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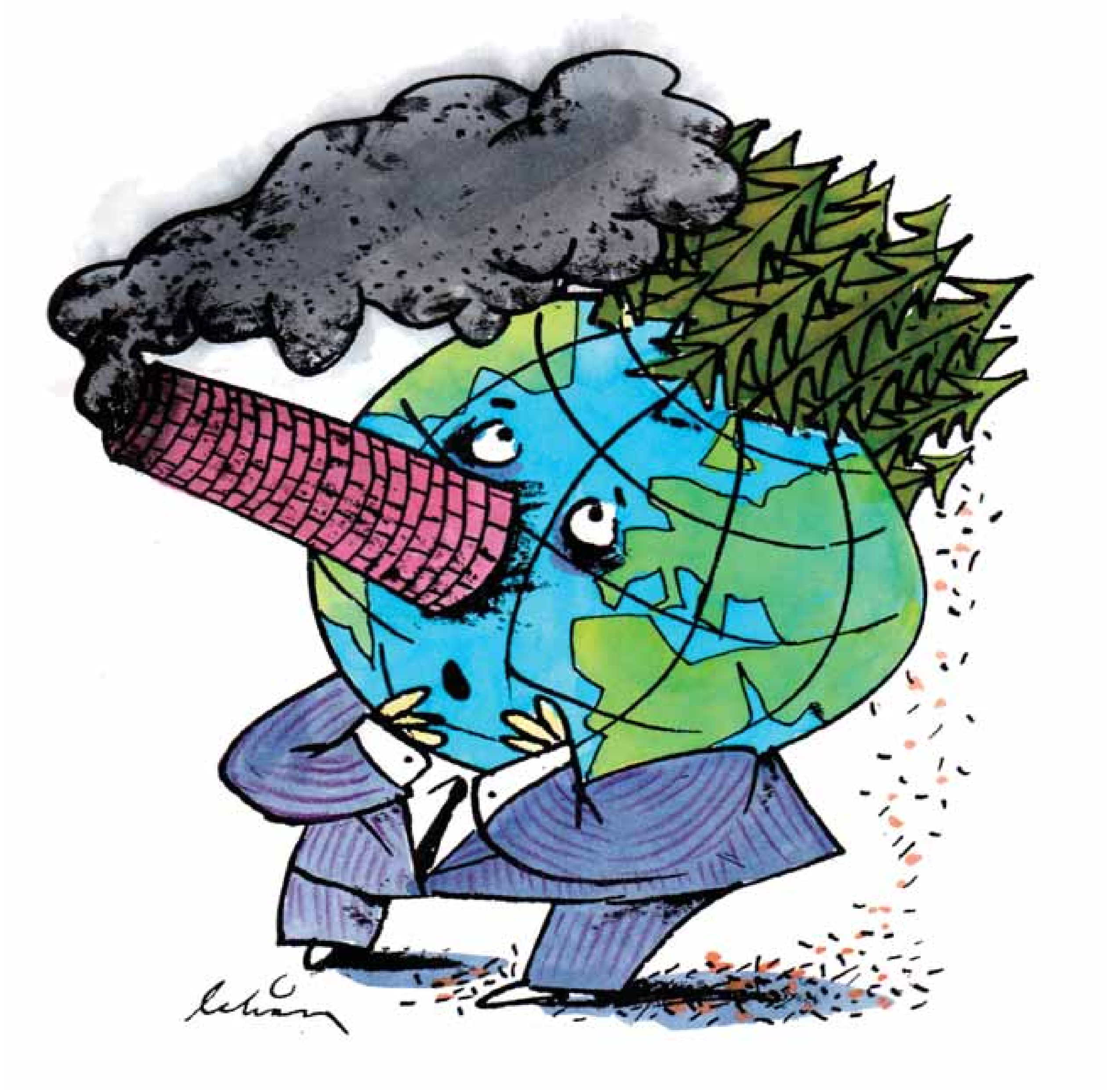

To Manage or Protect?

Boreal Forests from a Climate Perspective

Roger Olsson

Air Pollution & Climate Secretariat

AirClim

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To Manage or Protect? - Boreal Forests from a Climate Perspective

By Roger Olsson

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The study was supervised by a working group consisting of Peter Roberntz and Lovisa Hagberg from World Wide Fund for Nature (WWF), Sweden, Svante Axelsson and Jonas Rudberg from the Swedish Society for Nature Conservation and Reinhold Pape from AirClim. Many thanks also to a number of forest and climate experts who commented on drafts of the study.

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Contents

Summary

This report presents an overview of the relationships between boreal forests, forestry and climate change. It looks exclusively at climatic aspects, which does not mean that other aspects, such as socioeconomics or biodiversity, are seen as less important. The sole reason for this limitation is the wish for clarity.

A central assumption is that +2°C is a critical threshold for global warming, and that severe reductions in greenhouse gas emissions are needed over the next few decades to avoid exceeding this threshold. Analysis of the importance of boreal forests and the effects of various courses of action should therefore not be limited to a long-term perspective (100 years or more).

The amount of carbon stored in boreal forests is greater than that of any other land ecosystem, and almost twice that stored in tropical forests. This huge accumulation of carbon makes the boreal forest a key factor in future climate.

About half of the world's boreal forests are old-growth forests, mostly or entirely unaffected by forestry. They represent a very large share of the total carbon stored. These forests could continue to act as carbon sinks for centuries. However, continued global warming could transform old-growth boreal forests into a source of carbon source as the result of an increase in natural disturbances, such as fires and insect infestation. We can already see clear trends in this direction. If warming exceeds a critical level (3–5°C is suggested) heat stress and water scarcity could lead to widespread forest death in the boreal region. A large proportion of the stored carbon will then be released into the atmosphere, further driving global warming in an irreversible and self-sustaining process.

Turning old-growth boreal forest into managed forest has a negative impact on climate in the short and medium term, as some of the vast amount of stored carbon is released into the atmosphere during harvesting.

It takes a long time – 100 years or more – for new forests to bind the corresponding amount of carbon, which means that the felling of old-growth forest further accelerates global warming when seen in this short-term perspective.

In managed boreal forests, we have greater opportunities to influence the movement of greenhouse gases through forest practices and use of the harvested biomass. Once again it is important to take into account the need for rapid restrictions on emissions when we weigh up alternatives course of action. A solution that may appear optimum over a span of 100 or 200 years may be counterproductive when seen in the light of what we need to achieve in the next few decades.

More intensive forestry, which enables higher production and higher yields through widespread fertilisation, for example, poses risks to the climatic. Aside from the risks, it is not clear that these alternatives are positive, particularly in the short term. For example, if we were to start the widespread uprooting of stumps in Swedish forests to increase the yield of forest fuel it would create a carbon deficit – in other words be negative from the climate viewpoint – for at least the next 30 years.

Interesting opportunities are offered by forest management strategies that have other goals than maximising production and timber yield. Extending rotation periods in Scandinavian forestry has, for instance, been shown to have positive climatic effects, particularly in spruce forests, even after taking into account substitution effects (see below). This is mainly due to an increase in the sawn timber share of yield. Eliminating clear-cutting would also have immediate positive effects in relation to the impact of forestry on climate, since clear-cutting creates carbon sources.

One climatic disadvantage of extending rotation periods and eliminating clear-cutting in forestry is that it reduces the availability of forest residue and thus opportunities for replacing fossil fuels.

It is precisely this opportunity to replace or substitute fossil fuels with biomass from forests that is crucial for the total climate impact of managed forests.

Wood products can replace fossil fuels, both directly through combustion and indirectly, by replacing materials with high embodied energy, such as steel and concrete. Over time, the estimated substitution effects can be high, since the eliminated emissions are cumulative with each forest generation. In the short term (a few decades), it is however questionable whether the climatic benefits of substitution justify investing in increased forest logging or production.

In substitution studies it is often assumed that increased timber yield is used to substitute for materials or fuel, or a combination of both. This differs markedly from the actual situation in Sweden, where less than one fifth of the timber yield is used for long-lived structural timber, and where about half is used for papermaking. The manufacture and use of paper is on the whole negative from a climate perspective (although the effects are likely to differ between various paper products). Reducing consumption of paper and using more of the harvested wood for timber and fuel would thus benefit the climate.

It is also important to keep in mind that substitution effects are to some extent theoretical. They are based on the assumption that if a certain amount of wood is made available to the market, it will reduce the use of other materials accordingly. In practice, some of the wood may instead be used to increase consumption. None of the substitution studies referred to in this report take into account these market effects.

1. Global warming

The Earth is getting warmer. Levels of carbon dioxide and other greenhouse gases in the atmosphere have risen, mainly due to emissions from burning fossil fuels. The average temperature has risen by 0.8°C since the late 1800s (IPCC 2007a, Frieler et al. 2009). The extent and rate of warming in the future will depend on how successful we are in limiting greenhouse gas emissions. The UN Panel on Climate Change, IPCC, has described a variety of scenarios in which the global average temperature at the end of this century ranges from 1.1 to 6.4°C higher than today, depending on how emissions of greenhouse gases develop. To limit warning to no more than 2°C under these scenario studies, the level of atmospheric carbon dioxide must not exceed 400 ppm (parts per million). The atmosphere already contains about 380 ppm of carbon dioxide (IPCC 2007a).

In its fourth assessment in 2007, the IPCC estimated that global warming should be limited to a maximum of 2°C to limit the risk of consequences that society would find very difficult to manage. Subsequent research has confirmed this assessment, or even indicated that the limit may be lower (Fee 2011). Above this critical threshold, further small rises in temperature could trigger significant and irreversible changes that could then drive further warming in a self-sustaining process. A group of leading scientists have identified around ten of these "tipping elements", which in their view could be triggered before the end of this century. Melting of Arctic sea ice, thawing of permafrost areas and extensive forest death in the Amazon and boreal forests are three examples. In the cases described, the changes would take place within a few decades or at most a century. The thawing of permafrost and forest death would both affect climate change by releasing large amounts of greenhouse gases into the atmosphere (Lenton et al. 2008). Subsequent research has provided support for these assessments. The conclusion that global warming above 2°C could lead to sudden, irreversible changes in the global system, with runaway warming as a result, has received further support (Schellnhuber 2009a).

In order to keep warming below two degrees, according to the assessment of the IPCC, greenhouse gas emissions must start to fall by 2015 and be reduced by 50–85 per cent by 2050 (compared to 1990 levels) (IPCC 2007b). More recent assessments have concluded that the industrialised nations must effectively eliminate carbon dioxide emissions from fossil fuels by the year 2030, if there is to be any chance of meeting the two-degree target (Schellnhuber et al. 2009b).

Based on the commitments that governments around the world have made so far, however, emissions will continue to rise for the next few decades (IPCC 2007b). If this trend is not broken the world will face warming by more than 4°C by the end of this century. A rapid and dramatic reversal of the trend in greenhouse gas emissions is therefore vitally important.

Climate changes in the boreal region

Almost all climate models show that warming in the Arctic region (north of around 60° latitude) will be much greater than the global average. This is also supported by real-world developments to date (Rummukainen & Källén 2009).

The average temperature in the Arctic region has risen twice as fast as the global temperature over the last few centuries (IPCC, 2007a).

If the global average temperature rises by 2.8°C by the year 2100, large parts of the Arctic land mass will experience warming by 4–5°C (IPCC 2007b). With current emission trends and a global temperature rise of 4°C, the temperature could increase by 6°C in northern Scandinavia. Parts of Arctic Canada and Asia could see temperature rises of 10–12 degrees (UK Met Office, 2009).

With global warming of slightly more than two degrees it is calculated that the average temperature in Sweden would increase by 2–4°C, mostly in the north and more in winter than in summer. Winters will be milder and summers will be hotter. Spring will come earlier and autumn later. Precipitation is forecast to increase by an average of 10–20 per cent, mostly during the winter months. The number of extreme wet weather events (large amounts of precipitation in a short time) will increase. Water shortages could nevertheless still be a problem in southeastern Sweden, since evaporation increases as temperatures rise. The extent and duration of winter snow cover will decrease. Climate models do not provide clear information about the changes in wind patterns. On the whole, it is likely to be slightly windier. There may be fewer storms, but wind strength is likely to be higher (Rummukainen 2010). Some climate models predict that the average winter wind speed in Scandinavia will increase by 7–13 per cent by 2100, and that maximum wind speed will increase by the same amount (Eriksson 2007).

2. The boreal forest

Boreal forests cover about 14 per cent of the Earth's green surface and therefore make up the world's largest interlinked land ecosystem. They form a green belt of varying width in the northern hemisphere, roughly between latitudes of 45 and 70 degrees. The boreal forest belt covers 1.4 billion hectares, equivalent to 38 per cent of the world's forest area (Soja et al. 2007). More than half lie in Russia, and around six per cent in Scandinavia (Olsson, R, 2010). In the north, the boreal forest borders on treeless tundra. In the south, the boundary is more diffuse and often comprises a zone of mixed forests that merges into temperate deciduous forest.

Boreal forests are dominated by conifers, with some deciduous species such as birch and aspen. The harsh climate is a major factor in their ecology. Parts of the boreal forests, mainly in Siberia, grow in constant permafrost, and periodic permafrost also occurs south of this zone. Winter snow cover has great ecological importance because it protects the soil from the cold of winter and thus provides opportunities for many plant and animal species to survive the cold season (Tivy 1993).

Large-scale disturbances play a vital role in the dynamics of natural boreal forest ecosystems. Regular forest fires, insect infestations and storm-felled trees create ecological gaps that enable new generations to gain a foothold (Juday 2005). Natural forest fires caused by lightning occur at 50–200 year intervals, and each fire may affect tens of thousands of hectares of forest (Tivy 1993).

In managed forest, logging and other forestry operations are by far the main disturbance that affects ecosystem dynamics. Changes in forestry practices can affect both the vulnerability of the forest to climate change and its effects on climate (Juday 2005).

About half the world's boreal forests are currently unaffected to any significant degree by forestry or other human activities. There are large areas of old-growth forest in the northern part of the boreal zone, which is very sparsely populated and largely inaccessible (Bryant et al. 1997). More than half of the large old-growth forest areas that remain in the world are boreal forests in Canada and Russia (Juday et al. 2005). In Scandinavia, almost all forest has been affected by human activity, and mostly by the last half-century of industrial forestry. In Sweden, older forest and old-growth type forests in the biological sense are mainly limited to nature reserves and other protected areas. Estimates of the area of such forests outside reserves are uncertain. Overall, the proportion of old-growth type forests in Sweden is probably less than 10 per cent, much of it in small areas affected by the dynamics of surrounding managed forest (Cedergren 2008, SCB 2009).

In analysing the relationships between climate, climate change and boreal forests, it is essential to distinguish between old-growth forests, where natural dynamics hold sway, and managed forests, where human activity has the biggest influence. This difference is very significant for the effects of climate on forests and the feedback effects between forests and climate.

Global warming is already having considerable impact on the Earth's terrestrial ecosystems, and these effects will grow and increase in number as warming continues. Even with a global average temperature rise of 1.5–2.5°C, there is a risk of large-scale transformation of forests into treeless habitats.

Boreal forests are likely to be particularly hard hit by climate change, partly because warming in northern latitudes is expected to be far greater than the global average, and partly because temperature is a critical factor in boreal forests (IPCC, 2007a).

Figure 1. The boreal forest belt, schematically divided into untouched old-growth forest / virgin forest and managed forest. *(After Bryant et al. 1999.)*

Like most other ecosystems, boreal forests are likely to react non-linearly to changing environmental conditions. This means that the changes will not occur gradually or proportionally with rising temperature, but are more likely to occur suddenly when certain thresholds are exceeded (IPCC 2007d).

3. The climate and forest – links and processes

The greenhouse gas balance of an ecosystem – in this case the forest – is the net exchange of three greenhouse gases between the ecosystem and the atmosphere: carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O). In terms of volume and climate effect, carbon dioxide is by far the most important of these gases. Methane and nitrous oxide are much more effective greenhouse gases, which means that even relatively small amounts have a significant impact on the climate.

Carbon dioxide and methane contain carbon, and the movement of these gases is therefore part of the global carbon cycle.

The carbon cycle

The carbon cycle is the chemical engine that provides most of life on Earth with building materials and energy. The carbon cycle is also very important for the chemical composition of the atmosphere and hence the climate system.

Carbon paths

Green plants absorb carbon dioxide from the atmosphere and bind it by means of photosynthesis into carbohydrates, using energy from the sun. Some of the carbohydrates that plants build up are used to supply them with energy, and they release carbon dioxide into the atmosphere during this process. The process is known as autotrophic respiration, which in simple terms means that the plants breathe.

The balance (net primary production, NPP) is the amount of carbon that plants can use to build up biomass in their stems, roots, leaves, etc.

Plants and parts of plants are eaten by herbivores, or eventually die and are broken down by microorganisms. Herbivores and microorganisms use carbohydrates as a source of energy. In this way carbon is transported through the food chain and most of it returns to the atmosphere as carbon dioxide when animals breathe, or when they eventually die and decompose. This process is called heterotrophic respiration. Disturbances such as fires, insect infestation or logging increase heterotrophic respiration. They generally also produce a warmer climate.

Measurements and units

Stored carbon and the movement of carbon are usually quoted in this report in Mt (megatonnes) or Gt (gigatonnes).

1 Mt = 1 million (10^6) tonnes
1 Gt = 1 billion (10^9) tonnes
1 Gt is therefore 1,000 Mt.
In most cases, the movement of carbon dioxide (CO_2) is expressed as carbon (C). 1 kg of carbon is equivalent to 3.7 kg of CO_2. Conversely, 1 kg of CO_2 contains 0.27 kg of carbon.

1 m^3 of wood contains about 0.2 tonnes of carbon.

The CO_2 equivalent unit is a measure of the combined greenhouse effect of emissions of several greenhouse gases. For example, methane is 23 times more effective as a greenhouse gas than carbon dioxide, which means that 1 kg of methane has the same climate impact as 23 kg of carbon dioxide. The emission of 1 kg of carbon and 1 kg of methane is therefore 1 + 23 = 24 kg CO_2 equivalents.

Some of the carbon that plants absorb from the atmosphere accumulates in the soil as dead organic matter. This movement is small and diminishes as a forest grows older, but over time can still lead to the accumulation of large deposits of carbon.

Fires play a key role in the carbon cycle, in the same way that the respiration of living organisms breaks down plant biomass, returning carbon to the atmosphere. Tropical savannahs and boreal forests are ecosystems that are adapted to periodic natural fires. Fires in these ecosystems supply 2–5 Gt (gigatonnes) of carbon to the atmosphere each year (Scholes 2004).

In addition to the above processes, a number of smaller carbon paths make up the carbon cycle. Three of these should be noted here: VOCs, methane and dissolved organic carbon.

VOC (Volatile Organic Compounds) is an umbrella term for volatile organic compounds, such monoterpenes. Plants emit a large number of such compounds into the atmosphere, usually in small amounts (Scholes 2004). Emissions of VOCs from boreal forests can be roughly expected to rise with increasing photosynthesis, since the formation of these substances is closely linked to photosynthesis (Bäck & Hari 2009). VOCs condense in the atmosphere as aerosol particles that affect atmospheric absorption of radiation. They also act as nucleation points for cloud formation, which affect the lifetime of clouds and their response to radiation. According to the IPCC, these aerosols are currently the greatest element of uncertainty in estimates of climate impacts (Kulmala et al. 2009).

Methane is released when organic matter decomposes in oxygen-free or oxygen-poor environments (such as wetlands, landfills or in the gut of herbivores) (Scholes 2004). Methane is 23 times more effective than carbon dioxide as a greenhouse gas. This means that one molecule of methane produces the same warming effect as 23 molecules of carbon dioxide (Morén & Olsson 2007). Chemical conditions in the soil determine whether methane is produced or broken down (Nordin et al. 2009). In forested land it is mainly peatlands that emit methane, and the drainage of such land for forestry can greatly influence methane production. (Bergkvist 2007). (See also section 6 on the drainage of peatlands.)

Both methane and VOCs are converted more or less rapidly into carbon dioxide in the atmosphere. During this process they affect atmospheric chemistry in a way that can sometimes lead to the formation of another powerful greenhouse gas, low-level (tropospheric) ozone (Scholes 2004).

Dissolved organic carbon (DOC) from the partially decomposed material in the top layer of soil is carried by water filtering down through the soil bed. Some of this dissol-

Carbon stores, sources and sinks

A carbon store is a quantity of carbon stored in a given system, for example in the growing forest in Sweden or in a forest ecosystem. The size of a carbon store changes with time as a result of the movement of carbon to or from the pool.

A carbon sink is a system that absorbs more carbon from the atmosphere than it emits (reserves increase).

Carbon sequestration means that carbon is removed from the atmosphere and stored in a sink.

A carbon source is a system that emits more carbon into the atmosphere than it absorbs (reserves decrease).

The carbon balance or greenhouse gas balance is the net sum of all movements of carbon or greenhouse gases in the system being examined. If the sum of all carbon paths from the atmosphere to the forest ecosystem is equal to the sum of all paths in the opposite direction the carbon balance is then zero. The carbon balance varies over time.

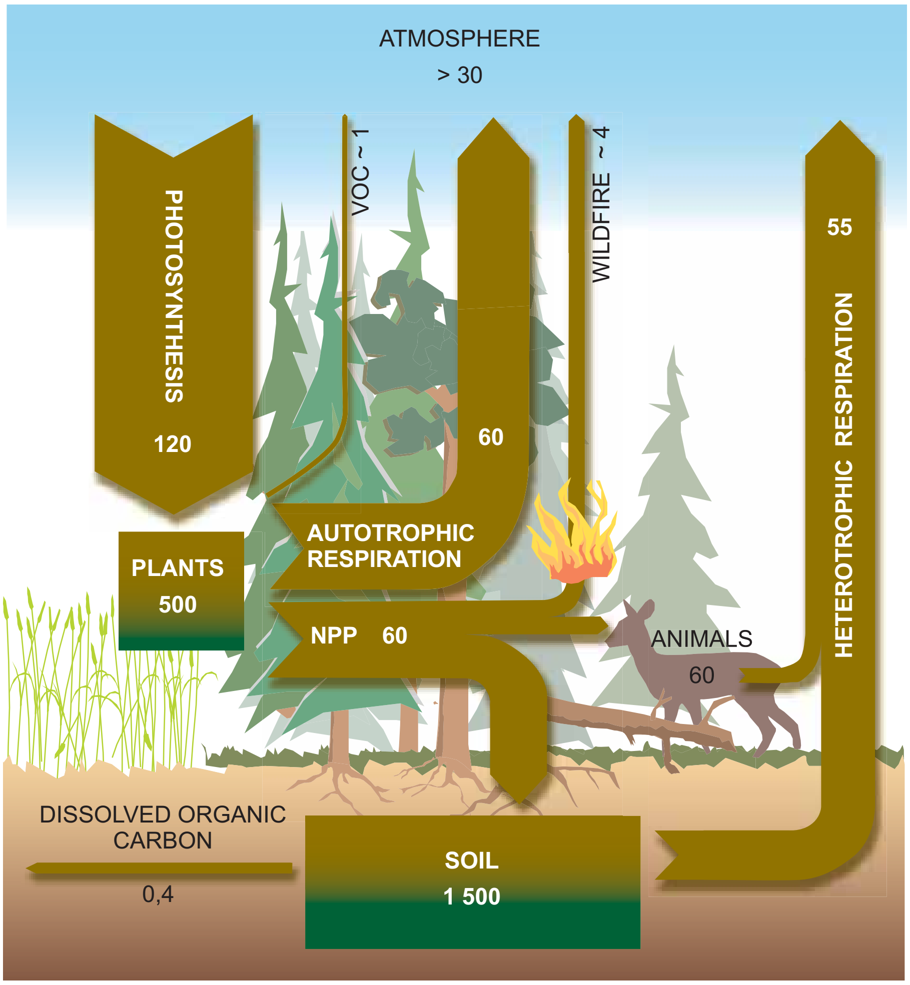


Figure 2. The carbon cycle in terrestrial ecosystems. The share of carbon stored by boreal forests in soil and plants is shown by the green shaded area in each box.

The diagram shows carbon paths under natural conditions, so the effects of human activity are not represented.

Stored carbon is given in gigatonnes (Gt) and carbon paths in Gt per year.

(1 Gt = 1 billion tonnes).

The natural carbon paths in the diagram can be compared with carbon dioxide emissions from industrial processes and the burning of fossil fuels, which are calculated to total around 8 Gt of carbon per year (Scholes 2004). *(After Steffen et al. 2004).*

ved organic carbon is transported by groundwater into lakes and streams, but in boreal forest ecosystems much of it is trapped in the soil, where it helps to build up relatively stable reserves of carbon. In Swedish forest land, a large proportion of stored carbon is held in mineral soil, carried there as DOC in groundwater (Morén & Olsson 2007).

Carbon stores

The quantity of carbon stored globally in living plant biomass is around 500 Gt, which is relatively little when compared with the carbon stored in the oceans and in fossil deposits (oil and coal). The carbon stored in plants is important, however, because it can increase or decrease quite rapidly if there are changes in the climate or the way we manage forests or agricultural land.

The total amount of carbon stored in soil in terrestrial ecosystems around the world is estimated at 1,500–2,000 Gt, in other words three times more than is present in growing biomass and 50 times more than is in the atmosphere. A very large proportion of this carbon, at least 40 per cent, is found in boreal forests (Scholes 2004).

Carbon paths and carbon storage in boreal forests

Globally

According to the UN climate panel, IPCC, 550 Gt of carbon is stored in boreal forests (in soils and vegetation), which represents 30 per cent of all the carbon in the world's ter-

Table 1. Carbon stored in soil and plant biomass in the world's forests (Gt). *(Woods Hole Research Center.)*

Biome	Area (mill ha)	Soil	Plant biomass	Total
Boreal forest	1 509	625	78	703
Tropical forest	1 756	216	159	375
Temperate forest	1 040	100	21	121

restrial ecosystems. Boreal forests sequester one Gt of carbon each year (IPCC 2007a). The figures in Table 1 are based on other sources and differ slightly from those mentioned, but still provide a fair comparison of carbon storage and carbon sequestration in the world's major forest regions.

Whichever estimates are used, the amount of carbon stored in the boreal forest ecosystem is greater than in any other terrestrial ecosystem, and almost twice as much as that stored in tropical forests (Kasischke 2000). Even when we consider unit area, boreal forests contain twice as much carbon as tropical forests (IPCC 2002). The reason for this difference is basically the climate. In most forests in warmer regions most of the carbon is held in living plants. Dead organic matter decomposes rapidly and carbon does not build up in the soil. In boreal forests, on the other hand, partly decomposed organic matter accumulates in the soil over time, because the low temperatures slow down decomposition. Boreal forests that are left to grow undisturbed, slowly build up stores of carbon in the soil over hundreds and thousands of years.

The amount of carbon stored per unit area is higher in natural boreal forests than in managed forests from which timber is regularly removed by felling. In an old-growth forest in Sweden (i.e. forest that has never been clear-cut and has mostly been left to grow undisturbed for at least a couple of hundred years), there can be 3-4 times as much growing stock as there is in the average managed forest, which means that the amount of carbon stored in the growing forest is likewise greater. There is also more carbon stored in the soil in old, unmanaged forest, as the store continues to be built up, albeit slowly, as long as the forest is allowed to grow undisturbed. On the other hand, young and middle-aged forests sequester more carbon than old forests, per unit area, since they grow faster (Olsson 2010).

The enormous amounts of carbon stored in soil and vegetation give the boreal forests a key role in the future climate, especially as they are expected to be very sensitive and react quickly to rising temperatures, with dramatic consequences for the carbon cycle and atmospheric levels of greenhouse gases. Such changes are already apparent, as we shall see in the following sections.

Sweden

The amount of carbon stored in Swedish forests is estimated at 1 Gt in growing biomass, 1.9 Gt in the forest soil (Olsson, M 2010) and a further estimated 0.6 Gt in drained peatland with productive forest (Bergkvist & Olsson 2008). The amount of carbon stored in both biomass and soil, per unit area, is much higher in southern Sweden than in the north, but with considerable differences between different soil types (Morén & Olsson 2007).

According to official Swedish reports to the Climate Convention (UNFCCC), the land use sector represented a carbon sink of about 0.04 Gt CO_2 equivalents in 2009 (Swedish EPA 2011), which equates to around 0.01 Gt of carbon. Forests and forestry account for almost all this carbon sink. This figure can be compared with Sweden's total emissions of greenhouse gases, which were around 0.06 Gt CO_2 equivalents (EPA 2011). It should be kept in mind that reporting to the UNFCCC is not governed solely by scientific principles, but is also influenced by the UNFCCC framework (see section 9).

Forest carbon sequestration has almost halved over the past decade. The reason is that logging has increased faster than forests have grown (Bergqvist & Olsson 2008). Modelling calculations show that, using the same forestry methods as today, the carbon sink provided by growing forest will remain largely unchanged over the next 20 years. Carbon sequestration in soil will not change significantly either. The calculations assume that climate change will favour forest growth. If this effect is excluded the carbon sink is reduced. (Lundblad et al. 2009).

Climate effects on carbon paths

The storage and release of carbon in boreal forests is primarily governed by four factors:

- growth of trees and vegetation,
- decomposition of dead organic matter,
- the frequency and extent of fires and other disturbances,
- changes in the extent of permafrost (Juday et al. 2005).

Permafrost is not addressed in this report.

Growth

Increased growth means that plants absorb more carbon dioxide from the atmosphere. Temperature rises may enhance forest growth, mainly by extending the growing season. In boreal regions the early arrival of spring has a particularly marked effect, because there is also plenty of light at this time of year, in contrast to autumn (Hari & Kulmala 2008). As the climate changes, availability of water may be a factor that limits growth, at least regionally, and this may counteract or offset the positive growth effects of higher temperature (Hari & Nikinmaa 2009). In large parts of the boreal region the availability of nitrogen is a growth-limiting factor.

Higher levels of carbon dioxide in the atmosphere can directly affect tree growth, since plants use carbon dioxide in photosynthesis. It is known that availability of carbon dioxide can be a limiting factor for growth, especially when there is plenty of light. However it cannot be assumed that carbon dioxide levels at current and expected levels will lead to increased photosynthesis. Nor is it certain that increased photosynthesis would lead to more tree growth, since internal mechanisms in trees and forests can offset the fertilisation effect of carbon dioxide (Hari & Kulmala 2008).

Decomposition

Like tree growth, microbiological processes in the soil are highly temperature-dependent. Organic matter decomposes faster as temperature rises. This not only means that more carbon is released, but also that the availability of nitrogen (and other nutrients) in the soil increases, which could accelerate forest growth (Hari & Kulmala 2008).

The movement of methane (CH_4) can also be affected by the release of more nitrogen in the soil, and by higher temperatures and changing rainfall patterns, but understanding of this area is very limited (Pihlatie 2009).

Disturbances

Disturbances are a very important factor in the carbon budget of terrestrial ecosystems. They usually entail large losses of carbon into the atmosphere as a result of trees and other vegetation dying and decomposing after the disturbance. Forest fires, which are the main form of disturbance in old-growth boreal forest ecosystems, also enhance decomposition in the soil. Large-scale insect infestations and the storm-felling of trees have similar effects on the carbon balance (Juday 2005). It has been questioned whether measurements of forest ecosystem growth or the direct exchange of carbon dioxide with the atmosphere are relevant in the climate context, since they do not take into account the importance of disturbances. It has been shown that disturbances play a major role in the large year-to-year variations in the boreal forest carbon balance (Magnani et al. 2007).

Feedback effects on climate

Changes in boreal forest growth and biomass, and in soil processes, therefore affect the carbon cycle and hence atmospheric levels of carbon dioxide and other greenhouse gases.

Climate-driven changes in forest ecosystems thus have feedback effects on the climate. This feedback can be positive, i.e. driving global warming, or negative, i.e. slowing warming (Juday 2005). There is still disagreement within the scientific community on the question of whether the net feedback effect between the climate and forest carbon balance is positive or negative – in other words whether a warmer climate will increase or decrease carbon sequestration by forests (Lagergren et al. 2006). In many cases the disagreements seem to depend on the timescale, and whether the effects of large-scale disturbances are considered or not.

If the analysis is limited to how warmer climate and higher carbon dioxide levels in the atmosphere affect forest growth, the net feedback tends to be negative, i.e. forests sequester more carbon. This assumes that the forest will be left undisturbed to react to changes in the climate and atmospheric chemistry, and that the trend is representative of the forest landscape as a whole. The picture changes if allowance is made for the fact that fires and other disturbances are expected to increase. The release of carbon due to more frequent disturbances is considered by many studies to be greater than carbon sequestration due to enhanced forest growth *(see section 5).*

Other links between boreal forests and climate

Boreal forests can also affect climate through mechanisms that are not directly linked to the carbon cycle. Two such mechanisms are briefly discussed here.

Albedo

In meteorology, albedo is the ratio between incident solar energy and the portion of solar radiation that is reflected back into space by cloud cover and the Earth's surface. The solar radiation that is not reflected is absorbed by soil or vegetation, for example, and transformed into long-wave thermal radiation. It therefore contributes to global warming. If the albedo decreases, it therefore means that more of the incident solar radiation is converted into heat, which increases global warming. Conversely, an increase in albedo has a cooling effect.

The Earth's albedo is thus very important for the planet's thermal balance. Changes in the prevalence of different vegetation types or the duration and extent of snow cover can be expected to affect the albedo, but the relationship is complex and the effects difficult to predict.

None of the world's other major biomes has such a large impact on albedo as boreal forest. Its dark, irregular surface absorbs much of the incident radiation, while the flat, snow-covered tundra has a high albedo. The reduced coverage of boreal forests and increased frequency of forest fires could both be expected to slow warming by changing albedo (Juday 2005).

Enhanced forest growth means more coniferous biomass, which may reduce the albedo of the forest landscape. At the same time this will increase transpiration, the amount of water vapour evaporating from trees into the atmosphere, and lead to increased cloud formation (Räisänen & Smolander 2009). As mentioned earlier, cloud formation can also be affected by VOC emissions.

These effects may be of great importance as a balancing factor in the global climate system. In a cold climate, the low albedo of boreal forest could have a warming effect. In a warmer climate, it may result in so much water vapour formation that the increased cloud formation has a cooling effect (Spracklen et al. 2008).

Nitrous oxide

Nitrates in forest soil can be released into the atmosphere as nitrogen gas, nitric oxide, or nitrous oxide (N_2O) in proportions determined by the chemical conditions in the soil (Nordin et al. 2009). As a greenhouse gas, nitrous oxide is 296 times more effective than carbon dioxide (Morén & Olsson 2007).

The formation of nitrous oxide is especially favoured in soils where the water table is high and variable (Morén & Olsson 2007).

Emissions of nitrous oxide from the boreal forest ecosystem total around 0.5 Mt of nitrogen per year, which in terms of climate impact is equivalent to just over 0.1 Gt of carbon (calculation based on Pihlatie et al. 2009). Emissions of nitrous oxide from Swedish forest land have been estimated at 4,700 tonnes, which in terms of climate impact is equivalent to nearly 0.0004 Gt of carbon. Drained peatland accounts for virtually all these emissions (Bergkvist 2007).

A warmer climate could lead to higher emissions of nitrous oxide. Experiments with nitrogen fertilisation have shown that forest ecosystems respond differently to nitrogen additions. Emissions of nitrous oxide seem to depend largely on whether forest growth is limited by the availability of nitrogen or not at the time the increase occurs. In nitrogen-limited systems, the additional nitrogen is quickly absorbed by plants, and nitrous oxide emissions increase only temporarily shortly after the addition. On the other hand, systems that already have high nitrous oxide emissions react strongly to nitrogen additions, and emissions increase further. If we assume that a system responds in the same way to nitrogen additions that arise from increased decomposition of organic matter due to rising temperature, it is possible to roughly estimate the nitrous oxide emissions from boreal forests. A Finnish modelling study has estimated that nitrous oxide emissions across the entire boreal forest region could reach 1.5 Mt of nitrogen per year with moderate global warming, which is approximately three times the current emission level (Pihlatie et al. 2009). The increase would, in terms of climate impact, be equivalent to the emission of around 0.12 Gt of carbon, which is roughly 10–20 per cent of the total carbon sequestered in boreal forests.

Draining of forested peatlands and fertilisation of forest are measures that may also affect emissions of nitrous oxide *(see section 6).*

The forest as a climate policy tool

Essentially there are three different ways to use forests to manage and influence the global carbon cycle and hence the concentration of carbon dioxide in the atmosphere (Lindner & Karjalainen 2007):

- **Protection.** Protecting forests is one way to prevent the carbon already stored there from being released and to preserve their natural ability to sequester carbon. This include measures to combat deforestation, increasing the area of forest protected in natural reserves and other protected areas, and measures to reduce the extent of fires and other disturbances that reduce carbon storage.

How reliable are the figures?

The figures given for carbon storage and carbon paths in this section show a wide spread. They give an indication of the current state of knowledge. Despite extensive in-depth research there is still considerable uncertaintyover the amount of carbon present in the Earth's forest ecosystems and the extent of annual carbon sequestration.

The difference between the highest and lowest values given in the literature for boreal forest carbon sequestration is about 0.5 Gt. Estimates of the carbon balance for European forests vary by a similar amount – from a source of 0.1 Gt per year to a sink of 0.46 Gt per year (Lindner et al. 2004). The difference is equivalent to almost half the carbon emissions of EU countries from fossil fuels (Luyssaert et al. 2010).

The fact that estimates of carbon balance give different results is duepartly to the method and the choice of carbon stores and paths that are considered. A comprehensive study of carbon balance in European forests based on inventory data, measurements of carbon dioxide paths andmodelling calculations shows a very wide range depending on the method or modelling assumptions that are used. Estimates of net primary production vary between 439 and 574 grams of carbon per square metre per year, i.e. by over 30 per cent (Luyssaert et al. 2010).

In Sweden and many other countries, the carbon stored as biomass above ground, i.e. in growing forests, is calculated from data on timber stocks etc., in forest inventories (in Sweden, the National Inventory of Forests). Data on the biomass in forest soil is not as good, and estimates are therefore more uncertain. The Kyoto Protocol also requires that other carbon stores are taken into account, such as organic carbon in the soil, and these are rarely measured to the required accuracy. The problem with estimating changes in the organic carbon content of soil is that changes over time are small in relation to the size of the carbon pool, while carbon content varies considerably between different soils. This makes it difficult to scale individual measurements up to the national level (Lagergren et al. 2006).

Technology exists for directly measuring carbon exchange between forests and the atmosphere (eddy covariance). However, this technology is expensive and measurements can therefore only be made in a few places. In Sweden, there were eight towers for carrying out such measurements in 2006, which is far from adequate for making direct estimates of the total forest carbon balance. To do this, it would require measurements in forests of different species composition, age class, soil conditions, climate, etc. (Lagergren et al. 2006).

Uncertainty in Swedish reports on carbon uptake by forest biomass for the UNFCCC have so far been around 20 per cent of the size of the carbon sink. Uncertainties in Swedish estimates of changes in the carbon stored in forest litter and soil are estimated at 70 and 35 per cent respectively (Lundblad et al. 2009). The figures for Sweden are still comparatively reliable, since there is detailed inventory data for both growing forests and forest soil in our country. Sweden is one of the few countries that have data for objectively estimating the accuracy of uptake or emissions of carbon from living biomass. Most countries rely on subjective assessments (Lundblad et al. 2009).

Forecasts of how the carbon balance in boreal forests will change are even more problematic. These must be based on the assumption that there will not be any fundamental changes in the behaviour of forests, despite the fact that key environmental factors will change beyond the evolutionary limits to which vegetation has had to adapt so far. Insect and fungal infestations are examples of ecosystem phenomena that are very significant and will eventually cause damage to ecosystems and reduce carbon sequestration.

This means that our estimates of future carbon sequestration are often likely to be over-optimistic (Hari et al. 2009).

From the perspective of climate policy, this large scientific uncertainty will naturally be a problem when countries try to account for carbon sinks in forest ecosystems or forest products in their emission reductions.

• **Forest management for carbon sequestration.** The way we choose to manage the forest and use forest products has a big influence on overall climate impact. Measures that favour forest growth, such as fertilisation and the creation of new forest on previously unforested land are two examples. Other options are to increase the carbon stored in forests and forest products, for example by extending rotation periods or prolonging the lifetime of products.

• **Substitution.** Substitution means that forest products are used to reduce the use of fossil fuels or to replace materials that produce emissions of greenhouse gases during manufacturing. This can be done by using wood as fuel, and by using wood as a substitute for more energy-demanding materials, such as steel or concrete in buildings.

These three methods have differing potential to help reduce levels of atmospheric carbon dioxide in the short and long term.

Protection is the most effective method in the short term in areas where old forests with large amounts of stored carbon are threatened by logging or other forms of exploitation (such as the extraction of oil and natural gas).

Boreal forests are naturally vulnerable to disturbances – fires, storm-felling of trees and infestation by pests – which return carbon to the atmosphere. In the long-term, natural boreal forest reaches a state where the amount of carbon lost through disturbances and decomposition is equal, or nearly equal, to the amount of carbon gained by sequestration in living biomass. The amount of carbon stored in the soil can continue to grow for thousands of years, however.

When forest is managed to benefit the climate it generally means that the rate of carbon sequestration or the total carbon stored in the ecosystem will increase compared to the alternative of taking no measures. It often takes time, however, for measures to take effect, and in the short term the effect on the carbon balance can be neutral or even negative, for example, because more carbon is released from the soil for some time after harvesting than is sequestered in new growth forest. No matter which management model is used, sooner or later forest production reaches a ceiling that limits carbon sequestration.

The same applies to the sequestration of carbon in forest products. Sooner or later the forest products decompose or are burned. Unless production of wood products rises continuously (which is obviously not possible in the long run), at some stage an equilibrium is reached between losses and gains in stored carbon.

The benefits of substitution are due to the fact that forest fuel provides much lower emissions of greenhouse gases than fossil fuels. Similarly, wood produces less emissions than other building materials. Each ton of oil, steel or concrete that is replaced by wood is assumed to reduce emissions of carbon dioxide into the atmosphere, compared with the situation if substitution did not take place. This means that substitution, in contrast to protection and forest management, makes a large, long-term contribution to limiting carbon dioxide levels in the atmosphere – assuming that there are fossil fuels to replace. Substitution can take place at several stages. Logging residues can be used as fuel. Wood can replace steel or concrete in buildings, and it can be burnt when the buildings reach the end of their life.

At the stand level, these three methods are mutually exclusive to some extent. If you want to build and maintain the largest possible carbon store in growing forests you cannot harvest raw material for substitution at the same time. Management can, on the other hand, be combined with substitution. Increasing forest production provides larger amounts of biomass that can be used for substitution. The timber produced by each forest generation adds to the substitution effect of earlier generations.

From a wider geographical perspective – regional or national – these methods may of course be combined. There is no need to manage all forests in the same way. From a climate perspective, there is, as we shall see, good reason to treat older uncultivated forests differently from production forests.

As mentioned, these approaches have different effects depending on the time scale. Measures that have considerable positive impact on greenhouse gas emissions in the long run, may have little or even a negative effect in the short term. In the present situation, when a rapid reduction in emissions is necessary to avoid dramatic climate effects and runaway warming, this is an extremely important point. An approach that appears ideal over a time frame of 100 or 200 years may be counter-productive in light of what we need to achieve in the next few decades.

4. About system boundaries

When discussing the link between forests and climate, one factor that is of central importance is how we define the system that is being analysed, in space and time. Different boundaries can lead to very different conclusions about how a particular action or strategy affects the movement of greenhouse gases, and hence the climate.

Estimates and projections of how a warmer climate will affect forest growth are often based on considering a forest stand. We limit ourselves to looking at how an individual growing forest stand reacts to changes in temperature and/or carbon dioxide in the atmosphere. If we also include forest soil and its related processes in the system it can change the outcome, however, since decomposition in the soil and hence carbon paths are also affected by climate. Extending the perspective to cover a larger area or ecosystem brings forest fires and other natural disturbances into the picture, as well as less productive areas of woodland, sometimes including treeless peatlands. The interaction between forests and the climate in uncultivated forests is best understood from this ecosystem perspective.

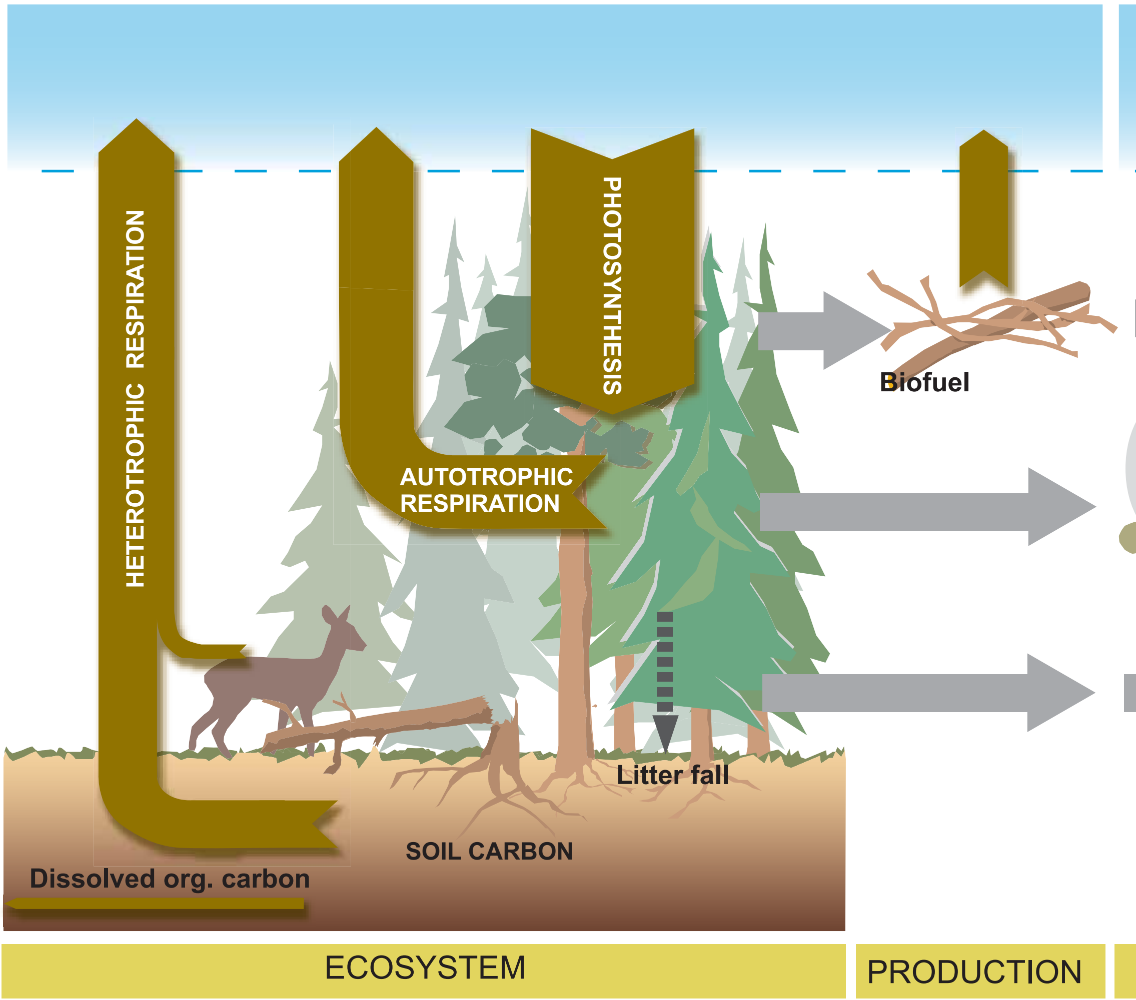
In managed forest ecosystems, there is an additional factor that has a large effect on the carbon balance, namely man's removal of biomass by harvesting. When discussing the climate impacts of timber harvesting we must make clear whether the analysis is confined to the harvested timber, or also includes the effects of logging (and other forestry activities undertaken to produce the harvested biomass). It is known, for example, that clear-cutting results in significant releases of carbon from forest land (Lindroth et al. 2009).

The effect of harvesting on the movement of greenhouse gases depends to a large extent on how the harvested wood is used. Under the rules that have so far governed the reporting of sinks under the Kyoto Protocol, it is assumed that the carbon in harvested timber immediately returns to the atmosphere. This assumption is also widely used in other analyses. In practice, however, some of the timber is used to build houses, for example. It remains as stored carbon for decades, before it finally decomposes or is burned. To make allowance for this effect, the purpose of the harvested timber must also be included in the system that is analysed. Carbon dioxide emissions from forest machinery, hauling of timber and forestry processes must then also be incorporated.

The analysed system can be extended even further, by taking into account the effects of substitution. Biomass from forests can be used as fuel to replace coal and oil. The resulting reduction in carbon dioxide emissions can be included in the calculation. Similarly, we can make allowance for the fact that wood replaces other building materials, such as concrete, which give rise to much higher carbon dioxide emissions during their manufacture. Cuts in emissions due to reduced production of concrete can therefore be included in the calculation. As we shall see later, these substitution effects play a very significant role in the overall climate impact of forestry.

The time frame plays a similarly important role to the spatial boundaries of the system. Almost all projections of climate change and the consequences of different scenarios or measures take 2100 as the far horizon, i.e. about one forest generation in managed forests. If we are to limit global warming to no more than two degrees, the critical time period is much shorter than this. As mentioned, greenhouse gas emissions must begin to fall by 2015 and be reduced by 50–85 per cent by 2050.

Few analyses of the climatic effects of different approaches to using forests and forest products consider this short-term perspective. A hundred years is a short time for a forest. It is common for analyses of climate impacts to look at time spans of several



rotation periods, often 200–300 years, without considering how social developments and changing climate may affect forests, forest production, the development of building materials or the global energy supply over such a period of time (e.g. Eriksson et al. 2007, Bergqvist & Olsen 2008, Olsson, M. 2010, Sathre et al. 2010).

What may be a wise way of using our forests for the sake of the climate in the longer term – a hundred years or more – is not necessarily the best option over the period that is crucial for our future climate, in other words the next 30 years. We will return to this in following sections.

System boundaries in this report

This report considers various different system boundaries. The aim is to state clearly which boundaries are applied and how they affect the analysis and conclusions.

Section 5, which deals with unmanaged boreal forests, analyses the ecosystem including forest land. As long as no biomass is removed from the forest through logging, the ecosystem can effectively be seen as a closed system.

The greenhouse gases emitted by the system end up in the atmosphere, and those absorbed by the ecosystem are removed from the atmosphere. The net exchange between the ecosystem and the atmosphere determines the climate effect.

Section 6, which looks at managed forests, discusses how various forest management strategies and actions affect the uptake and release of greenhouse gases in the forest.

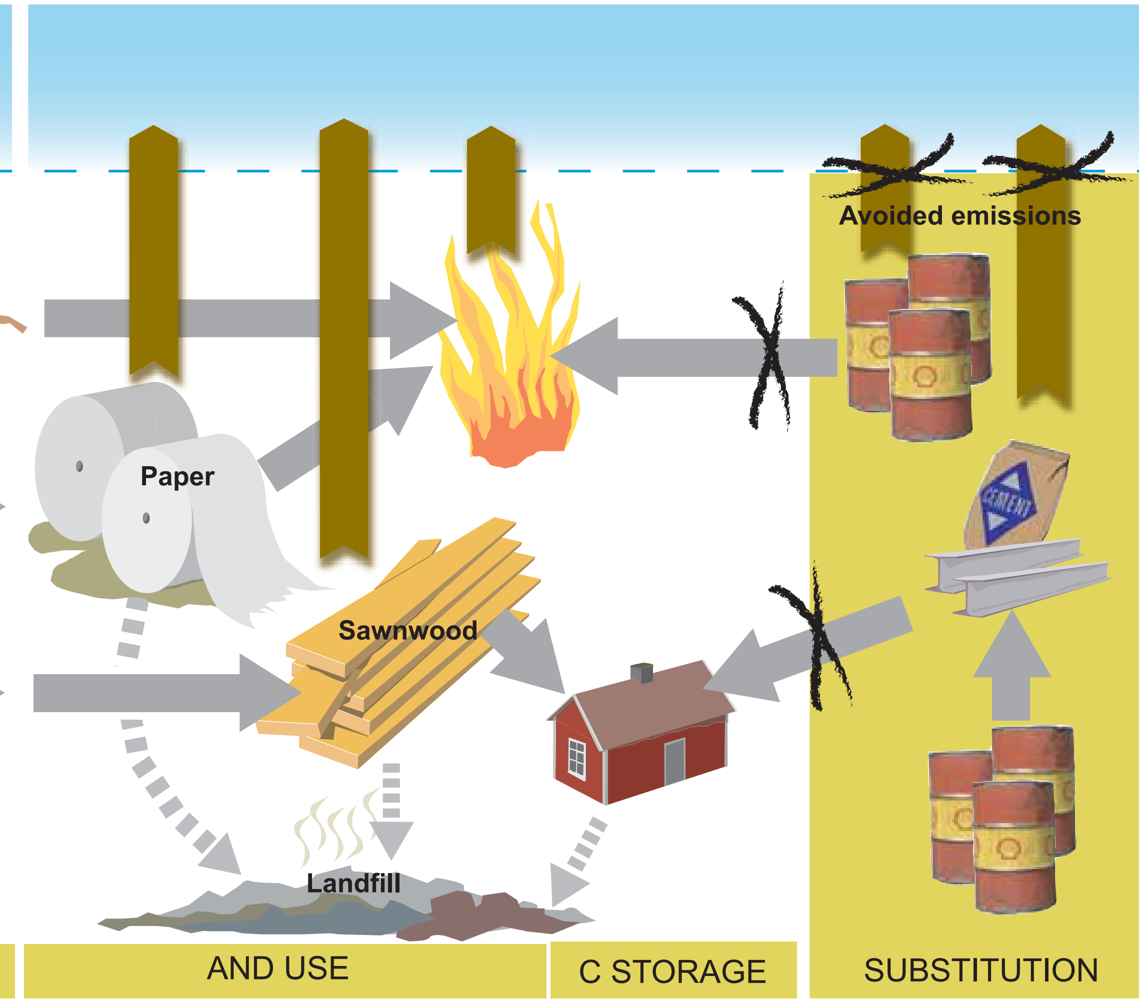


Figure 3. Links between forests, forestry and forest products from the climate perspective. In undisturbed forests, from which timber is never removed, the climatic effect is determined by the net flow of greenhouse gases between the forest ecosystem and atmosphere. In practice the forest ecosystem and atmosphere can be seen as a closed system. When biomass (wood) is removed from the system it not only affects the carbon balance in the ecosystem, the forest products also have an effect throughout their lifetime. Greenhouse gas emissions are produced during transport, production and use.

The harvested forest products also contain stored carbon. Accounting for the effects of substitution means further extending the system, by including greenhouse gas emissions that are eliminated when forest products (fuel and timber) replace fossil fuels and materials produced with the aid of fossil fuels.

Once again the starting point is an ecosystem perspective. In managed forests, however, the extracted timber and what is done with the harvested biomass have a much greater impact on the climate than what takes place within the forest ecosystem. This applies particularly to substitution effects, as discussed in section 8. Carbon storage in harvested wood products is dealt with in Section 7.

In the case of time frame, this report also looks at the short-term perspective. The reason is that our ability to limit warming to a maximum of two degrees will, as mentioned, be decided over the next few decades. If we fail, there is greater risk that climate change will accelerate as a result of positive reinforcement mechanisms, such as thawing permafrost and extensive forest death, with consequent emissions of greenhouse gases into the atmosphere. In such a situation the conditions for boreal forests and forestry in the region could change dramatically. At the same time the opportunities for halting runaway warming through forestry and wise use of forest materials will shrink or even disappear since the changes in carbon paths that can be achieved by these means will no longer be sufficient to compensate for the massive injection of greenhouse gases into the atmosphere due to positive reinforcement mechanisms.

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5. Natural forest ecosystems

The fundamental difference between natural and managed forests in relation to the climate is that no harvesting of biomass (through felling) takes place in forests where natural dynamics prevail. No biomass leaves the system. Trees and other plants decompose when they die, and the carbon stored in their biomass either returns to the atmosphere as carbon dioxide, or is locked up in the soil for varying periods of time. The proportion of carbon that is stored in the soil and the rate of decomposition are of great importance from a climatic point of view. Fires, insect infestations and storm-felled trees are natural disturbances in boreal forests and may affect carbon paths dramatically.

This section discusses boreal forests mainly from the global perspective, since most of the natural boreal forest ecosystems lie in North America and Russia.

Forest growth

Effects of climate warming

It seems reasonable that a warmer climate would favour the growth of boreal forests, as the temperature and length of the growing season are limiting factors in the ecosystem. Studies of the way in which boreal forests have responded to warming so far show conflicting results, however. In recent decades, growth has increased in some cases and decreased in others, depending on the region, habitat and species. In some cases, considerable reductions in growth have been observed. One explanation may be the stress caused by drought, which is in turn a consequence of climate warming (Juday et al. 2005). Growth studies based on annual rings in trees throughout the boreal region have shown that a negative growth response to temperature increases during the 1900s is widespread. It can be seen across almost the entire boreal region and among a wide range of the conifer species investigated. Reduced growth is more common in the warmer areas of the each species' habitat, suggesting that temperature stress may be a contributing factor. In many places, the response of trees to rising temperature changed around 1950. The relationship was weakened or shifted in some cases from positive to negative (Lloyd & Bunn 2007). As temperatures rise, the negative effects on tree and forest growth could become more common as species and ecosystems are unable to adapt to ever more extreme environmental conditions (IPCC 2007d).

In parts of the boreal forest region, forest growth is affected by nitrogen deposition from anthropogenic sources. It is difficult to distinguish these effects from growth changes due to the climate (see below).

In the case of boreal forests in Canada, it has been shown that the potential increase in growth that results from a warmer climate may be enhanced or attenuated depending on the way precipitation patterns change (Kang et al. 2006).

Effects of carbon dioxide fertilisation

Increased levels of atmospheric carbon dioxide could favour tree growth, since green plants use carbon dioxide for photosynthesis. However, it is not certain that carbon dioxide concentrations at expected levels will lead to increased photosynthesis (Barnes 2003). Plants have not had time to evolve and adapt to such high levels of carbon dioxide and it is therefore not possible to predict how different species will react (Hari et al. 2009).

A number of trials in laboratories and in the field show that photosynthesis increases sharply if the level of carbon dioxide in the surrounding atmosphere rises. Plants seem to adapt to the higher levels, however, and within a few months, or at most years, the rate of photosynthesis returns to the original level. Field experiments in which entire trees have been grown in elevated carbon dioxide levels for several years have shown that the long-term increase in photosynthesis depends on nutrient availability in the soil (Eriksson, H 2007). Nitrogen availability could similarly be a limiting factor in temperature-induced growth. This makes forecasts of expected growth due to carbon dioxide fertilisation uncertain (Hari & Kulmala 2009).

Nitrogen deposition affects carbon sequestration in forests

Under natural conditions, growth in boreal forests is generally limited by the availability of nitrogen in the soil. Positive effects on forest growth due to climate warming have mainly been observed in areas where water and nutrients are not limiting factors, such as in Europe and eastern North America. These parts of the boreal region lie close to densely populated and industrialised areas and are therefore affected by nitrogen deposition from anthropogenic sources. In some of these areas, nitrogen deposition is ten times higher than the natural background level. Anthropogenic nitrogen deposition has been estimated to affect about 30 per cent of the boreal forest region (Hari & Kulmala 2008). In European forests, growth has generally increased since the late 1900s as a result of nitrogen deposition (Lindner & Karjalainen 2007). In Sweden, nitrogen deposition may account for up to 70–80 per cent of the difference in carbon storage between forests in southern and northern Sweden (Morén & Olsson 2007).

Deposition of nitrogen from air pollution therefore plays a very significant role in the growth of forests and how they react to a warmer climate. Modelling studies have shown that deposition of anthropogenic nitrogen can cause increased carbon sequestration totalling 0.44 to 0.74 Gt per year in the world's terrestrial ecosystems, mainly in boreal and temperate forests (Magnani et al 2007). As mentioned above, however, only a small part of the boreal forest region is affected by nitrogen deposition from anthropogenic sources.

Emissions of nitrogen oxides in the EU fell by 39 per cent between 1990 and 2008 (EEA 2010). According to most emission scenarios, nitrogen deposition over Europe will continue to decline over the next few decades (Luyssaert et al 2010). This means that the effects of nitrogen deposition on forest growth will also decrease.

Changes in ecosystems and vegetation types

Many modelling studies show that the climate zones in the northern hemisphere may shift around 500 km north with global warming of 2°C by 2100 (Kirilenko & Sedjo 2007). It might be imagined that the boreal forests would respond to such a change by migrating north with the climate zones. There are a number of studies based on vegetation models that outline such scenarios. The models rely, however, on the assumption that each tree species will grow wherever the climate is suitable, which in practice is highly unlikely, at least in a time frame as short as a hundred years (Aitken et al. 2008).

The reason is that the migration of the habitat of forest trees by an average of five kilometres per year, far exceeds the natural dispersal rate of these species, which averages 200–300 metres per year (IPCC, 2007 c). Isolated individuals may naturally spread faster than this and establish outposts that serve as starting points for continued dispersal, but this does not mean that the forest ecosystem can migrate northwards to keep up with climate change. The changes that can currently be seen, for instance in Alaska and at the tree line in the Scandinavian mountain chain, instead indicate a century-long time lag (IPCC 2007 d, Kullman & Oberg 2009, Lloyd 2005).

A more likely scenario is that high temperature peaks during the summer together with scarcity of water will lead to increased stress, lowered resistance to pests and diseases, and hence tree deaths. In combination with changes in disturbance regimes – larger and more frequent forest fires and insect infestations – this may lead to widespread forest decline that turns boreal forests into semi-open, savannah-like landscapes or open grasslands. This in turn would mean that very large amounts of carbon dioxide are released by forests and forest land into the atmosphere. Extensive

boreal forest death has been identified as one of the critical tipping points that could accelerate global warming in a vicious cycle if the temperature rises above a certain threshold level. A threshold level of 3–5 degrees rise in global mean temperature has been suggested for this scenario, but this figure is very uncertain (Lenton et al .2008).

Natural disturbances

The frequencies of fires and insect infestations have both increased in boreal forests in recent decades, and further warming is expected to reinforce this trend (Balshi et al., Kurz et al. 2008a, Kurz et al 2008b). More extreme weather events brought on by the future climate may also increase storm damage in forests (Lindroth et al. 2008).

Fires

Fires have a major role in the carbon cycle in the boreal zone, by not only releasing carbon during the fire, but afterwards as well. The combination of direct and indirect carbon paths due to forest fires in the boreal zone makes up more than 20 per cent of global emissions from burning biomass (Juday et al 2005). Changes in fire patterns have been shown to be a dominant factor in the carbon balance in Canadian boreal landscape over a fifty-year period (1948-2005) (Bond-Lamberty et al. 2007).

Sites of forest fires may remain a carbon source for around 30 years after a fire. Studies in boreal forests in Alaska have shown that about 20 per cent of the carbon in the upper layer of the soil is lost to the atmosphere through decomposition during the first 20–30 years after a fire, due to elevated soil temperature (Juday 2005).

In North America's boreal region, the total forest area affected by fire increased by a factor of 2.5 between the 1960s and 1990s. In western North America the area affected by fire doubled in the last 20 years of the twentieth century (Juday 2005). According to Russian data, the area of forest fires was 29 per cent higher in the 1990s than in the 1980s. Russian official forest fire statistics are problematic, however, and estimates based on satellite data consistently yield much higher figures. Both statistics and satellite data nevertheless show that the area of forest fires has increased since 1998 (Soja et al. 2007).

Emissions of carbon from forest fires in North America are estimated to have doubled from the 1960s to the 1990s, from around 0.03 Gt per year to more than 0.06 Gt. In Eurasia, emissions are estimated to have increased from 0.1–0.2 Gt per year in 1996/97 to nearly 0.5 Gt in 2002 (Kang et al. 2006).

Results from modelling studies suggest that the frequency and extent of forest fires will continue to increase with global warming (Juday 2005, Olsson, R 2010). It has been estimated that the number of days of high fire risk in Russia's boreal zone will increase by 12–30 per cent if the global mean temperature rises by 2.4°C (Malevsky-Malevich et al. 2008). If warming reaches +4°C the area affected by forest fires in North America could grow by 74–118 per cent by the year 2100 (Flannigan et al. 2009).

One modelling study has shown that an increase of 50 per cent in the area affected by fire may increase the amount of carbon released into the atmosphere by 0.33 to 0.8 Gt per year for the next 50–100 years, depending on fire frequency and on assumptions regarding the distribution of carbon stored in soil between organic soils and mineral soils (Kasischke et al 1995).

Modelling studies of warming by 2.4 to 3.4°C show that atmospheric carbon emissions from forest fires may increase by a factor of 2.5–4 compared with the1990s. This risks driving warming even further, which in turn creates conditions for more extensive forest fires (Soja et al. 2007).

At the same time, more frequent fires will increase the albedo of the boreal zone, which will have a cooling effect (Goetz et al. 2007). At least one study suggests that negative feedback due to the albedo effect would be greater than the positive effect of carbon losses over an entire forest fire cycle of 80 years (Bonan 2008).

Insect infestations

Extensive insect infestations that damage or kill large areas or forest are a natural disturbance in boreal forests, like forest fires. In terms of the area affected, insect infestations represent a bigger disturbance than fires. In eastern Ontario, Canada, the spruce budworm (Choristoneura) infested an area of forest 20 times larger than that affected by forest fires between 1941 and 1996 (Volney & Fleming 2007). In British Columbia, the largest outbreak ever of lodgepole pine bark beetle (Dendroctonus ponderosae) has been in progress for several years (Kurz et al. 2008a). Infestation by the Siberian silk moth (Dendrolimus superans sibiricus) in the Krasnoyarsk region of Siberia in the 1990s led to the loss of 50 million cubic metres of timber, equivalent to seven years' harvest for the region (Olsson, 2010). Even larger infestations have occurred in the last 100 years (Soja et al. 2007).

Insect infestations are expected to become more frequent and more extensive as a result of climate change, partly due to direct effects on insect populations and through disruption of forest ecosystem interactions (Stireman et al. 2005).

Extensive and more frequent insect infestations affect the carbon balance of boreal forest in the same way as forest fires, and these effects can be considerable. Dead and damaged trees that occupy large areas of forest reduce the uptake of carbon dioxide by the forest, while emissions increase when the dead wood subsequently decomposes. Spruce budworm infestations in British Columbia have transformed 37 million hectares of forest from a small carbon sink into a significant carbon source. At the peak of the outbreak its affect on the carbon balance was equal to 75 per cent of all forest fires in Canada (Kurz et al. 2008a).

While major fires mainly occur in natural forest ecosystems, major insect infestations also affect managed forests.

Storm-felled trees

The number of extreme weather events, including storms, is expected to increase in the boreal region as a result of global warming (IPCC 2007a). This means it is very likely that there will be more storm-felled trees and storm-related damage to forests, which will affect the forest carbon balance.

Data concerning the effects of storm-felling comes mainly from managed forests. (See also section 6.)

Old-growth boreal forests as carbon sinks

It was widely believed that old-growth forests are carbon neutral, that is, they cease to act as carbon sinks. However, a review of existing data shows that this is not the case, and

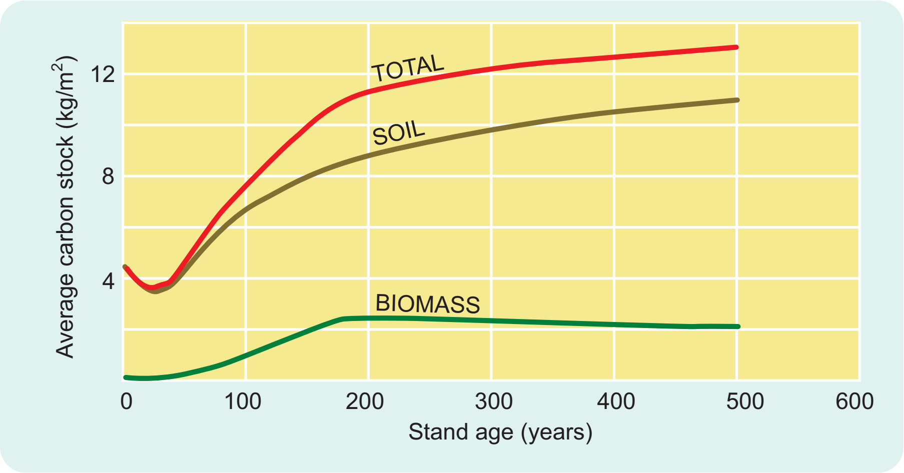


Figure 4. How stored carbon changes with time in an Alaskan black spruce forest. Carbon stored in biomass reaches a peak when the forest is around 200 years old, while the total carbon stored continues to rise even after 500 years, thanks to carbon uptake by the soil. The graph is based on estimates and shows idealised trends. *(After Kasischke et al 1995).*

that temperate and boreal old-growth forests usually continue to sequester carbon even when they are several hundred years old. Even 800-year-old forests can act as carbon sinks (Luyssaert et al. 2008). It has recently been reported that forests that have existed for thousands of years on islands in the north of Sweden continue to act as carbon sinks by storing carbon in the soil. Over 90 per cent of the carbon stored in these forests is soil carbon (Johnson & Wardle 2010).

Half of the world's remaining old-growth forests are found in temperate and boreal zones, and most of these forests are in turn in the northern part of the boreal zone. They are estimated to sequester 0.8 to 1.8 Gt of carbon per year, which is roughly 10 per cent of the carbon sequestered by global ecosystems.

Because old-growth forests continue to sequester carbon for centuries, they contain very large amounts. Much of this stored carbon will be released into the atmosphere if forests are felled or disturbed in other ways (Luyssaert et al. 2008).

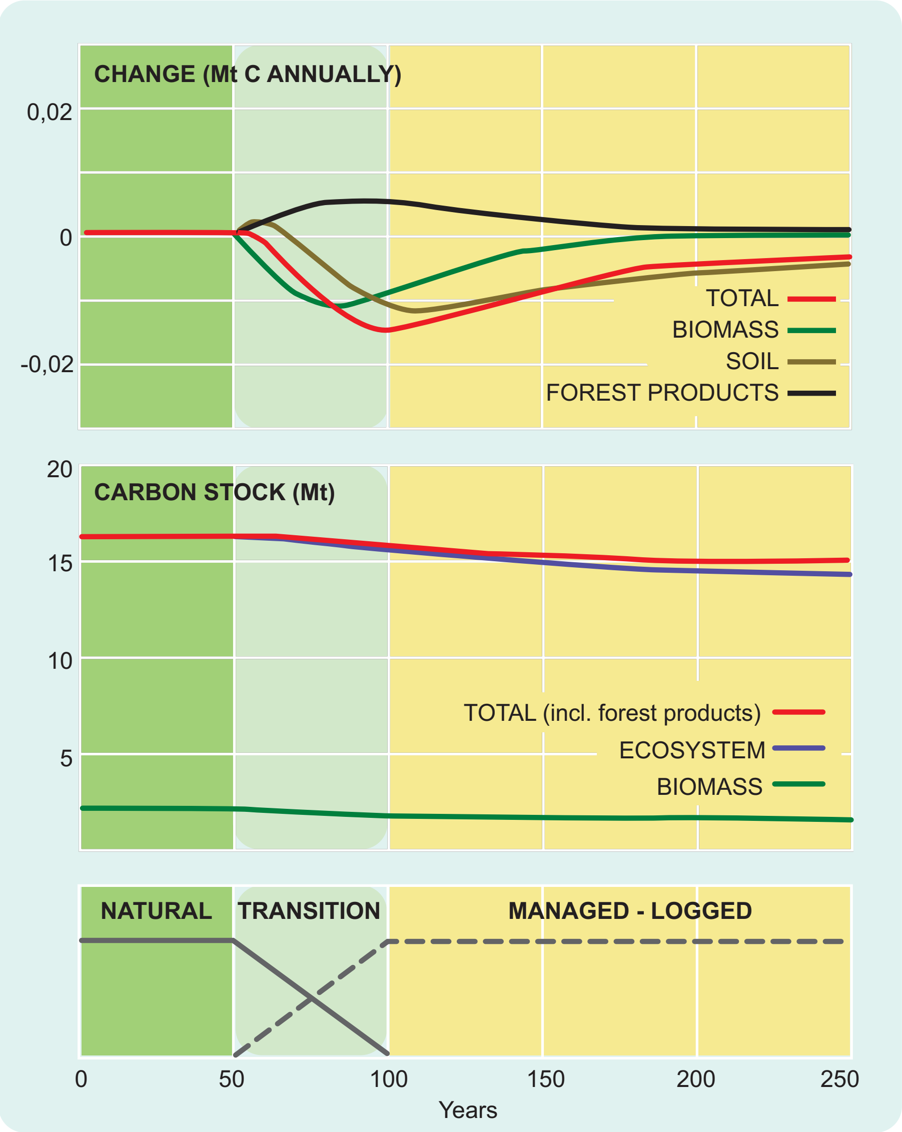
Although boreal old-growth forests are partly protected by their inaccessibility, continuing fragmentation, deforestation and exploitation (including mining, peat cutting and dam construction) will ultimately undermine their role as carbon sinks and carbon stores. Only a small percentage of boreal forests (less than 10 per cent) have some form of formal protection. As a result of fragmentation and increased human presence, forest fires caused by humans will become more common, especially in Siberia. In Russia, some 7.5 million hectares of forest were burned in 2002, and 14.5 million hectares in 2003. Most of these fires were started by man (Bradshaw et al. 2009).

Should we manage or protect old-growth forests?

Boreal primeval forests contain much more stored carbon than managed forests, mostly in the soil but also in the growing forest (Lindner & Karjalainen 2007). Old forests sequester carbon more slowly than younger forests (which grow faster), but they are not – as often claimed – carbon neutral. Even centuries-old forests may be carbon sinks, as mentioned above. How they are likely to affect the climate depends on the speed and extent of the anticipated changes in natural disturbances, which in turn are determined by climate change.

It may be worth noting that of all the carbon stored in timber stocks over the next 20 years it is estimated that 70 to 90 per cent will be in forest reserves and conservation areas, in other words generally older forest which for conservation reasons is protected from logging (Sundstrand et al. 2009).

Figure 5. Changes in annual carbon paths (top) and carbon stored (middle) in a boreal forest landscape in Canada during the transition from old-growth forest to managed forest. In years 0–50 the forest is unmanaged and is subject to natural disturbances (with a disturbance frequency of 80 years). In years 50–100 the natural disturbances are gradually replaced by logging, to the same extent but with a longer rotation period (120 years). The results are based on modelling simulations. The analysis does not include the greenhouse gas emissions that arise from processing, transport and use of the harvested timber. The study takes into account the carbon stored in harvested forest products, but not substitution effects. *(After Kurz et al. 1997).*

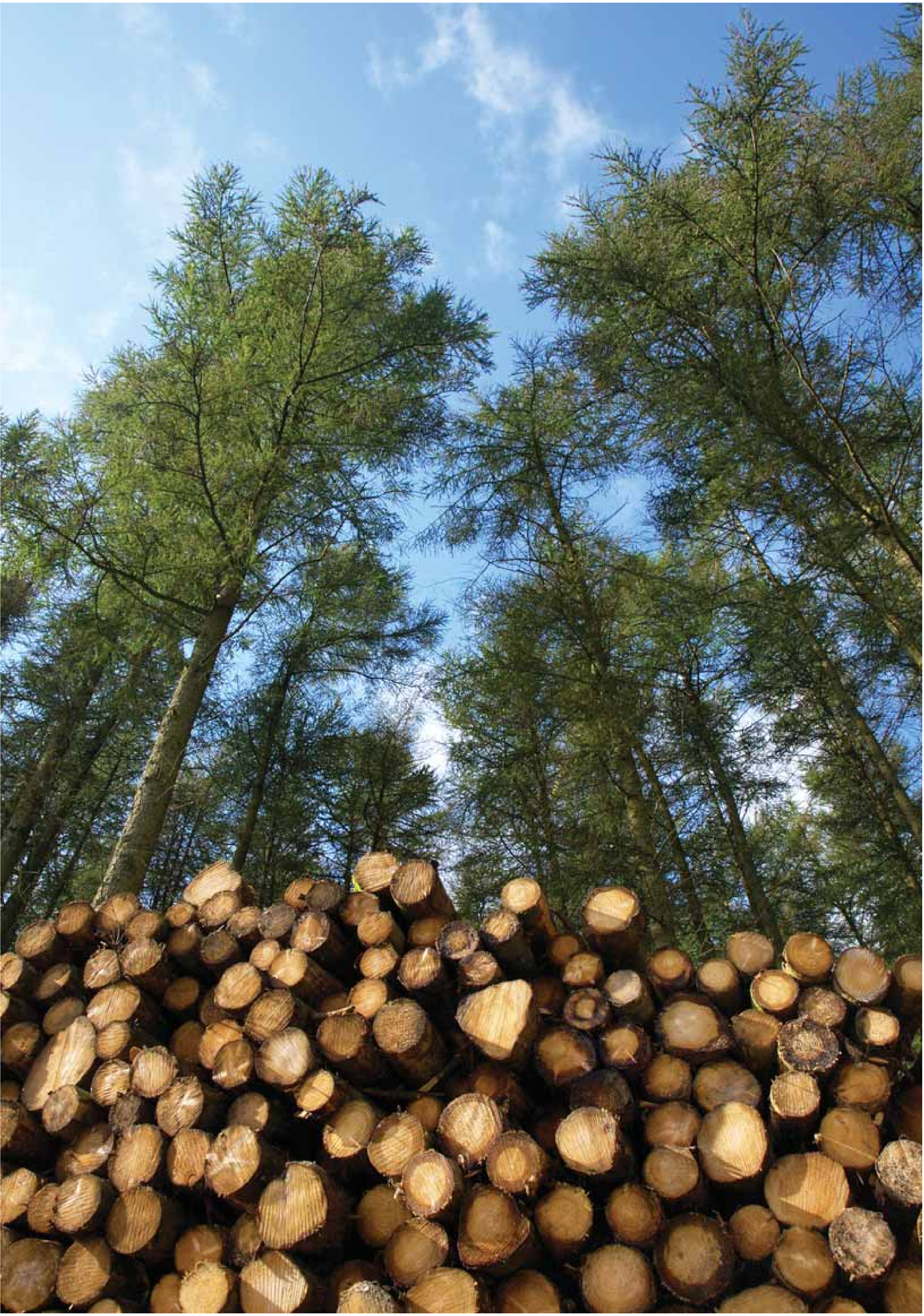


One of the risks of storing carbon by preserving boreal forests is that changes in disturbance patterns (fires, insect infestations and storm-felling) could lead to some of this stored carbon being released. This risk will grow with time and increased climate warming. However, replacing natural disturbances with forestry, in which logging is the dominant disturbance, is not an answer to this problem.

If the old forest is felled, carbon sequestration will be temporarily halted, but more importantly, some of the stored carbon will be released into the atmosphere. Since the carbon stored in the soil and as biomass is greater than in a managed forest, more carbon dioxide will also be released into the atmosphere during logging and it will take a long time for the next generation of trees to sequester the same amount of carbon.

A Canadian modelling study indicates how the carbon balance is affected by the transition from old-growth forest to managed forest. The study looked at six 100,000-hectare forests, one of which was boreal forest in eastern Canada. The effects of natural disturbances on the carbon balance were assessed first. Over a hundred-year period, natural disturbances were gradually replaced with logging, and the systems were then monitored for another 250 years. The results show that the transition from natural forest ecosystem to managed forest resulted in net losses of carbon to the atmosphere even in the very long term. In the boreal forest ecosystem that was included in the study the loss at the ecosystem level was around 12 per cent 350 years after logging began. During the century-long transition phase the carbon losses were much higher (see figure 5) (Kurz et al. 1997).

It should be stressed that this is the result of one modelling exercise, and that there are differences between forestry in Canada and Scandinavia that could have an impact on carbon paths. The outcome could also be affected by various changes in forest management. The results are nonetheless interesting, not least in the medium term (50–100 years), because the effects are so pronounced.



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6. Managed forest ecosystems

In managed forest ecosystems the harvesting of wood is normally the main disturbance. The carbon balance of the forest is also affected in different ways by management activities such as ground preparation, species selection and fertilisation. Natural disturbances are also affected by forest management. In particular, the frequency of fires is much lower than natural in most boreal forests that are managed. The risk of windthrow and infestation by pests may decrease or increase as a result of forestry activities.

One fundamental difference between natural and managed forest ecosystems is that in the latter case biomass is removed from the system by logging. From the climate perspective the issue of greatest significance is what happens to the harvested timber. If wood is used as building material, for example, it can take many decades or even centuries before it finally decomposes or is burned, releasing the stored carbon. Forest biomass may also, as mentioned earlier, be used to reduce consumption of fossil fuels, either by directly replacing coal, oil or fossil gas, or by using wood to replace other materials that are made using fossil fuels (such as concrete or steel).

The emphasis in this section is on forests and forestry in Sweden, but with some references to other countries.

Climate effects on forest growth

In most of Sweden, forest growth is normally limited by temperature, and we can therefore expect that a warmer climate will increase growth. In a study that looked at the effects of raising the forest soil temperature in mature spruce forest in Västerbotten by 5°C above the natural level, stem volume growth almost doubled over six years. Estimates indicate that production from Swedish forests could rise by 5–14 per cent by the year 2040 due to climate warming. Production is expected to increase even more beyond this date (see table 2) (Bergh et al in Eriksson 2007).

Increased forest growth means that biomass increases, so more carbon is stored in the growing forest. This assumes, however, that logging does not increase in the same area and that there is no fall in production as a result of increased losses due to fires, pests and felling of trees by wind. The model that was used for the growth forecasts does not take into account the effects of changes in disturbance regimes (Eriksson 2007), due to a scarcity of data that would make it possible to weigh in such effects. It should therefore be kept in mind that the results of the model do not give a complete and realistic picture of the trend that can be expected.

We should also keep in mind that increasing stem volume growth in forest trees is not the same as increasing biomass growth, and thus not the same as increasing energy content or carbon storage. Faster growth often means that the density of the wood decreases. Doubling the growth may mean that the density decreases by 20 per cent. (Lundgren, C, undated).

Natural disturbances in managed forests

As we have seen, natural disturbances are a factor of vital importance to the ecology and carbon balance of old-growth boreal forests. In managed forests, they can be more or less controlled and restricted, but it nevertheless seems likely that climate changes will

Table 2. Relative production increase in Swedish forests (per cent) for 2.5 and 4.5°C global warming (IPCC scenarios B2 and A2). In the warmer A2 scenario, the increase in spruce production is expected to level off or even fall towards the end of the century. The climate will become too hot to suit spruce. *(Bergh et al in Eriksson 2007.)*

Period	Rise in production (%)	
	Scenario B2	Scenario A2
2011- 2040	5	14
2041 - 2070	14	25
2071 - 2100	24	31

affect disturbance regimes, again in a way that will have significant consequences on the carbon balance.

There are already examples of individual weather events producing such effects. The exceptional temperatures and drought across Europe in summer 2003 are estimated to have reduced carbon storage in vegetation by about 30 per cent, which meant that it was transformed into a carbon source of around 0.5 Gt per year. This is equivalent to four years of carbon sequestration in these ecosystems under normal weather conditions (Ciais et al. 2003).

Fires

The frequency of forest fires in Sweden has declined dramatically. Nowadays, the frequency of fires in an individual forest stand is less than one fire every 1,000 years, compared with one fire every 50–200 years in the early 1900s. The reason why fires are less frequent is a combination of more effective firefighting and forest management that reduces the risk of fires, partly due to a big reduction in the amount of dry deadwood in forests. During the 1950s and 1960s, forest fires did increase temporarily, but thanks to improved firefighting, they have subsequently declined in frequency and seriousness.

The risk of forest fires is likely to increase throughout Sweden as a result of more hot summers and low rainfall. The fire risk is likely to increase most in Götaland, where the summers are generally becoming drier (Lagergren et al. 2006).

Storm-felled trees

Wind was the form of disturbance that caused most damage to European forestry in the twentieth century. The extent of damage varies greatly from year to year, but the general trend over the last century was for storm damage to increase. In southern Sweden at least, where storm damage was greatest, this cannot be explained by storms becoming more frequent. One contributing factor may however be that the proportion of standing trees has increased and clear-cutting practices have created distinct forest margins that are more vulnerable to storms. A milder, wetter climate also reduces the stability of forests. There was also an increase in the proportion of spruce, a species that is relatively sensitive to high winds, across the province up until the 1990s. Climate change can be expected to increase the likelihood of tree loss, both directly through changes in climate, and indirectly through changes in species distribution. The vulnerability of future forests to wind can be influenced by the selection of species and by management practices (Eriksson 2007).

Hurricane Gudrun, which swept over southern Sweden in January 2005, felled 66 million cubic metres of stemwood over an area of about 2,720 square kilometres. Carbon losses from the hurricane-affected area in the first year after the storm were many times greater than from clear-cutting, per unit area. Total carbon emissions into the atmosphere as a result of Gudrun were estimated at 2.3–3.4 Mt in the first year after the storm. In addition there was also the effect of loss of carbon sequestration from the hurricane-affected forest, estimated at 0.4 Mt per year (Lindroth et al. 2008). The overall effect, in round numbers, was a halving of the carbon sink in Swedish forests. Hurricane Lothar, which hit Europe in 1999, is estimated to have reduced carbon uptake in European forests by 16 Mt. This shows that the effects of storm damage due to increased storm frequency must be considered when assessing and calculating the forest's role in future carbon balances (Lindroth et al. 2008).

Milder and wetter winters in the future will mean less stability. The vulnerability of future forests to wind will be influenced by forest management, tree species selection and spatial planning. Thinning may affect the height and shape of trees, the number of stems per unit area and decomposition rate. Modelling studies show that without changes in management practices, expected climate changes will increase the vulnerability of Swedish forests to wind (Blennow 2007).

Insects and fungal attack

A number of pests in Swedish forests can be expected to benefit from a warmer climate. These include the fungus that already causes Swedish forestry the largest losses, namely pine root rot *(Heterobasidion annosum*). Clear-cutting and year-round harvesting are providing conditions for an increase in root rot in coming decades. A warmer climate is very likely to drive this trend further. The form of root rot that attacks pine can be expected to spread northwards (Eriksson 2007).

Other pathogenic fungi that may be favoured by a warmer climate are *Gremeniella*, pine twisting rust *(Melampsora pinitorqua)* and pine needle cast *(Lophodermium pinastri)*. In the case of *Gremeniella* it appears that heavy precipitation in a single year could trigger a large-scale epidemic. Climate change may also lead to new fungal pests becoming established in Sweden (Eriksson 2007).

Both the eight-toothed spruce bark beetle *(Ips typographus)* and the pine weevil *(Hylobius abietis)*, two insects that cause the most damage to Swedish forestry, are likely to benefit from climate change. From a climate perspective, the bark beetle is the most harmful of insect pests, since it attacks old trees, which contain a large amount of stored carbon. The spruce bark beetle is favoured by three interacting biological mechanisms:

- increased frequency of storms means more windthrown trees, which are ideal breeding grounds for the spruce bark beetle.
- spruce are stressed by heat and drought, while the bark beetle is favoured by warmer conditions.
- warmer climate extends the season for the bark beetle.

In 2006 and 2007 the bark beetle managed to produce two generations each summer in Sweden. This is a development that had long been a concern and was expected to become a reality by the end of this century, but is already happening (Schlyter 2008). Under favourable conditions for the bark-beetle this could lead to the population multiplying many times and result in much more serious infestations than at present (Eriksson 2008).

Pest infestations mean a decrease in forest growth and hence carbon sequestration, even if the forest survives. If the forest dies, it becomes a carbon source as the dead wood decomposes. In combination with other disturbances, two major insect outbreaks are expected to change managed Canadian forests from carbon sinks to carbon sources, with an estimated loss of between 0.030 and 0.245 Gt of carbon over the period 2008–2012. This shows that the strategies that are intended to control the carbon balance of forests through management practices may be negated by increases in natural disturbances (Kurz et al. 2008).

Forestry practices from a climate perspective

Felling and site preparation

During felling, large amounts of tree biomass and the carbon it contains are removed from the forest. But the largest share of the carbon stored in a forest lies in the soil, which clear-cutting exposes to light, heat and oxygen, especially during soil scarification. Decomposition in the soil increases, leading to increased emissions of carbon dioxide from forest soil. This makes felling sites a carbon source for up to 15 or 20 years, even if new forest is planted as soon as possible after harvesting. It takes another couple of decades for carbon sequestration by the growing forest to offset these emissions. It can take 30–40 years after planting for the carbon balance to be restored to its original level before harvesting (Lindroth et al 2009, Grelle 2010).

Forests where clear-cutting is practised therefore lose a large proportion of soil carbon at each harvest. The carbon store is built up again as the forest grows, but this build-up is slow and the carbon stored in the soil never reaches the level of forests where clear-cutting is not practised (Grelle 2010). This indicates that the net uptake of carbon dioxide in Swedish forests could be significantly increased by eliminating this phase and instead managing the forest without clear-cutting.

Continuous harvesting methods, which do not involve clear-cutting, but the regular removal of a certain proportion of trees from the forest, has a different impact on the carbon balance of the forest than clear-cutting. It eliminates the clear-cutting phase, with its large carbon losses, and instead maintains a continuous carbon sink. Carbon dioxide uptake in the growing forest is hardly affected at all by small removals of biomass, because the trees that are left benefit from reduced competition. This means that forestry without clear-cutting is better from the climate perspective, despite the fact that growth and harvests are slightly lower than with clear-cutting. The amount of carbon stored in forests that are not clear-cut is generally slightly higher than in the forests where clear-cutting is practised (Grelle 2010). Continuous harvesting methods make it more difficult and more expensive to remove logging residue, which means that there is less potential for substitution of fossil fuels.

In terms of impact on the forest carbon balance, thinning may be equated to harvesting without clear-cutting. Carbon uptake is hardly affected at all by a normal thinning (Lindroth 2009).

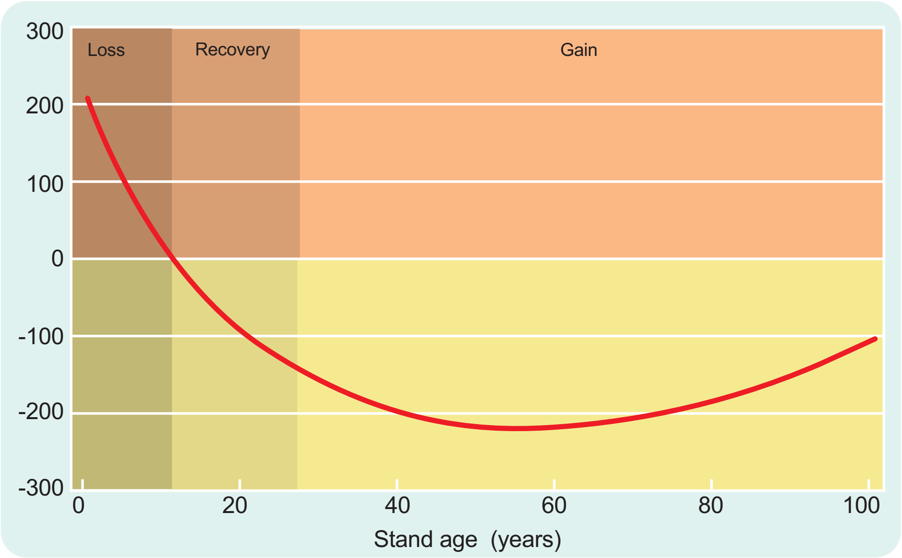

Figure 6. Net exchange of greenhouse gases between ecosystems and the atmosphere in forests after clear-cutting. Clear-cutting begins in year 0. The forest is a source of greenhouse gas emissions for more than 10 years after clear-cutting. It takes a full 10 years more for the new trees to offset losses from clear-cutting. Graph based on data from forests in Sweden, Finland, Great Britain and France.

Figure 7. Effects on carbon stored in forest (top) and on annual carbon flows for four forest management alternatives, two with extended rotation periods and two with extended rotation periods combined with reduced thinning (denser stands). The results are shown in relation to a baseline for forest managed according to current Finnish forestry guidelines.

Wood extraction is broken down into saw wood, pulpwood and biofuels, and it is assumed that 70 per cent of the available biomass in the form of logging residue is collected during final harvesting. The study takes into account the substitution effects that occur when forest products replace fossil fuels or materials.

In spruce forests (left), climate impact will be favourable for all management regimes: there is an increase in both carbon stored in the forest and in substitution effects. In pine forests, the effects on annual emissions are negative for management regimes that only extend the rotation period. It is worth noting that saw wood accounts for all the positive effect on emissions, while pulpwood and biofuels have a net negative effect, with one exception. (*After Pingould et al. 2010.*)

Significance of rotation period

If storing the maximum amount of carbon in soil and trees is a priority it may be beneficial to postpone felling.

Modelling studies have shown that extending the rotation period by 20 per cent would increase carbon storage in biomass by 13 per cent and in the soil by 10 per cent, over a hundred-year period (Bergkvist & Olsson 2008). The effects may be even greater in the short term. Reducing felling by 10 per cent in Swedish forests could increase carbon storage by 60 per cent by 2030. No other changes in forest management have such large effects on the carbon balance over such a short period (Lundblad et al. 2009).

Extending rotation periods also leads to reductions in the amount of timber extracted and the logging residue available for use as biofuels. Even taking into account the fact that biofuels replace fossil fuels, and thus reduce emissions of carbon dioxide, extending rotation periods gives a greater reduction in emissions than shortening them, seen over a hundred-year period (Bergkvist & Olsson 2008).

This is confirmed by a study that also takes into account the effects of material substitution *(see figure 7)*. It shows that forest management models that combine a longer rotation period with reduced thinning can increase the carbon stored in the forest while at the same time reducing emissions through substitution. The positive effect is due to increased production of saw wood. Increased extraction of pulpwood and biomass on the other hand has a generally negative impact on the carbon balance. The study thus also indicates that a forestry strategy that aims to extract the maximum volume of wood is not the best from the climate perspective (Pingould et al. 2010).

It should be kept in mind that strategies to increase the carbon stored in growing forests are limited in time. The carbon store cannot continue to grow indefinitely. The risk that the carbon stored in forests will be released by disturbances also grows with time (Bergkvist & Olsson 2008).

Tree species selection

The choice of tree species is important for the forest's ability to adapt to changing climate, as well as its carbon balance.

Stands of spruce and birch build up larger stores of carbon in the soil than pine. The reason may be that the litter from these trees contains more nitrogen than pine litter. In northern Sweden, the carbon content of the soil is 65 per cent higher in spruce and birch forest than in pine forest, and in southern Sweden the difference is 33 per cent. Increased intermixing of spruce and/or birch in pine stands in parts of the country, for instance in east Götaland, northern Dalarna and Gästrikland, may be one way of increasing carbon sequestration in Swedish forests in the future (Bergkvist & Olsson 2008).

We can expect the future climate in southern Sweden to be both warmer and drier in summer. This means that pine will become a more attractive choice in many areas. Pine is not as vulnerable to high winds as spruce, but on the other hand it is not as good as spruce and birch at sequestering carbon (Bergkvist & Olsson 2008).

Intensive cultivation of forests

The main methods for intensively cultivating forests are increased fertilisation, involving frequent fertilisation during the forest rotation period (known as demand-driven fertilisation) and greater use of foreign species such as lodgepole pine, larch and Sitka spruce. The use of carefully cultivated saplings (hybrids of spruce and hybrid) in combination with fertilisation is also part of the intensive forestry arsenal (Larsson et al. 2009). The spreading of up to 1,500 kilograms of nitrogen per hectare over a full rotation period may be required (Nordin et al. 2009). (In modern forestry around 150 kg of nitrogen per hectare is generally applied on one occasion around ten years before felling.)

In trials in which 600 to 1,800 kg of nitrogen per hectare was spread over a period of 14–30 years, the carbon stored in trees increased on average by 25 kg per kg of nitrogen. Soil carbon reserves also increased by 11 kg per kg of nitrogen added. Where phosphorus and potassium were also added, the corresponding figures were 38 kg for trees and 11 kg for soil (Bergkvist & Olsson 2008). Because the production of fertilisers also creates greenhouse gas emissions equivalent to 0.4 to 1.2 kg of carbon per kg of nitrogen, the climate effect is therefore very positive.

An example in Västerbotten shows that a spruce forest that was fertilised repeatedly until it was felled had a 26 per cent higher average carbon content than a corresponding forest that was not fertilised. The fertilised forest yielded 80 per cent more raw material than the unfertilised, enabling it to replace a great deal more fossil fuels or materials (Lundmark 2010).

One study of the potential for intensively cultivating forests in Sweden estimates that about 15 per cent of Swedish forest land could be intensively managed, mainly for intensively fertilised lodgepole pine or high-yield spruce hybrids. (Larsson et al. 2009). This would increase carbon sequestration by 3.8 Mt per year from 2030 to 2040 compared with the baseline alternative without intensive cultivation (Lundblad et al. 2009).

As yet, however, no experience has been gained in intensive cultivation of forest on a large scale or over a longer period in Sweden. The uncertainties and risks are significant. We know that the composition of the stand and the ground vegetation change considerably after long-term fertilisation. There are as yet no measurements of net flows showing increased uptake of carbon dioxide in forests that have been fertilised for many years (Grelle 2010).

Intensive forestry leads to more homogeneous populations and less diverse forests, which could mean increased risk of attack by pests and lowered resistance to climate change. At present there is no scientific evidence to permit assessment of the risk of forest damage in intensively cultivated forests (Witzell 2009).

Fertilisation can increase the risk of attack by certain pests, such as pine stem rust (Cronartium flaccidum) and snow blight (Phacidium infestans). Fertilisation of decaying forest may also increase root rot, which in turn may increase the risk of trees being felled in storms. The chemical defences of trees could be impaired, leading to greater damage by grazing elk (Witzell 2009). All these effects reduce growth and thus carbon sequestration.

If nitrogen is added to the forest in the form of fertiliser it is eventually likely to lead to an increase in emissions of nitrous oxide from forest soil, since there is a strong correlation between the amount of nitrogen in the soil and nitrous oxide emissions. At present, 80–90 per cent of nitrous oxide emissions in Sweden come from agricultural land, which is fertilised with nitrogen to boost production. Forest fertilisation entails adding nitrogen to the forest ecosystem in the same way. Increased nitrogen supply will increase the relative proportion of nitrogen to carbon in organic matter in forest soil, increasing the likelihood of nitrification and thus the emission of nitrous oxide (Bergkvist & Olsson 2008).

In forests, the proportion of added nitrogen that is emitted in the form of nitrous oxide has been measured at 0.5–1 per cent. With the levels of fertilisation that are planned for intensive forestry and the growth effects seen in trials, these emissions will be more than offset by increased carbon sequestration in the forest. At most, it is estimated that around 20 per cent of the sequestered carbon will be needed to offset nitrous oxide emissions equivalent to three per cent of the added nitrogen (Nordin et al. 2009). The precise levels of nitrous oxide emissions from different soils during large-scale intensive forestry are unknown. Little is also known about what happens to soil nitrogen when intensively fertilised forest is harvested. Because nitrous oxide is a very effective greenhouse gas, small changes in the levels can have large effects on the overall greenhouse gas balance.

Greenhouse gas levels can also be affected indirectly by the effects of fertilisation on lakes and streams in the forest landscape. These effects are currently difficult to quantify (Nordin 2009).

Several studies have reported that nitrogen fertilisation decreases the ability of forest soil to break down methane, but there are also studies that show the opposite effect. Calculations based on Finnish conditions indicate that current atmospheric nitrogen deposition is inadequate to limit methane oxidation. It is probable that a slow increase in nitrogen in forest soil will not affect methane oxidation to any great extent, and the influence of methane in the atmosphere will be relatively insignificant (Pihlatie 2009).

Extensive intensive cultivation of forests would change the timber grade distribution. The proportion of saw timber will decrease, while the proportion of pulpwood and fuel wood will increase. In regard to the use of intensively cultivated timber the previously mentioned study on intensive forestry suggests that the raw material would be suitable for the pulp industry and could perfectly well be used as saw wood, although the proportion of poorer grades is likely to increase slightly (Larsson et al. 2009). The main motive for intensive forestry is thus to increase the yield of raw materials.

Drainage and forestry on peatlands

There are 5 million hectares of wetland forests, in other words peat-covered land that is used for forestry production, in Sweden. This is around 20 per cent of forested land and half of all peatland in Sweden (Bergkvist & Olsson 2008). Since 1850, more than 1.5 million hectares of peatland have been drained to create forest (Bergkvist 2007).

When peatland is drained it increases the oxygen supply and allows peat to decompose. This results in emissions of carbon dioxide and sometimes nitrous oxide into the atmosphere. On the other hand, it reduces emissions of methane, since methane is produced in oxygen-free (anaerobic) conditions. The purpose of drainage is to improve forest growth, and if this is successful it increases the uptake of carbon dioxide by the forest. The estimated net effect of fresh drainage on the climate is generally neutral or negative, even when the potential energy benefits of the increased forest production are included (Eriksson 2008).

Drained land makes up about seven per cent of Sweden's forested land, but accounts for 15 per cent of the total greenhouse gas emissions from forest land. Emissions of carbon dioxide from drained forest land are estimated to be around 10 Mt per year. Finland, which has three times more drained peatland (about 5 million ha) reports emissions of around 5 Mt, which gives some idea of the uncertainty of estimates (Lundblad et al. 2009).

If allowance is made for the sequestration of carbon by forest that grows on drained peatland it could represent a source of greenhouse gases on the order of 1–2 Mt of CO2 equivalents per year (Bergkvist 2007).

Between 300,000 and 450,000 hectares of farmland on drained peatland and old lakebeds has been taken out of use since the early 1930s. Much of this area is probably used for forestry today. As much as 30–45 per cent of drained forest land in Sweden may be former farmland of this type. A Finnish study has shown that this type of soil is a major source of emissions of nitrous oxide. Annual rates of up to 30 kilograms per hectare were measured. This means that drained forest land may emit more nitrous oxide than previously thought (Bergqvist 2007).

When trees in peatland forests are felled and no longer extract water, the groundwater level rises. The water level has a big influence on which greenhouse gases are released and in what amounts. Generally, methane emissions rise with rising groundwater level, while carbon dioxide emissions fall with rising groundwater. Because methane is 23 times more effective as a greenhouse gas, an increase in the groundwater level can still mean greater climate impact. Nitrous oxide emissions are also affected by the groundwater level. Greenhouse gas emissions are at a minimum when the groundwater level is neither high nor very low (Bergkvist & Olsson 2008).

If harvested wetland forest is to be reforested, overgrown ditches must be cleared, which also leads to a rise in greenhouse gas emissions. Another alternative is to allow the ditches to become clogged, which has complex effects on both the carbon balance of the forest and on wood production (Bergkvist & Olsson 2008). The LUSTRA research programme recommended that drained forest land where ditches have become overgrown should be managed in a way that will maintain forest production. Groundwater should be kept at a level that enables the forest to continue growing. However, results indicate that further reductions will increase emissions from the soil more than can be offset by increased forest growth, and that this would therefore have a negative climatic effect (Bergkvist 2007).

Harvesting forest fuel

The use of forest fuel in Sweden has almost tripled over the last decade. Most of this fuel is logging residue (slash – branches and tree tops). Logging residue is currently gathered from around one-third of the area that is clear-cut each year (Eriksson 2011).

The extraction of forest fuel means that biomass is removed from the forest and burned. Decomposition, and hence the release of carbon dioxide into the atmosphere, occurs faster than if the material had been left to decompose in the forest. If the material had been left in the forest a small proportion of its carbon content would eventually have been stored in soil.

Harvesting of logging residue also means that nutrients are removed from the forest soil, especially if harvesting takes place before the needles have fallen. If it leads to reduced growth in the next forest generation, the consequence is that less carbon is stored in biomass. The gathering of branches and twigs is reported to cause growth losses of between 6 and 32 per cent in subsequent forest production (Jacobson et al. 2000, Sterba 2003 in Nabuurs et al. 2008). When logging residue is gathered during thinning there are indications that growth is reduced by 11–26 per cent (de Jong 2010).

Stump removal

Nearly 20 per cent of the biomass of a tree is in the stump, which makes tree stumps a large potential forest fuel resource. Interest in stump removal has risen sharply in recent years, but this method is still used on a relatively limited scale.

What is forest fuel?

Any fuel derived from biological material is called biofuel. Wood fuel is biofuel derived from trees or parts of trees.

Forest fuel is wood fuel that has had no other previous use: logging residue, wood that has not been used for industrial purposes (from clearing operations, for example) and by-products from industry.

Wood fuel that comes directly from the forest is sometimes called primary forest fuel.

Slash (branches and tree tops) is logging residue left after the harvesting of stemwood.

The effects of stump removal on carbon balance and the environment have not been widely studied (Grelle 2010). Research is ongoing, but few results have yet been reported. The severe disturbance of the soil during stump removal could increase decomposition and hence lead to increased carbon release. On the other hand, soil disturbance could favour the establishment of new forest and thus promote carbon sequestration in the long term.

One study has shown that carbon dioxide emissions were the same during the first year after stump removal as after land preparation. In the second year there was a tendency for increased emissions from land cleared of stumps, but the reason for this was unclear. One noticeable difference was that the proportion of land that was affected by wheel tracks or in some other way was much greater on land cleared of stumps. Heavy rutting reduces emissions of carbon dioxide, but can also make soil waterlogged, which increases the risk of methane emissions (Mjöfors & Strömgren 2010).

According to another study, the carbon stored in the soil, tree biomass and the entire ecosystem was still lower 27 years after stump harvesting, when compared to similar areas where stumps and logging residue were left behind. The difference in stored carbon was roughly equivalent to the carbon content of the stumps that were harvested, which means that no climate benefit was achieved by using the stumps as biofuel in this case. These results suggest that stump harvesting also reduces the carbon content of soil and tree biomass in the longer term, although this was a limited trial with results that were difficult to interpret in some respects. Further studies are needed to draw reliable conclusions on the climatic effects of stump extraction (Mjöfors & Strömgren 2010).

The effects of increased stump removal on carbon flows have been estimated at 25 TWh by the year 2030. This represents about 30 per cent of the stumps created each year in Sweden. Stump clearance on this scale is estimated to reduce carbon sequestration in biomass by 1.8 Mt in 2030. The impact on carbon sequestered in the soil was not included in the calculation (Lundblad 2009).

Manage or allow to grow?

There is significant potential for our managed forests to store carbon if they are left to grow well beyond the normal felling age (Olsson, M 2010). On the other hand, harvested wood can be used to replace fossil fuels and thereby reduce emissions of greenhouse gases.

Modelling studies have compared the carbon balances of two alternatives in Swedish forests. In the first alternative, the forest is left to grow without interference for 200 years.

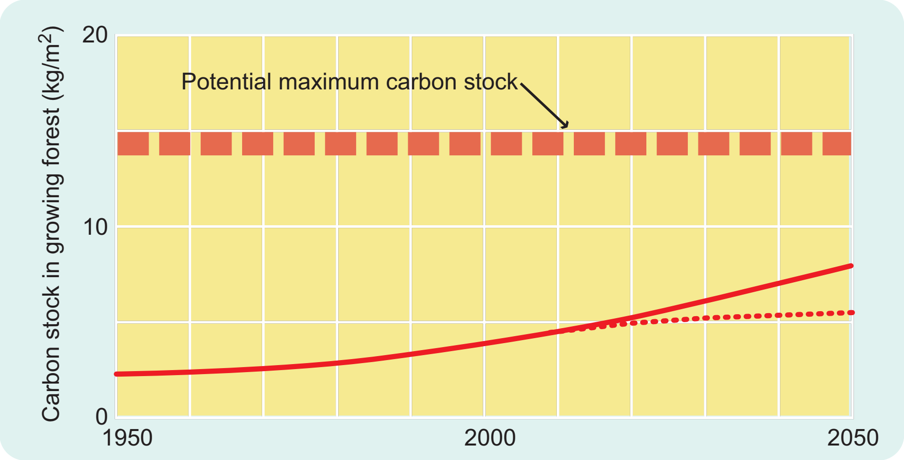

Figure 8. Present and future carbon storage in European forests from 1950 to 2050. The graph is based on measured data until 2010. The solid line is a simple trend projection; the dashed line is a model calculation based on moderate timber extraction, but without any allowance for increased carbon dioxide levels, warmer climate or nitrogen deposition. The thick dashed line indicates the potential maximum carbon storage in European forests, calculated using old forest data. The figure shows that there is significant potential to increase carbon storage in European forests. *(After Ciais et al. 2008.)*

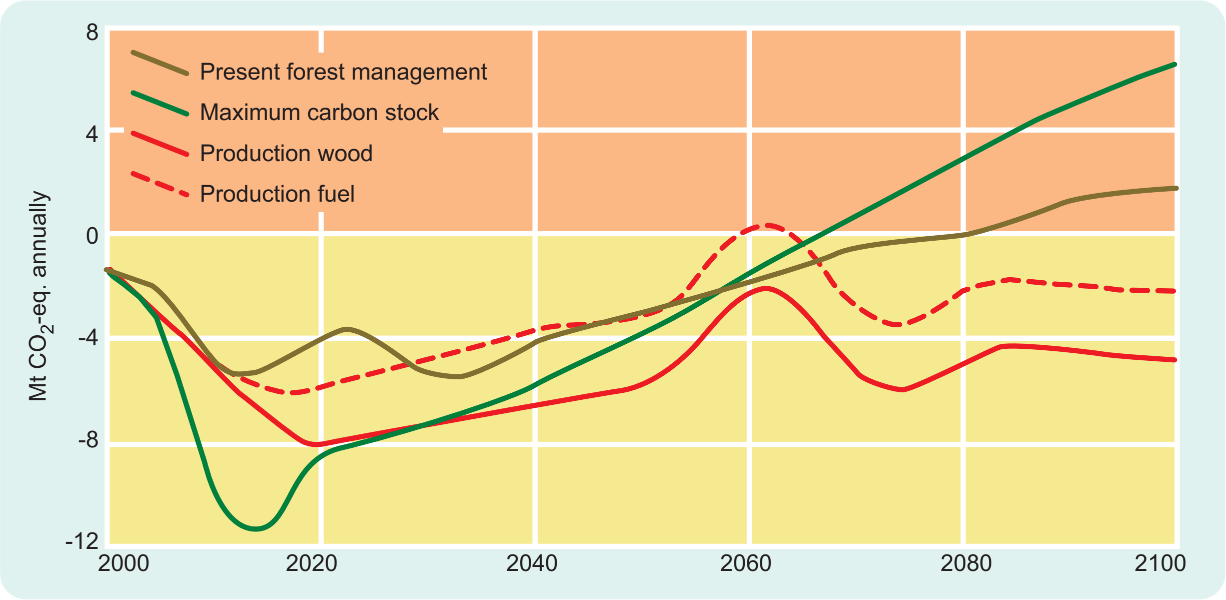

Figure 9. Effects on greenhouse gas balance of four forest management strategies in Swiss forestry from 2000 to 2100. Values above zero mean that the forest is a carbon source.

Forestry today entails maintaining current practices and the intensity of forest management.

Maximum carbon storage means managing forests in a way that greatly reduces timber extraction and focuses on building up the maximum carbon storage in forests.

Materials production means more intensive forestry, focusing on the maximum substitution of materials.

Fuel production means more intensive forestry, focusing on the maximum substitution of fossil fuels.

The modelling study does not include the substitution effects of pulp and paper.

According to the chart the forests that are left to grow become a carbon source within 50 years. This relies on the assumption that decomposition of the additional dead organic matter in unmanaged forests gives rise to more greenhouse gas emissions than are sequestered by the growing forests.* This applies to temperate forests, where dead material decomposes faster than in boreal forests, and where there is less carbon stored in the soil. The picture is likely to be different for boreal forests – forest that is left to grow freely would remain a carbon sink for a longer period than shown. *(After Werner et al. 2010)*

In the second, the forest is cleared after ten years, thinned at 30 and 60 years, and finally harvested when it is 100 years old. This is followed by a new rotation period comprising the same treatment. After 200 years the unmanaged forest contains 13 kg of carbon per square metre, while the managed forest contains 11 kg. In addition, the carbon removed from the managed forest during thinning and final felling yields a total of 11.9 kg. The managed forest has therefore sequestered a total of 22.9 kg of carbon over the 200-year period. According to the modelling study, the forest soil in the unmanaged forest contains 0.2 kg more carbon per square metre after 200 years, which is marginal in relation to the carbon sequestered in tree biomass (Olsson, M 2010).

To compare the climatic impact of the two alternatives we must take into account what happens to the harvested biomass. From a strict ecosystem perspective – i.e. assuming that the carbon that leaves the system immediately returns to the atmosphere – it is better from the climate viewpoint to leave the forest untouched. However, if we assume that the harvested timber is used to replace fossil fuels and/or building materials with high embodied energy, such as steel and concrete, the picture changes. We will return to this later on.

The example described is based on two recently established forest stands that are treated in different ways in the future. In the current situation, the choice is rather between leaving an old forest to grow, or harvesting it and replanting. As previously shown, the net effect on the carbon balance over 50–100 years is positive (net emissions of carbon into the atmosphere) when old-growth forest is felled and replaced with managed forest. (See section 5.)

**) Dr. Frank Werner, personal communication*

Focusing exclusively on increasing stored carbon by allowing the forest to grow is a climate strategy that has restricted scope, since the amount of carbon that can be stored in a forest is limited. It can, however, be effective in the short term (Lundmark 2010). European forests have the potential to continue building up stores of carbon over many decades to come, provided that the share of growth taken up by felling does not increase.

This means that forests play an important role as a carbon sink in a climate policy that focuses on winning time (Ciais et al. 2008).

A study of various strategies for the management and use of forests in Switzerland over a hundred-year timeframe shows that the best option for the climate is to maintain high growth, and continuously harvest at the maximum sustainable level (see Figure 9). Timber should be used primarily as a construction material for as long a period as possible, and then be burned as a substitute for fossil fuels. Forest residue that cannot be used for other purposes should be used as fuel. The alternative of focusing on managing forests to produce more fuel is not an optimum solution (Werner et al. 2010).

The strategy that enables the maximum carbon sequestration in the short term is to greatly reduce logging. Although the wood yield is reduced by 45 per cent (compared to business-as-usual) and therefore has similar substitution effects, this would be the most effective strategy from a climate perspective that spans several decades (Werner et al. 2010).

The study refers, as mentioned, to forest in Switzerland, i.e. in the temperate zone, and the results cannot therefore be applied directly to boreal forest management. Among other things, there are differences in the decomposition rates of organic matter and the amounts of carbon stored in the soil. The study is still interesting in principle, however, as it gives a picture of the overall effects of different forest management options in combination with substitution effects.

7. Storage of carbon in forest products

When the greenhouse gas balance of forest ecosystems is analysed, all harvested timber is often counted as adding to emissions. It is assumed that the carbon in tree biomass returns to the atmosphere immediately. In reality, some of the carbon is stored in wood products, which means that emissions are delayed. The length of this delay varies significantly. In the case of paper, it may be a few years, while for wood used in buildings it can be many decades or even centuries (Lundblad et al. 2009).

The greenhouse gas emissions reported by countries under the Kyoto Protocol have so far not included the carbon content of the harvested forest products, but the possibility of doing so is now being negotiated. This raises questions about how exports and imports of forest products should be reported, which calculation methods should be used and what assumptions should be made regarding the life of different forest products. The latter factor is particularly important.

Life expectancy is usually given as half-life, in other words how long it takes for half of the carbon in a certain amount of forest product (timber, fuel or paper) to return to the atmosphere. In the Nordic countries the half-lives of timber products have been estimated at around 15–20 years. The normal half-life of paper is 1–2 years. Half-life is a major source of uncertainty in calculations. As shown in figure 10, different assumptions for half-life (10–50 years) yield values for carbon sequestration in harvested wood in Sweden that range between 0.5 and 6 million tonnes of CO2 per year (Lundblad et al. 2009).

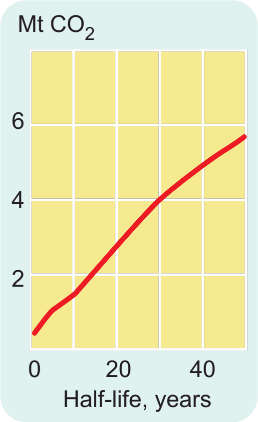

Figure 10. Importance of half-life for carbon storage in forest products. The graph shows the carbon stored (average 1990–2007) in Swedish-produced timber and wood-based panels based on different half-life assumptions. (*After Lundblad et al. 2009.)*

In Sweden, the last inventory of the amount of wood used in buildings was conducted in 1996, when the carbon stored in the housing stock was estimated at 34 Mt (Lundblad et al. 2009). Any increase in this stored carbon is, however, likely to be marginal or non-existent. The rate of demolition is about the same as the rate of construction (Eriksson 2008).

The timber that has been harvested from Swedish forests in recent years is equivalent to just over 16 million tonnes of carbon per year. The equivalent of a further 1.5 million tonnes is imported. More than 80 per cent of this is used as fuel, paper pulp or waste, which is generally burned within a few years. In other words there is no significant storage of carbon in forest products. The remaining 20 per cent is used for the production of sawn timber and wood-based panels. Further wastage occurs during processing before the timber is incorporated in the end product, some of which – formwork and packaging – has a short life. This means that only a small fraction – significantly less than 20 per cent – of the total timber harvest eventually ends up in products with a long life, such as houses or furniture, and can then be considered to act as a carbon sink (Lundblad et al. 2009).

Even if the total stock of wood used in buildings were to increase by 10 per cent, the carbon stored would represent little more than one per cent of Sweden's total emissions (Eriksson 2008).

MAHEY / FOTOLIA

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8. Substitution

Tree biomass can be used as a fuel to replace fossil energy. Wood can be used to replace materials (e.g. plastics, concrete and steel) that give rise to greenhouse gas emissions during production, both directly and because production requires energy that is generated from fossil fuels. The substitution of fuel and materials is a critical factor in the total impact of forests and forestry on greenhouse gas flows, particularly in the long term, because the benefits of lower carbon dioxide emissions accumulate with time.

To calculate the substitution effects of biomass we must take into account all the greenhouse gas flows that are associated with a product, such as greenhouse gas emissions during the transport of wood and manufacture of products. The effects also depend on which alternative products are chosen for comparison, e.g., coal or natural gas in the case of fuels, and concrete or steel in the case of materials (Olsson, M 2010). A substitution factor indicates how much fossil carbon is replaced by a certain amount of carbon in harvested wood. If one kilogram of carbon in wood replaces one kilogram of carbon in fossil fuels the substitution factor is 1. The substitution factor for all the biomass removed from the forest is generally estimated to be less than 1, meaning that in the short term, substitution does not compensate for carbon losses from the forest due to timber harvesting (Pingould et al. 2010).

Existing studies of the substitution effects that arise from various forest management and harvesting strategies generally assume that increased wood yield is used to replace fossil fuels or building materials, or a combination of the two. This does not match the real-life situation in forestry today, where much of the harvested timber ends up as pulpwood that is used for making paper. As we will see, paper production is a major factor in the overall substitution effect of the forest sector.

Substitution of fuels

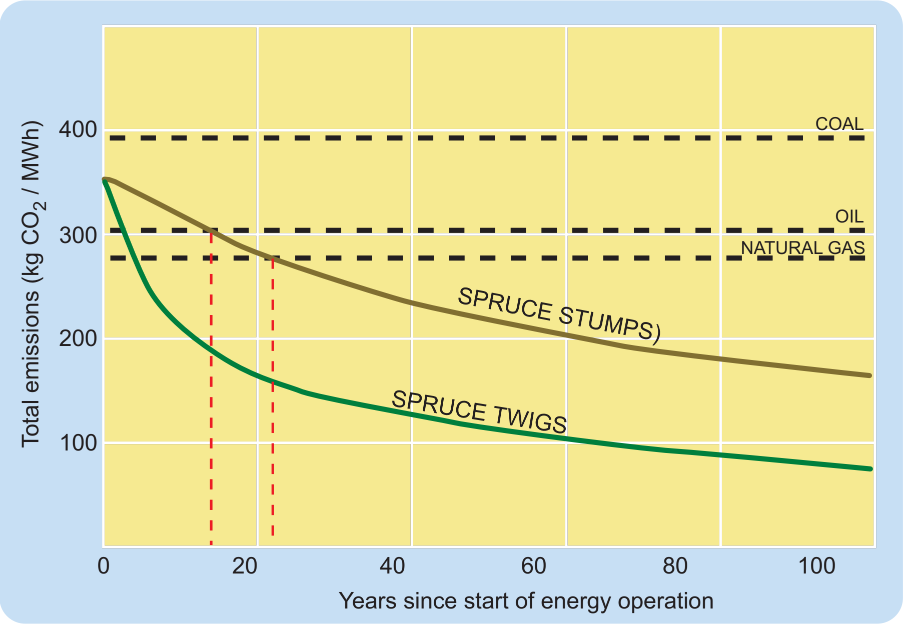
The replacement of fossil fuels with forest fuel for energy generation releases carbon dioxide into the atmosphere, but the carbon dioxide that is released would have been emitted anyway when the tree dies and decomposes. If the forest is replanted after harvesting, the growing biomass eventually absorbs the same amount of carbon as was produced during combustion (Bergkvist & Olsson 2008). This does not however mean that forest fuel is carbon neutral. The climatic benefit of using forest fuels depends on the balance between, on one hand, emissions from the fossil fuels that are replaced by forest fuel, and on the other hand:

- the rate of decomposition of fuel if it is left in the forest.
- greenhouse gas emissions due to disturbance of the soil when harvesting fuel.

Table 3. Substitution factors for saw timber and forest fuel. The table gives marginal substitution factors, i.e. for further additions of material from the forest. The substitution factor indicates how much carbon in fossil fuel can be replaced by wood with a specific carbon content. So a substitution factor of 1 means that wood containing 1 kg of carbon can replace the same amount of carbon in fossil fuel. A substitution factor of less than 1 means that the carbon losses from forest due to logging are not compensated for in the short term by the substitution effect. *(Pingould et al. 2010).*

	Substitution factor fossil fuel	
	Coal	**Natural gas**
Sawnwood *(for construction of housing, Sverige)*	2.05	1.52
Sawnwood *(for construction of housing, Finland)*	1.31	0.91
Forest fuel	0.89	0.50

Figure 11. Climate effects of substituting for fossil fuels with branches and stumps. The effect is positive where the curves drop below the line for each fossil fuel. Stumps thus provide climate benefits after 14 years in relation to oil and 22 years in relation to natural gas. After 100 years the climate benefit of stumps still does not exceed 40 per cent. When other assumptions are made about the decomposition period or the soil carbon loss for stumps, the curve is shifted upwards, which means that it takes longer to achieve climate benefits. *(After Repo et al 2010.)*



- effects of harvesting fuel on forest growth.
- emissions from machinery during harvesting and transport.

Other factors that can contribute significantly to overall emissions of greenhouse gases in the production of forest fuels are land management practices (especially on drained peatland) and fertilisation (Bergkvist & Olsson 2008).

Forest fuel harvesting in Sweden currently amounts to 8–10 TWh per year. An increase to 15 TWh by 2030 is expected to reduce carbon storage in forests by 4–6 per cent. This decrease is offset many times over by the substitution effect, however. If the branches and tops were harvested from all logging operations in Swedish forests for 150 years it would reduce stored carbon by 0.34 million tonnes per year. At the same time it would yield 11 million tonnes of carbon as fuel (Ågren & Hyvönen-Olsson 2006). Even assuming a low substitution factor of 0.5 the climatic benefit would be considerable (Bergkvist & Olsson 2008).

One problem with initiatives to harvest forest fuels in the short term is that they take some time to show a net positive effect. The main reason is that if the felling residue were left in the forest it would take several years for it to decompose, while breakdown is immediate with combustion. Logging residue (slash) is expected to yield climate benefits within 4–20 years if we assume it is used as a substitute for natural gas. The "payback" time is shorter if it is used as a substitute for oil or coal, (Repo et al. 2010).

The greater the diameter of the material concerned, the longer the delay in effect and hence the lesser the climate benefit. This is particularly true of tree stumps. It takes at least 20–30 years before harvesting stumps as fuel has a positive climatic effect (assuming they replace natural gas) (Repo et al. 2010). If the effects of soil disturbance and reduced growth in the next generation of forest are taken into account, it takes even longer to benefit the climate.

There is a wide spread of data on the climate benefits of forest fuel over the lifetime of a stand. In the case of logging residue (slash) the long-term climate benefit is reported as 70–90 per cent. This means that one kilogram of carbon in forest fuel offsets emissions from fossil fuels equivalent to 0.7 to 0.9 kg of carbon (Repo et al. 2010). For stumps, the long-term climate benefit is reported as being between 40 (Repo et al. 2010) and 80–90 per cent (Lindholm 2010).

The spread of these figures is due to different life-cycle analyses making different assumptions about the rate of decomposition and emissions from processing, transport and combustion. None of them takes into account the possible effects on forest growth and greenhouse gas emissions due to soil disturbance. This is an area where we still lack knowledge, but as mentioned earlier, experimental data indicate significant growth reductions after gathering slash (de Jong 2010).

The time delay before forest fuels can benefit the climate may seem insignificant. But at a time when there is pressure to greatly increase the use of forest fuels and there are strong arguments to cut greenhouse gas emissions as rapidly as possible, this is a very important aspect. If it is not taken into account we are likely to overestimate the climate benefits of increased biofuel use to a considerable extent.

Substitution of materials

Materials substitution means using wood as a substitute for other materials that are produced from fossil fuels. This has a positive effect on the climate by eliminating the emissions of greenhouse gases that would have occurred during production of the materials that are replaced. In most substitution studies the materials that are replaced are steel or concrete.

In the Swedish case the main focus of analysis is the climate benefits of substituting concrete framing with timber framing in buildings. Over a longer period it turns out that substituting materials in this way has bigger climatic benefits than fuel substitution.

If harvested wood is used wherever possible as a structural material for building, a yield of 1 tonne of carbon from the forest is equivalent to a reduction in emissions of 1.04 tonnes of carbon. This assumes that large trees are used for structural timber, and that smaller trees, logging residue and wood from demolished buildings are used for fuel. The reference fuel is taken as bituminous coal. If instead the comparison is made with natural gas, the reduction in emissions is 0.76 tonnes of carbon (Olsson, M 2010). In this case, unmanaged forest reduces emissions by an average of 77 grams of carbon per m2 per year (in biomass and soil) over two rotation periods. Managed forest reduces emissions by an average of 95–130 g (depending on whether natural gas or coal is used as the reference fuel). Almost the entire difference between the two alternatives, 18–53 g of carbon per m2 per year, is due to the substitution effect (Olsson, M 2010). The comparison assumes that the felled trees are replaced with new trees that can absorb carbon dioxide from the burned biomass.

A similar Swedish modelling study compares the net effects on greenhouse gas emissions of a number of alternative forest management scenarios and uses for harvested forest products. The greatest reduction in greenhouse gas emissions was achieved with intensive fertilisation, harvesting of logging residue and stumps, and the use of the harvested timber for construction. The factor that had the greatest effect on the outcome was how the harvested timber was used, i.e. whether it was used for construction or as fuel (Eriksson et al. 2007).

When interpreting the results of these two studies it must be kept in mind that they analyse the outcome over very long periods: 200 and 300 years respectively. As can be seen in figure 12, the substitution effects only become significant over periods of several forest rotation cycles.

Furthermore, the assumptions made about the type of buildings in which the timber is used are central to the results of the substitution studies. Substitution factors for wood as a construction material were estimated at 0.78 to 1.11 kg of carbon per m2 of living

Global forestry and climate

The global forest industry uses about 420 million cubic metres of logs each year. Some of the carbon content of the harvested timber is bound up in paper products or timber for varying periods of time. The IPCC has given a half-life (the time it takes for half of the carbon to return to the atmosphere) of two years for paper and 30 years for wood products. Using these values, global use of paper and wood products represents a carbon sink of 20 and 243 Mt CO_2 equivalents per year respectively (based on production in 2007). Added to this is the carbon stored in some forest products that are not burned after use, but end up in landfills. A study by the United Nations Forestry and Agriculture Agency, FAO, (Miner et al. 2010) compares this stored carbon with the greenhouse gas emissions that arise during the manufacture, use and final disposal of forest products. The conclusion is that emissions are significantly higher than carbon sequestration, and that the global flow of forest products represents a carbon source of almost 500 Mt of CO_2 equivalents per year. This corresponds to 0.15 Gt of carbon. If we take into account the substitution effects of wood as a replacement for building materials with more embodied energy, however, the forest industry and forest products become a small carbon sink (see table).

One conclusion that can be drawn from the FAO study is that production and consumption of paper would remain a source of greenhouse gases even if all paper products were used to replace fossil fuels after use. The carbon source would be at least 0.09 Gt per year (see table). In other words there are good reasons to distinguish between paper and wood products when discussing forest sector impacts on the flows of greenhouse gases.

Table 4. Effect of global forest industry's impact on greenhouse gas flows, millions of tonnes of CO_2 equivalents per year. + indicates source, - indicates sink.

1) Converted to carbon dioxide equivalents.

2) Considered impossible to quantify due to large national differences.

	Stored carbon	TOTAL
Forestry	+36.9	
Direct emissons from manufacturing	+297	
Emissions from purchased electricity	+193	
Inputs including fossil energy	+92.4	
Transport	+51.2	+670.5
Carbon stored in paper products used	-20	
Carbon stored in wood products used	-243	
Combustion of forest products	-3	+404.5
Methane from landfill forest products 1)	+234.6	+639.1
Caerbon stored in landfill forest products	-160.6	+478.5
Electricity produced by forest industry2)	???	
Substitution of fossil fuels	- 25.8	+452.7
Substitution of building materials	- 483	-30.3

Table 5. Effect of global paper use on greenhouse gas flows, millions of tonnes of CO_2 equivalents per year.

1) Split 50/50 between paper and wood products.

2) This includes full potential for substitution of fossil fuels, including share allocated to sawn timber.

	Stored carbon	TOTAL
Forestry1)	+18	
Direct emissions from manufacturing	+231	
Emissions from purchased elecricity	+106	
Inputs including fossil energy	+57.4	
Transport1)	+25.5	+437.9
Carbon stored in paper products used	-20	
Substitution of fossilf fuels2)	-135	+282.9

space per year in Finland and from 0.38 to 0.51 carbon per m^2 of living space per year in Sweden. This gives an idea of the uncertainty in the calculations (Pingould et al. 2010).

The study illustrated in figure 12 assumes that a large proportion of the timber extracted is used for wood products. It is assumed that all roundwood larger than 12 cm in diameter is used as structural timber for buildings, and that the life of this timber is on average 100 years (Eriksson et al. 2007). Both these assumptions are a long way from reality. As mentioned earlier, less than 20 per cent of all the timber extracted is used as long-lived construction timber, and the half-lives of harvested wood products are often reported as 15–20 years. The type of buildings and the rate of new construction naturally also set limits on how much construction material can be replaced with wood.

Furthermore, the studies referred to assume that the raw material that is not used as construction timber is used as fuel. So no allowance is made for the production of pulp and paper. This again differs markedly from the real situation in Swedish forestry, where about half of all harvested roundwood is used as pulpwood (Swedish Forest Agency 2010).

The results are very different if we assume a realistic picture of how wood from the forest is used. A life cycle assessment of different management options for Swedish forests on this basis shows that pulp and paper production as a whole has negative climate impact. The effect is so significant that if it is included in the calculations, substitution of fuels becomes a more positive factor in the total climate impact of forestry than substitution of materials (Hofer et al. 2008). *(See figure 13.)*

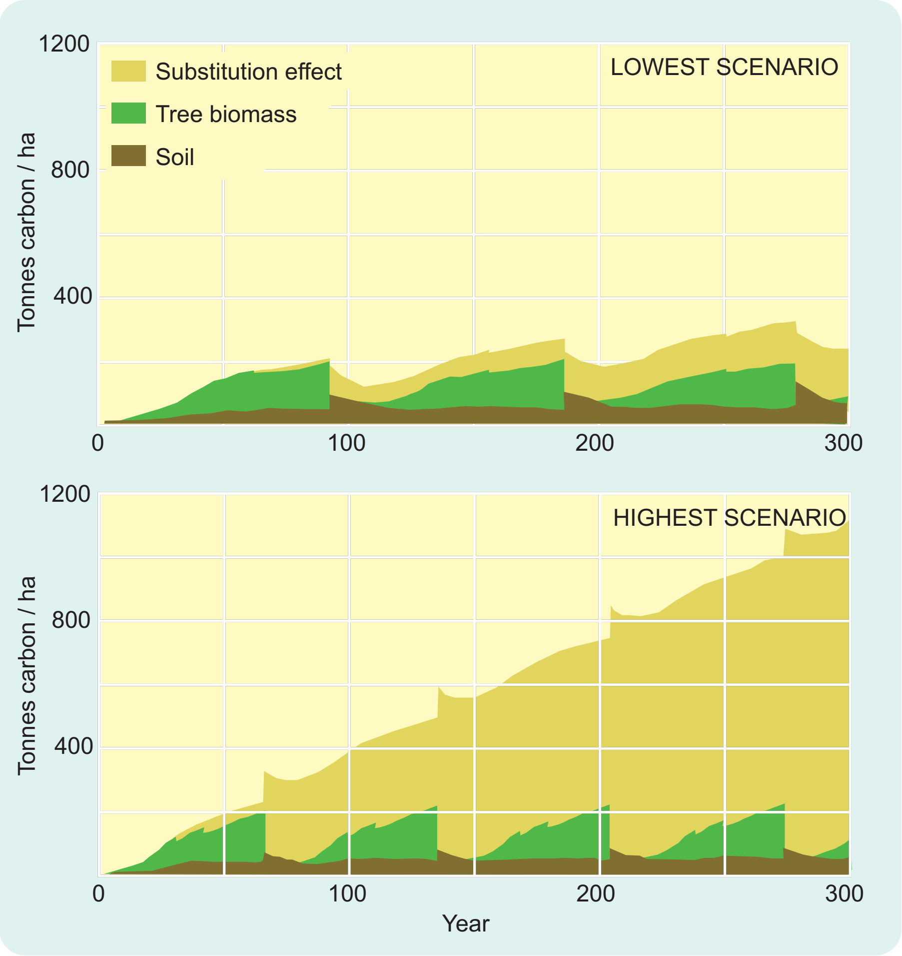


Figure 12. Stored carbon in tree biomass and soil, and the cumulative effects of materials substitution for two scenarios. The upper graph, with the least positive climate effect, is based on present-day forestry, with no harvesting of stumps or logging residue, and takes natural gas as the reference fuel. The lower graph, with the highest positive impact on climate, is based on intensive forestry with stump harvesting, extensive materials substitution, and takes coal as the reference fuel. *(After Eriksson et al. 2007.)*

The highest scenario assumes that all roundwood over 12 cm in diameter is used as construction timber. This is an assumption that is a long way from reality today.

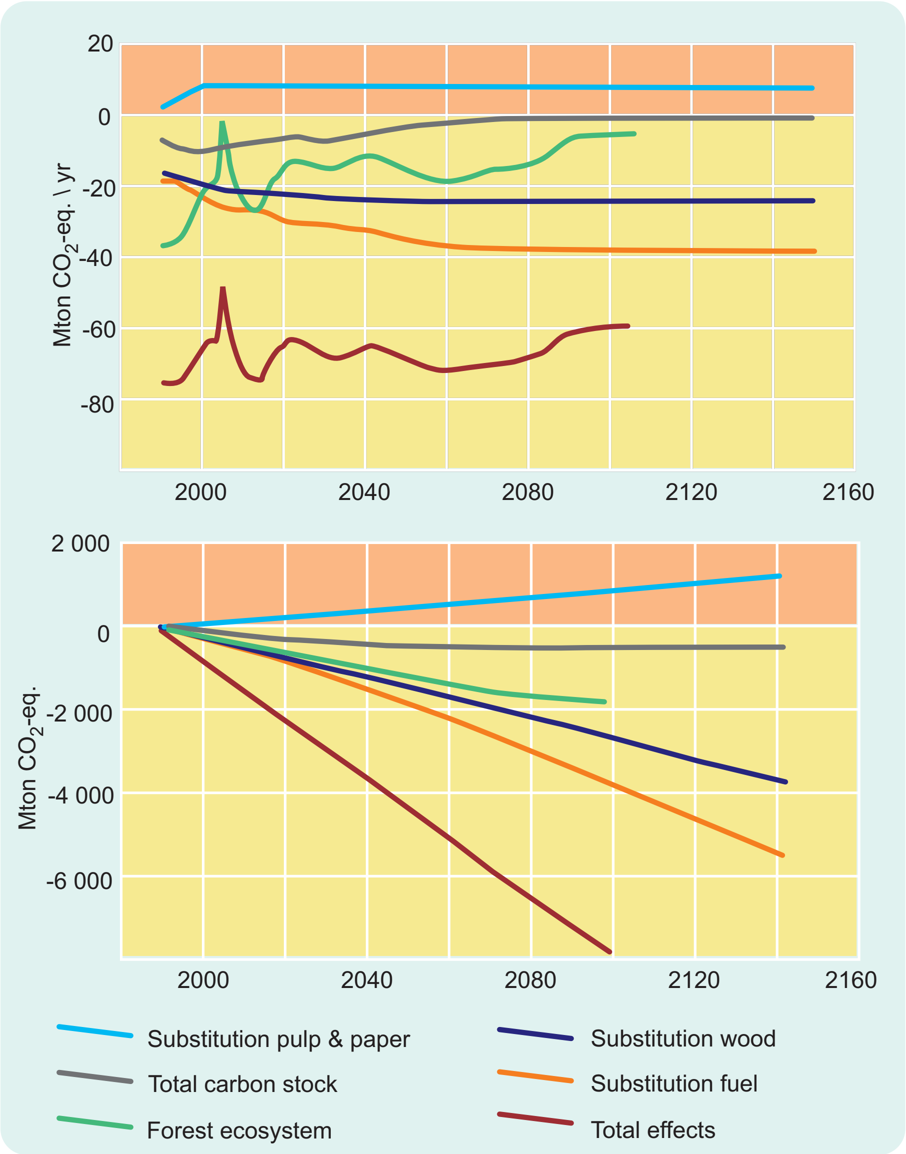


Figure 13. Effects on carbon flows and stored carbon in Swedish forestry from a lifecycle perspective. The upper graph shows annual changes, while the lower graph shows cumulative changes under a scenario where forestry and the forest industry develop in line with current trends until 2035. Conditions are then "locked" to show the long-term consequences up to 2160.

Note the negative effects of pulp and paper.

The study takes into account the effects of fuel substitution by burning used paper, but not materials substitution by paper, i.e. using paper to replace other materials such as packaging.

The sharp peaks in the curves in the upper graph are the impact of Hurricane Gudrun in 2005. *(After Hofer et al. 2008.)*

The study compares a baseline scenario, in which forestry and the forest industry continue to develop in line with current trends until the year 2035, with a scenario in which the harvesting of fuel from the forest increases sharply, and an intensive scenario, in which forest production is increased by means such as fertilisation, species selection and more intensive forest management. Production of roundwood in this scenario is almost 40 per cent higher than in the baseline scenario. Fuel extraction is the same as in the fuel scenario.

It is assumed that the changes made in the various scenarios are completed by 2035. The models then forecast development up to the year 2160 to provide a picture of how the carbon balance is affected in the long run.

In the long term, the baseline scenario results in a carbon sink of 16 Mt of carbon per year, the biofuel scenario 18 Mt of carbon per year, and the intensive scenario 28 Mt of carbon per year. In all three scenarios, fuel substitution is the biggest single factor.

Materials substitution comes in second place, since it also incorporates flows of pulpwood, pulp and paper. Taken together these are such a significant source of carbon that they partially offset the effect of materials substitution by timber products. Based on the assumptions of increased production that are made here, their greenhouse gas emissions would be doubled by the year 2035.

The study does not take into account the materials substitution effects of paper, which is obviously a limitation. Paper could conceivably replace plastics or glass in packaging, for example, and thus have positive effects on the climate. This should not, however, alter the overall conclusion of the study – that a shift in consumption of forest products towards a higher proportion of timber products and forest fuels, and less paper, would have positive effects on climate. It would reduce emissions during production, and enhance the substitution effect. It would also increase carbon sequestration in forests due to longer rotation periods and a larger timber stock (Hofer et al. 2008).

JODA / FOTOLIA


JODA / FOTOLIA

9. Forests and the Climate Convention

This section is based on Macey, K et. al. 2010.

Emissions of greenhouse gases from different types of soil and land use are covered by the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. The collective term for this field is LULUCF – Land Use, Land Use Change and Forestry. Put very simply it enables countries to "offset" carbon sinks in the land use sector against emissions from burning fossil fuels to help meet their agreed emission limits. A country that has, for instance, agreed to cut greenhouse gas emissions by 10 per cent can achieve its target by reducing the amount of fossil fuels it burns by five per cent and increasing carbon sequestration in land use by the same amount, by reforesting previously deforested land, for example. Reducing carbon sequestration in the forest by felling more than is grown will similarly count against the country as emissions. One of the key ideas behind incorporating land use in the climate convention was to create incentives for conserving and managing forests, especially tropical rainforests.

Under article 3.3 of the Kyoto Protocol, parties are required to report greenhouse gas emissions and sinks that arise from planting, deforestation and reforestation. Article 3.4 of the protocol also provides the opportunity to include other land use activities in their accounts, including forestry. Sweden is one of the countries that have chosen to use this facility. It means that Sweden not only reports changes in emissions due to increases or decreases in forest area (changes which in Sweden's case are negligible), but also the growing forest carbon sink and changes in it.

The underlying logic is simple: the more carbon sequestration countries can report in the land use sector, the less need they have to reduce emissions from burning fossil fuels. This has created a negotiating situation in which many countries have an interest in maximising LULUCF credits. They try to drive through accounting rules that favour deductions for carbon sinks rather than the reporting of emissions. The regulatory framework for LULUCF can be seen as a battery of tests to reduce the uncertainty in the system and steer it in a direction that does minimal damage, but can still be accepted by the parties that are pushing for generous carbon credits. So far, the outcome of this process has been a set of complex and rather fragmented rules.

It is important to appreciate that the accounting rules have been negotiated in this way. Even though accounting should be based on scientific grounds, the rules also reflect climate policy. They are the result of a negotiating game that focuses on creating political incentives for various measures, and on closing loopholes. This means that emissions data from countries' official reports under the climate convention cannot easily be compared with scientific data for carbon sources and sinks in nature. As mentioned before, the scientific basis for calculating carbon storage and carbon flows is very inadequate in many countries *(see box on page 18).*

Marrakech principles

At the Seventh Conference of the Parties (COP 7) to the UNFCCC, in Marrakech in 2001, agreement was reached on eight principles for the accounting of LULUCF activities, in order to prevent the undermining of the Kyoto Protocol as an environmental policy tool (see box). The parties agreed that these principles should also apply to the next commitment period (after 2012), but it remains to be seen how closely they are actually followed.

Negotiations over LULUCF rules have continued since 2008 and have become increasingly complicated as parties try to close various loopholes and as demands are made to include an growing number of land use activities. The last Conference of the Parties – COP 16 in Cancun in December 2010 – failed to reach agreement in this area.

Negotiations for the second commitment period are continuing, and there are strong signs that a bias towards sinks rather than actual emissions will persist. It appears that many states not only want to increase the scope for accreditation of sinks, but also want to avoid reporting certain emissions. They have continued to propose various solutions to benefit their own interests, and some states have linked their targets for 2020 to these negotiating manoeuvres. One example is New Zealand, whose target for a 20-per-cent cut in emissions is expressly linked to certain demands concerning the LULUCF rules. The range of emission cuts that Russia has given is based on the requirement that LULUCF is allowed to count towards the achievement of objectives.

Proposed amendments and additions

In April 2011, a string of proposals for amendments and additions to the LULUCF rules are on the negotiating table, including:

- the addition of new land use activities, such as forest degradation and the conversion of wetlands,
- effects of forest management on greenhouse gas flows
- effects of natural disturbances (such as forest fires)
- crediting of carbon storage in forest products.

The conversion of forest into open land is currently included in LULUCF accounting, while the rules do not take into account the degradation of forests – in other words reduction in biomass without total deforestation. If degradation were included, as proposed by the Polynesian state of Tuvalu, it would correct an imbalance in the system, especially for those countries that choose to include the effects of forest management in their reports.

Management of wetlands has been proposed as a new LULUCF activity. The drainage

Marrakech principles governing LULUCF

That the treatment of these activities be based on sound science;

That consistent methodologies be used over time for the estimation and reporting of these activities;

That the aim stated in Article 3, paragraph 1 of the Kyoto Protocol not be changed by accounting for land use, land-use change and forestry activities;

That the mere presence of carbon stocks be excluded from accounting;

That the implementation of land use, land-use change and forestry activities contributes to the conservation of biodiversity and sustainable use of natural resources;

That accounting for land use, land-use change and forestry does not imply a transfer of commitments to a future commitment period;

That reversal of any removal due to land use, land-use change and forestry activities be accounted for at the appropriate point in time;

That accounting excludes the effects of:

- elevated carbon dioxide concentrations above their pre-industrial level,
- indirect nitrogen deposition,
- the dynamic effects of age structure resulting from activities and practices before the reference year.

of wetlands is a significant source of greenhouse gas emissions, but it is doubtful whether the emissions can be quantified accurately and reported in a way that can be verified.

Under the Kyoto Protocol, parties are able to credit the effects of forest management, up to a ceiling agreed in the Marrakech accord. Some countries have proposed new possibilities in this area for the next commitment period, in an effort to encourage more states to include forest management in their accounts. Some of the proposals would increase the scope for forestry-based credits dramatically – and thus reduce the required emission reductions by the same amount.

As mentioned earlier in this report, emissions of carbon dioxide from disturbances such as forest fires and pest infestation are considerable. They could potentially be even greater in the future, not least in boreal forests. Some countries are now looking for opportunities to discount these emissions from their LULUCF accounting. In negotiations, such disturbances are referred to as "force majeure", despite the fact that they are dynamic effects that are entirely natural in most of the world's forests.

A number of parties have proposed that carbon storage in forest products (harvested wood products – HWP) should be included in LULUCF accounting from the next commitment period, something that other parties are opposed to. Advocates argue that some of the carbon in harvested timber is not released into the atmosphere immediately, but is stored in long-lived wood products (such as timber houses) or in landfills. Critics claim that there are no effective, consistent and reliable methods for calculating this stored carbon. If it were possible to credit carbon stocks in harvested wood products without also having to report total emissions from forest land use, the critics claim that this would also create incentives for increased logging and hence unsustainable forestry.

Commitments and reference levels

Countries' commitments are expressed as changes in emissions relative to a baseline year. The baseline year for the first commitment period of the Kyoto Protocol is 1990, and objectives are to be achieved by 2008–2012. The choice of LULUCF objectives and baseline year for the next commitment period is an important and complex issue that is also subject to negotiation. One requirement in the case of deforestation is that commitments must reflect actual reductions in emissions from deforestation and not create incentives to increase the rate of logging before the commitment period begins. All forest ecosystems in a country must be included, and both private and state-owned land must be accounted for. It is likely to prove difficult to obtain a reliable picture of the starting position, since the background information is poor and environmental monitoring is inadequate in many countries. One possibility is to set limits under which countries can obtain credits for reducing deforestation gently, allowing good safety margins. This would require countries to make active efforts to reduce their emissions before they can receive credits in this area.

There are effectively two different ways to define the reference levels. One is based on starting from historical data on deforestation rates, and the other on projections for the future. Reliable reference levels based on historical data have the advantage of ensuring that reported emission reductions have actually taken place. Reference levels based on projections mean that countries would be able to gain credits for loss of deforestation, in other words the deforestation that would have taken place under a theoretical "business-as-usual" scenario.

9. Discussion and conclusions

The purpose of this report is to present an overview of the relationships between forests, forestry and the climate. Forests and forestry in the boreal region are discussed solely from a climate perspective. A measure or strategy that reduces greenhouse gas emissions is described as positive, regardless of the consequences it may have in other respects. This does not mean that the climate is considered more important than other aspects, but is simply motivated by a desire for clarity. It is only when we have a picture of the climatic effects of different courses of action that we can weigh them against the consequences in other areas, such as economics, social value, impact on forest biodiversity or other environmental considerations. These aspects are not discussed here.

A central assumption in the analysis is the estimate that 2°C is a critical threshold for global warming, and that drastic limitations on greenhouse gas emissions are needed over the next few decades to avoid exceeding this limit. This means that analysis of the climate significance of boreal forests must not be limited to the long term. Developments over the next 30–40 years are of critical importance.

About 30 per cent of all the carbon in the world's terrestrial ecosystems is found in boreal forests. The carbon stock is greater than in any other terrestrial ecosystem, and almost twice as large as that of tropical forests. Nearly 90 per cent of this carbon lies in the forest soil. These enormous carbon reserves make boreal forests a key factor in the future climate, particularly as they are expected to be especially sensitive and respond quickly to rising temperatures.

Boreal old-growth forests

About half of the world's boreal forests are old-growth forests, entirely or almost entirely unaffected by forestry. They exist mainly in Alaska, Canada and Siberia. These forests can continue to act as carbon sinks even when they are many centuries old, and over time they build up very large deposits of carbon in the soil. This is where the bulk of carbon is stored in boreal forests. Even from a global perspective, the amount of carbon stored in soil in the northern part of the boreal forest belt is enormous, and it is of utmost importance for the future climate that this stored carbon is not released into the atmosphere.

As the climate becomes warmer, the frequency of natural disturbances – fires and infestations by insects and other pests – will increase. Such trends are already apparent, and they lead to a decrease in carbon sequestration and carbon stocks in the forests. If warming exceeds a critical level, the resulting heat stress combined with water shortages could cause widespread forest loss in the boreal zone. A large proportion of the carbon stored in boreal forests would then be released into the atmosphere, further driving warming in an irreversible and self-sustaining process. It has been suggested that the critical limit for this mechanism is a 3–5 degree rise in average global temperature.

Against this background one might ask whether the best option for the climate is to leave old-growth boreal forests untouched, or if it is better to log them and use the harvested raw materials to replace fossil fuels and building materials with high embodied energy while planting new forest? From an international perspective and in the short term the issue is largely irrelevant. Even if it were desirable, it is not possible to convert the vast old-growth forests of Siberia and northern Canada into managed forest in the course of a few decades.

Most of these areas will continue to be subject to natural dynamics. How they will affect the climate will depend on the speed and extent of the anticipated changes in natural disturbance regimes, which, in turn depend on climate change.

Furthermore, the climatic effects of converting old-growth boreal forests into managed forests are negative in the short and medium term. During logging, some of the stored carbon is lost to the atmosphere. Because the carbon stored in both soil and biomass is greater here than in managed forests, carbon dioxide emissions will also be higher. It takes a long time, probably 100 years or more, for a new generation of trees to sequester the equivalent quantity of carbon, which means that the logging of old-growth forest further increases global warming in the short term.

Managed boreal forests

In managed boreal forests, humans have greater opportunities to influence greenhouse gas emissions, through forestry and through the use of the biomass that is harvested. When the impact of various courses of action are analysed it becomes clear that the time frame is very significant. Measures that have a very positive effect on greenhouse gas emissions in the long term may have little or negative effect in the short term. What appears to be an ideal solution over 100 or 200 years may be counterproductive in light of what we need to achieve in the next few decades.

One strategy that has been proposed is investment in intensive forestry, which increases the sequestration of carbon in growing forests and, more significantly, increases the availability of timber as a raw material. Studies have shown that there is considerable potential in Sweden for intensive forestry with the aid of fertilisation and the use of fast-growing species of trees. From a climate perspective, the thinking behind such a strategy is that the more wood that can be harvested, the more forest fuels can be used in the energy sector, and the more materials with high embodied energy (steel and concrete) can be replaced with wood. In both cases, positive climate effects would be achieved by eliminating emissions of greenhouse gases from burning fossil fuels.

There are, however, several serious objections to such a course of action. The risks are significant. Infestations by certain pests could increase, which would mean higher carbon dioxide emissions. There would also be greater risk of a rise in emissions of nitrous oxide, a powerful greenhouse gas, from forest soil. We have very limited knowledge of what would happen to the large amounts of nitrogen bound in the forest soil during the harvesting of intensively fertilised forests. This also applies to the effects of the fertilisation that takes place today under current management practices.

Production of forest fuel could be increased considerably if stumps were harvested after felling, since almost 20 per cent of tree biomass is in the stump. Because the carbon in stumps is released into the atmosphere much faster if they are burned instead of decomposing in situ in the forest, it would take time for stump removal to have a positive effect on climate. One study indicates around 15 years if we assume that the fossil fuel that is replaced is oil. It takes even longer if the effects of soil disturbance and reduced growth in the next forest generation are also taken into account. Another study has shown that carbon losses from the ecosystem were the same as the carbon content of the harvested stumps a full 27 years after stump extraction, which means that the climate effect was clearly negative. Stump clearance is not practised to any significant extent in Swedish forestry today. If it takes 30 years or more before stump harvesting yields any climate benefits it would therefore be counterproductive from the climate perspective to start using this method, as it would increase greenhouse gas emissions over the next few critical decades.

Forest management strategies that focus on aims other than maximising production and wood yield have not been given much attention in the debate on forests and climate. However, there are some interesting possibilities that should be studied further.

To begin with we can say that there is significant potential for managed forests, in Sweden and Europe as a whole, to continue storing carbon for many decades if they are left to grow and if logging does not increase in line with this growth. In terms of climate policy, forest carbon sinks can thus play an important role in gaining time. At the same time, it should be emphasised that there are risks in storing large quantities of carbon in standing forests. With time, there is a growing risk that this carbon will be released by fires, pest infestations or storms.

The protection of forests for conservation purposes means that carbon stocks in these forests can continue to grow, but the preservation of biodiversity and protection of forests as carbon sinks do not necessarily go hand in hand. Increasing the amount of dead wood in the forest landscape increases the risk of fires, for example, and hence the release of carbon. Forests that have the highest conservation value are not necessarily the most effective carbon sinks.

If we want to store the maximum amount of carbon in soil and trees, postponing harvesting can be a useful course of action. At the same time this also decreases wood yield and hence our opportunities for fuel and materials substitution. It has been shown, however, that the effect of extending rotation periods by 20–40 years in Scandinavian forestry has positive effects on climate, particularly in pine forests, even taking into account substitution effects *(see figure 7)*. This is mainly due to an increase in the proportion of saw timber in the wood that is harvested.

Forestry without clear-cutting would have immediate and lasting positive effects in terms of the impact of forestry on the climate. Forest that is clear-cut remains a carbon source for up to 15 years after logging, and it takes the newly planted forest a few decades to compensate for these emissions. The carbon balance is not restored until around 30–40 years after clear cutting. If forest is harvested on a continuous basis, without clear-cutting, but instead regularly harvesting small amounts of wood from the forest, there will be no major carbon losses from the soil and the forest will remain a continuous carbon sink. Further analysis is needed to determine the impact of any decrease in wood production that arises from eliminating clear-cutting on substitution effects and thus overall greenhouse gas balance.

The other side of the coin is that both extended rotation periods and continuous felling practices reduce the availability of logging residue (though only temporarily in the first case) and therefore the potential to replace fossil fuels with forest fuels.

Substitution of fuel and materials

Substitution effects are a major factor in the overall climate impact of managed forests and forestry. Forest products can replace fossil fuels, either directly as fuel, or indirectly by replacing materials that require a lot of energy to produce, and thus reduce greenhouse gas emissions.

It is important to keep in mind that substitution effects are in a sense theoretical. They rely on the assumption that if a certain amount of wood is available to the market it reduces the use of other materials accordingly. In actual fact it would be quite reasonable to assume, for instance, that greater market availability of forest fuels will affect fuel pricing, leading to lower energy prices and hence higher energy consumption than otherwise. Put another way, a certain proportion of the forest fuel will be used to increase energy consumption rather than substituting for fossil fuels. None of the substitution studies referred to in this report takes into account these potential market effects or analyses the impact of an increased supply of forest fuels on a system with growing energy use.

Even if we ignore any market mechanisms, it generally takes time for measures that increase forest production to produce any significant substitution effects. As illustrated earlier (see figure 12), even a scenario that sets materials substitution at an unrealistically high level has relatively little impact in the short term, and the difference under a scenario of very limited substitution is small.

With time, substitution effects become larger, since they are cumulative. The eliminated emissions add up with each forest generation. There are a number of reasons to ask how meaningful it is to calculate substitution effects over a period of 200 or 300 years. The far horizon for climate policy is barely a hundred years, and it is unreasonable to expect anyone to make factually based assumptions about which fuels or materials will be replaced with timber in 300 years' time.

Another important question is how the harvested wood is actually used. In substitution studies it is generally assumed that the additional wood yield is used as a substitute for fuel or materials, or a combination of the two. This is not the case in real life. Considerably less than 20 per cent of the total wood yield is used for long-lived construction timber. The manufacture of paper and paper products appears on the whole to have a negative climate impact, even if it is assumed that the products are burned and replace fossil fuels after use (see figure 13), since it takes a lot of energy to make them. This means that increasing wood yield reduces greenhouse gas emissions only if the bulk of it is used to replace fuel and/or materials, not to replace paper.

One conclusion that can be drawn is that reducing paper consumption while keeping harvesting at the same level would have a positive effect on the climate, by shifting production in the forest and forestry towards a higher proportion of sawn timber and fuel. This would reduce the emissions associated with production, while increasing substitution effects. It would also increase carbon sequestration in forests by extending rotation periods and increasing timber stocks. There is one reservation though: the way in which we achieve a reduction in paper consumption is likely to be a significant factor, since different paper products probably have different impacts on the climate. Replacing plastic packaging with paper packaging is likely to have more positive impact than using newsprint as a fuel substitute, for example. However, no studies have been found that shed light on this aspect.

References

Aitken, S N m.fl. 2008: Adaption, migration or extirpation: climate change outcome for tree populations. Evolutionary applications, vol 1:1, p. 95 -111.

Balshi, M S m. fl. (in press): Vulnerability of carbon storage in North American Boreal Forest to wildfire during the 21st century. Global Change Biology.

Bergkvist, B & Olsson, M (red) 2008: Kolet, klimatet och skogen - Så kan skogsbruket påverka. Information från LUSTRA.

Bergkvist, B (red) 2007: Kolet, klimatet och skogen. Skogsklädda, torvtäckta marker. Information från LUSTRA.

Bernes C 2003: En varmare värld? Monitor 18, Statens Naturvårdsverk.

Blennow, K 2007: Risk för vindfällning i skogsbruket. I ”Alnarps forskare om klimatförändring”, SLU.

Bonan, G B 2008: Forests and climate change: Forcings, feedbacks and climate benefits of forests. Science, vol. 320:5882, p. 1444-1449.

Bond-Lamberty, B m. fl. 2007: Fire as the dominant driver of central Canadian boreal forest carbon balance. Nature, vol. 450:7166, p. 89-+.

Bradshaw, C J A m. fl. 2009: Urgent preservation of boreal carbon stocks and biodiversity. Trends in Ecology and Evolution, vol 24, no 10, p. 541-548.

Bryant, D m. fl. 1997: The last frontier forests. World Resources Institute.

Bäck, J & Hari, P 2009: BVOC emissions from boreal forests. In Hari, P & Kulmala, L (ed.) 2009: Boreal Forest and Climate Change. Advances in Global Change Research. Springer. (Kap 10).

Cedergren, J 2008: Kontinuitetsskogar och hyggesfritt skogsbruk. Skogsstyrelsens meddelande 2008:1.

Ciais, P m. fl. 2003: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature, vol. 437, p. 529-533.

Ciais, P m. fl. 2008: Carbon accumulation in European forests. Nature Geoscience vol 1, p. 425-429.

de Jong, J (red) 2010: Konsekvenser av skogsbränsleuttag. Preliminär rapport. En syntes av Energimyndighetens forskningsprogram inom skogsbränsle och miljö 2005-2009.

Eriksson, E m. fl. 2007: Integrated carbon analysis of forest management practices and wood substitution. Canadian Journal of Forest Research, vol. 37, p. 671-681.

Eriksson, H 2007 (red): Svenskt skogsbruk möter klimatförändringar. Skogsstyrelsens rapport 8:2007.

Eriksson, H 2008: Skogens roll i klimatarbetet. PM 2008-05-30. Skogsstyrelsen.

Eriksson 2011: Muntlig uppgift Hillevi Eriksson, Skogsstyrelsen.

EEA (European Environmental Agency) 2010: European Union emission inventory report 1990-2008 under the UNECE convention on long-range transboundary air pollution (LRTAP). EEA technical report 7/2010.

Fee, E (red.) 2011: Scientific Perspectives after Copenhagen. Information Reference Document. European Union.

Flannigan, M m. fl. 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest. Global Change Biology, vol. 15: 3,p. 549-560.

Frieler, K m. fl. 2009: High noon for +2°C. Fact sheet. Air Pollution and Climate Secretariat.

Goetz, S J m. fl. 2007: Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. Env. Research letters, vol. 2:4, #045031.

Grelle, A 2010: Skogens kolbalans bestäms av upptag och utsläpp. I ”Sverige i nytt klimat - våtvarm utmaning.” Formas Fokuserar 16.

Hari, P & Kulmala, L (ed) 2008: Boreal forest and climate change. Advances in global change research 27. Springer.

Hari, P & Nikinmaa, E 2009: The response of boreal forest to climate change. In Hari, P & Kulmala, L (ed.) 2009: Boreal Forest and Climate Change. Advances in Global Change Reesearch. Springer.

Hari, P m. fl. 2009: Evaluation of the Connections between Boreal Forests and Climate Change. In Hari, P & Kulmala, L (ed.) 2009: Boreal Forest and Climate Change. Advances in Global Change Reesearch. Springer.

Hofer, P m. fl. 2008: Forest and Carbon. Greenhouse gas dynamics of different management and wood use scenarios in Sweden. Geopartner AG, Zurich. Rapport för SLU. Opublicerad.

IPCC 2007 a: Fourth assessment report, Climate Change: Synthesis report.

IPCC 2007 b: Fourth assessment report, Climate change. Working group I report, chapter 11: Regional Climate Projections.

IPCC 2007 c: 4th assessment report, Climate Change Working group II report: Impact, adaptation and vunerability, chapter 1: Assessment of observed changes and responses in natural and managed systems.

IPCC 2007 d: Fourth assessment report, Climate change. Working group II report: Impact, adaptation and vulnerability, chapter 4: Ecosystems, their properties goods and services.

Jacobson, S m. fl. 2000: Impact of whole-tree harvesting and comp+ensatory fertilization on growth of coniferous forest stands. Forest. Ecol. Management 129, p. 41-51.

Johnsson, M & Wardle, D 2010: Inlagring och kolbalanser en åldrande skog. Presentation vid FSC-seminarium ”Klimat, energi och skogsförvaltning" 2010-11-10: *www.fsc-sverige.org/images/dokument/micael_johnson.pdf*

Jord- och skogsbruksministeriet, Finland 2010: *ww.mmm.fi/sv/index/amnesomraden/pressmeddelanden/100824_suo_sv.htm*

Juday G m. fl. 2005: Forests, land management and agriculture. Chapter 14 in "ACIA, Artctic Climate Impact Assessment". Arctic Council.

Kang, S m. fl. 2006 a (i **Bradshaw, C J A m. fl. 2009):** Urgent preservation of boreal carbon stocks and biodiversity. Trends in ecology and evolution, Vol 24, no 10, p.541- 548.

Kang, S m. fl. 2006: Simulating effects of fire disturbance and climate change on boreal forest productivity and evapotranspiration. Science of the Total Environment, vol. 362: 1-3, p. 85-102.

Kasischke, E S 2000: Boreal ecosystems in the global carbon cycle. In Kasischke, E S m. fl. (eds): Fire, Climate Change and Carbon Cycling in the Boreal Forest. Ecological Studies Series, Springer Verlag.

Kasischke, E S m. fl. 1995: Fire, global warming and the carbon balance of boreal forest. Ecological applications 5 (2) pp. 437 - 451.

Kirilenko A P & Sedjo R A 2007: Climate change impacts on forestry. PNAS, vol 104:50, p. 19697-19702.

Kulmala, M m. fl. 2009: Climatic Effects of Increasing Aerosols. In Hari, P & Kulmala, L (ed.) 2009: Boreal Forest and Climate Change. Advances in Global Change Reesearch. Springer.

Kullman, L & Öberg L 2009: Post Little-Ice Age treee line rise and climate warming in the Swedish Scandes: a landscape ecological perspective. Journal of Ecology, vol. 97:3, p. 415-429.

Kurz, W A m. fl. 1998: Carbon budget implications of the transition from natural to managed disturbance regimes in forest landscapes. Mitigation and Adaption Strategies for Global Change. No 2, p.405-421.

Kurz, W A m. fl. 2008 a: Mountain pine beetle and forest carbon feedback to climate change. Nature vol. 452:7190, p. 987-990.

Kurz, W A m. fl. 2008 b: Risk of natural disturbances makes future contribution of Canada´s forests to the global carbon cycle highly uncertain. PNAS, vol 105:5, p. 1551-1555.

Lagergren, F m. fl. 2006: Current carbon balance of the forested area in Sweden and its sensitivity to global change as simulated by Biome-BGC. Ecosystems 9, p. 894-908.

Larsson, S m. fl. 2009: Möjligheter till intensivodling av skog. Slutrapport regeringsuppdag Jo 2008/1885. SLU

Lenton, T M m. fl. 2008: Tipping elements in the Earth´s climate system. PNAS vol. 105:6, p 1786-1793.

Lindholm, E 2010: Energy use and Environmental impact of roundwood and forest fuel production in Sweden. Doctoral thesis, Dept of Energy and Technology, SLU.

Lindner, M & Karjalainen, T 2007: Carbon inventory methods and carbon mitigation potentials of forests in Europe: a short review of recent progress. Eur. Forest Institute, Finland.

Lindner m. fl. 2004 i **Nabuurs, GJ m. fl. 2008:** Hotspots of the European carbon cycle. Forest Ecology and Management, vol 256, p- 194-200.

Lindroth, A 2009: Brev till Göran Persson, Sveaskog 2009-07-01.

Lindroth, A m. fl. 2009: Storms can cause Europe-wide reduction in forest carbon sink. Global Change biology, vol. 15:2, p. 346-355.

Lloyd A H 2005: Ecological histories from Alaskan tree lines provide insight into future change. Ecology, vol. 86:7, p. 1687-1695.

Lloyd, A H & Bunn A G 2007: Responses of the boreal forest to 20th century climate variability. Environmental research letters, vol 2:4, #045013.

Lundblad, M m. fl. 2009: Flöden av växthusgaser från skog och annan markanvändning. Slutrapport regeringsuppdrag JO 2008/3958.

Lundgren, C (odaterad) : Fiberskog som vedråvara. Rapport rån granprojektet, SLU, *http://www-gran.slu.se/Webbok/PDFdokument/Ved_slutrapport.pdf*

Lundmark, T 2010: Gödslad skog ger största klimatnyttan. I ”Sverige i nytt klimat - våtvarm utmaning". Formas Fokuserar 16.

Lundström, A m fl 2009: Prognoser för markanvändningssektorn - 2030. I ”Flöden av växthusgaser från skog och annan markanvändning. Slutrapport av regeringsuppodrag Jo 2008/3958. SLU.

Luyssaert, S m. fl. 2010: The European carbon balance. Part 3: forests. Global Change Biology, vol 16: 1429-1450

Luyssaert, S m fl 2008: Old-growth forests as global carbon sinks. Nature 455, p. 213-215

Macey, K m.fl. 2010: ”LULUCF Briefing". Underlagsmaterial framtaget av Climate Analytics för AirClim Secretariat.

Magnani, F m. fl. 2007: The human footprint in the carbon cycle of temperate and boreal forests. Nature, vol. 447, p. 848-850.

Malevsky-Malevich, S P m. fl. 2008: An assessment of potential change in wildfire activity in the Russian boreal forest zone induced by climate warming during the 21st century. Climate Change, vol. 86:3-4, p. 463-474.

Miner, R 2010: Impact of the global Forest Industry on atmospheric Greenhouse gases. FAO Forestry Paper 159.

Mjöfors, K & Strömgren, M: Förändringar i skogens kolförråd - ett mått på stubbränslets klimatnytta. I ”Stubbskörd och miljöeffekter - en populärvetenskaplig lägesrapport, våren 2010". SLU

Moren, A-S & Olsson, M (red) 2007: Kolet, klimatet och skogen - så funkar det. Information från LUSTRA 2007.

Nabuurs, G J m. fl. 2008: Hotspots of the European carbon cycle. Forest Ecology and Management, vol 256, p- 194-200.

Naturvårdsverket 2011: National Inventory Report Sweden 2011. Submitted under the UN Framework Convention on Climate Change and the Kyoto protocol. Swedish Environmental Protection Agency.

Nordin, A m.fl. 2009: Effekter av ett intensivare skogsbruk på skogslandskapets mark, vatten och växthusgaser. Faktunderlag till MINT-utredningen. SLU.

Olsson, M 2010: Lagra eller använda skogen? I ”Sverige i nytt klimat – en våtvarm utmaning”. Formas Fokuserar 16. Formas.

Olsson, R 2009: Boreal Forest and Climate Change. AirClim report 23. Air Pollution and Climate Secretariat.

Olsson, R 2010: Boreal Forest and Climate Change - regional perspectives. AirClim Report 24. Air Pollution and Climate Secretariat.

Pihlatie, M 2009: CH_4 fluxes in Changing Climate. In Hari, P & Kulmala, L (ed.) 2009: Boreal Forest and Climate Change. Advances in Global Change Research. Springer.

Pihlatie, M, Pumpanen, J & Hari, P 2009: N_2O emissions from Boreal Forests. In Hari, P & Kulmala, L (ed.) 2009: Boreal Forest and Climate Change. Advances in Global Change Research. Springer.

Pingoud, K, Pohjala, J & Valsta, L 2010: Assessing the integrated Climatic Impacts of Forestry and Wood Products. Silva Fennica, vol. 44(1), p. 155-175.

Repo, A m. fl. 2010: Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. Global Change Biology - Bioenergy. DOI: 10.1111/j.1757-1707-.2010.01065.

Rummukainen, M & Källén, E 2009: Ny klimatvetenskap 2006-2009. Kommissionen för hållbar utveckling.

Rummukainen, M 2010: Sveriges klimat i framtiden. I ”Sverige i nytt klimat”. Formas fokuserar 16. Formas.

Räisänen, J & Smolander, S 2009: Climatic Effects of Increased leaf Area: reduced surface albedo and Increased Transpiration. In Hari, P & Kulmala, L (ed.) 2009: Boreal Forest and Climate Change. Advances in Global Change Reesearch. Springer.

Sathre, R m. fl. 2010: Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization. Biomass and Bioenergy, vol. 34: p. 572-581.

SCB 2009: Skyddad natur 31 dec 2009. Statistiska meddelanden MI 41 SM 1001.

Schellnhuber, H J 2009: Tipping elements in the Earth system. PNAS 106:49, p. 20561-20563.

Schellnhuber, H J m. fl. 2009: WBGU Special report: Solving the climate dilemma - the budget approach. German Global Change Advisory Council, Berlin.

Schlyter, F 2008 : Granbarkborren- klimatförändringens vinnare. I ”Alnarps forskare om klimatförändringen”, SLU.

Scholes, R J 2004: TheTerrestrial Carbon Cycle. In Steffen, W m. fl. 2004: Global Change and the Earth System (chapter 2, p. 43.) Springer Verlag

Skogsstyrelsen 2010: Skogsstatistisk Årsbok 2010.

Soja, A J m. fl. 2007: Climate-induced boreal change: predictions versus current observations. Global and Planetary Change, vol 56. p. 274-296.

Spracklen, D m. fl. 2008: Boreal forests, aerosols and impacts on clouds and climate. Philosophical Transaction s of the Royal Society A - Mathematical, Physical and En gineering Sciences, vol. 366:185, p. 4613-4626.

Steffen, W m. fl. 2004: Global Change and the Earth System. A planet under pressure. Springer Verlag.

Stireman, J O m. fl. 2005: Climatic unpredictability and parasitism of caterpillars: Implications of global warming. PNAS, vol. 102:48, p. 17384-17387.

Tivy, J 1993: Biogeography. A study of plants in the ecosphere. Longman Scientific & Technical, UK.

UK Met Office 2009. Map available at *www.guardian.co.uk/environment/interactive/2009/oct/22/climate-change-carbon-emissions.*

Watson, R T m. fl. 2002: IPCC special report on Land Use, Land Use Change and Forestry. IPCC 2002.

Werner, F m. fl. 2010: National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environmental Science & Policy, vol 13, p. 72-85.

Witzell, J m. fl. 2009: Skador på skog. Skogsskötselserien nr 12. Rapport, Skogsstyrelsen.

Volney, W J A & Fleming, R A 2007: Spruce budworm *(Choristoneura spp.)* biotype reactions to forest and climate characteristics. Global Change Biology, vol. 13: 8, p. 1630-1643.

Woods Hole Research Center: *http://whrc.org/global/highlatitude/index.html.*

Ågren, G & Hyvönen-Olsson, R 2006: Fungerar kretsloppen om vi använder mera biobränslen? Fakta Skog nr 3 / 2006. SLU.

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