures costing less than USD 100/t CO_2, a level close to the carbon tax in Sweden (Griscom *et al.*, 2017). When compared to the current emissions of CO_2 and the land sink, these numbers are impressive and illustrate the dynamic potential of the biogenic systems.

Over half the mitigation potential, 16.2 Gt/y of CO_2, is in forestry measures like natural forest management, improved plantations, fire management, halting deforestation, and planting new forests – reforestation. One of the major measures evaluated in the study is reforestation on 678 Mha of land, twice the forest area of Canada. Almost all of this is assumed to be with "natural forest" and only 7% plantations. To make these massive investments in afforestation possible, landowners need incentives: income from sales of wood for products and for bioenergy. This will also give added climate benefits on top of the increased carbon stock.

Photograph 8.1 Afforestation in Ireland (planted forest south of Dublin)

Photograph: Svebio

Ireland's forest area increased by 62% between 1990 and 2015, while the volume of wood in Irish forests doubled.

Global forest strategies

To increase the climate benefits of forests, a number of strategies must work together:

- Reduce and halt deforestation, particularly of carbon-rich and highly biodiverse tropical forests.
- Reforest already deforested and degraded lands, either with the mix of species in nearby natural forests or with fast-growing plantations to maximise wood production for energy and other products and to maximise carbon sequestration.
- Use existing and new forests better for production of bio-based materials and energy, while setting forest aside for conservation and practicing managed forestry methods with multi-purpose benefits (production, environment, recreation).
- Use residues in forest industry and forestry that would otherwise decompose.

Recent research shows that the global forest resource is expanding, contrary to common perception. The global stock of wood in forests, the total growth, and the forest areas are all increasing, despite deforestation in tropical regions. The increased forest resource offers an opportunity to increase the harvests of wood products and biomass for energy, with big climate benefits. The Nordic forestry model can serve as an inspiration.

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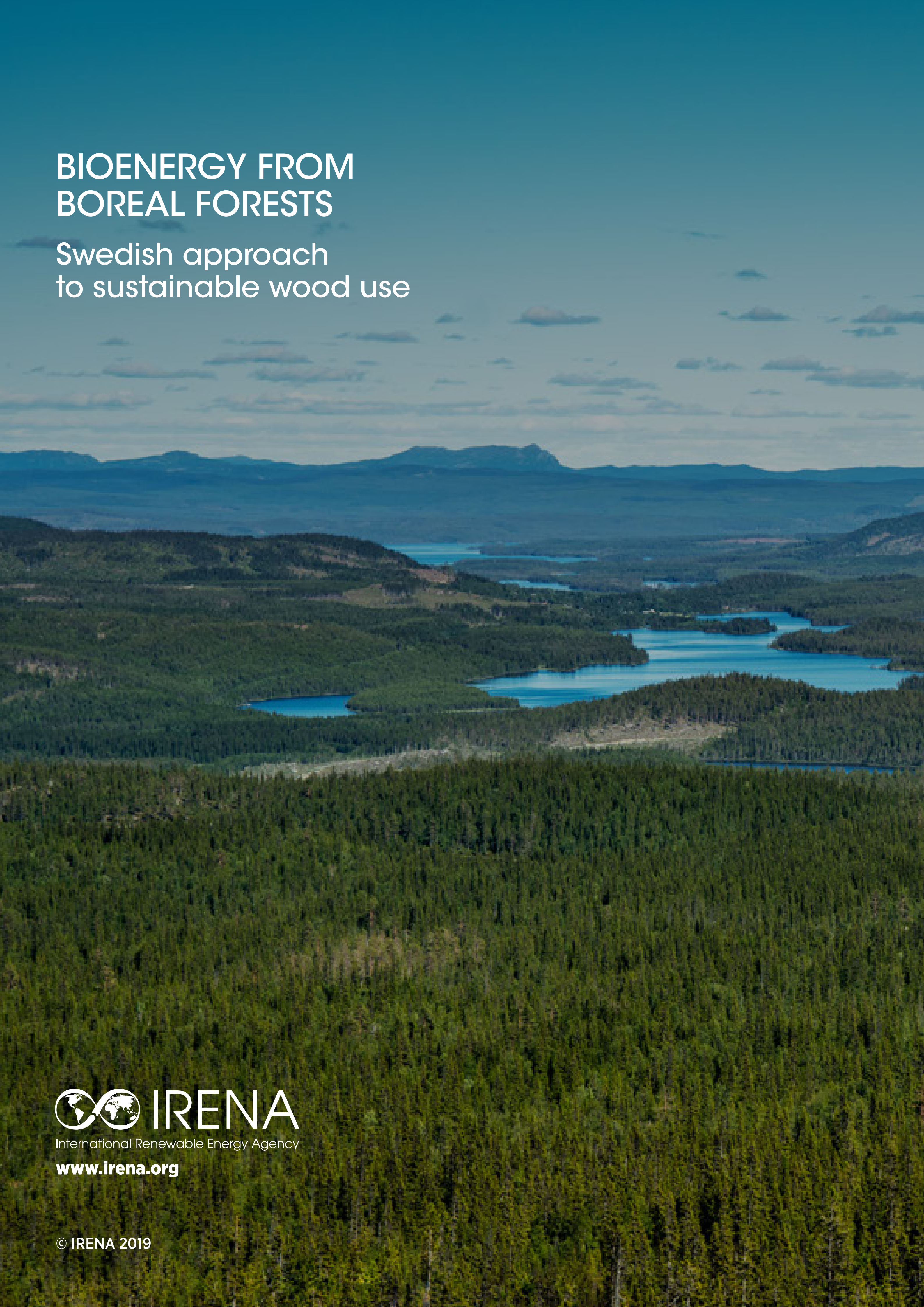

BIOENERGY FROM BOREAL FORESTS

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