Effects of forest fertilization for carbon sequestration

Additional Carbon Removal in the Swedish forestry - The Forest Solution

Introduction

Fertilization of forests to increase production has occurred in Sweden since the sixties. In 1980, the scale reached a maximum of over 160,000 ha fertilized. Since then, fertilization has decreased significantly and over the past twenty years there has been between 20,000 and 30,000 ha (Figure 1). Fertilization occurs mainly in the forests of large forest industry companies, while fertilization in private landowners estates is marginal.

Fertilized area (1 000 hectare) every year

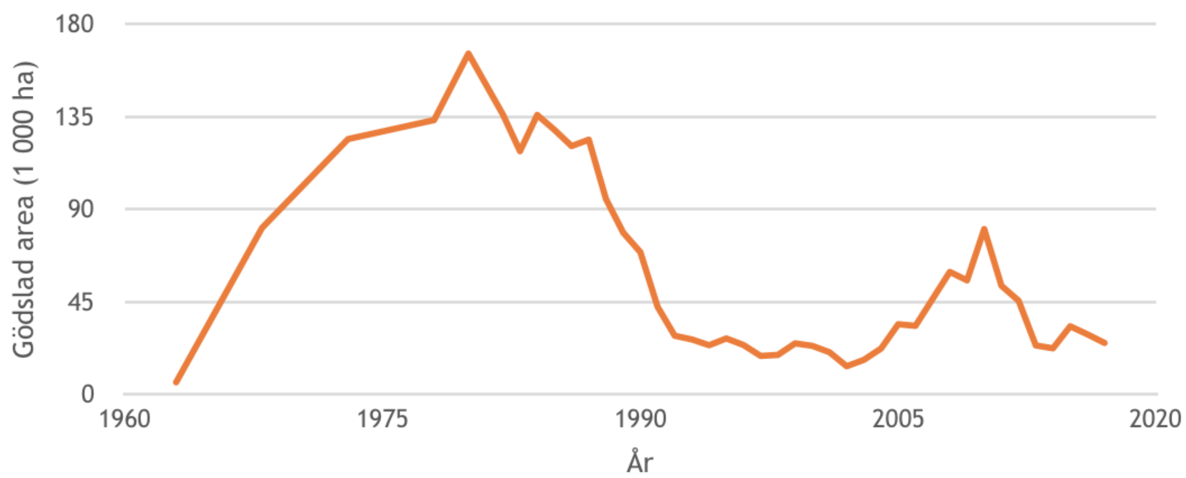

Figure 1. Fertilized forest land during the period 1960-2017. Data is taken from the forest statistics yearbook 1991, 2014 and the Swedish Forest Agency's statistical database. Until 2005, only the large-scale forestry was included and the small-scale was reported to be between 1000 - 3000 hectares.

Forest fertilization with the purpose of carbon offsetting has not existed before, but the fact that forest fertilization increases the absorption of carbon dioxide in a forest ecosystem is well known. The climate benefit remains even if it is expected that the production and distribution of fertilizers will lead to greenhouse gas emissions.

This report describes the climate benefit of forest fertilization and how it affects the absorption and emissions of greenhouse gases. It also describes other environmental impacts of fertilization, such as the impact on nitrogen leakage that can contribute to eutrophication, acidification and biodiversity. Many scientific studies have been done on the effects of fertilization on production and the environment, and the results of these have been compiled in different syntheses. This report is based on the results of these syntheses that reflect a Nordic perspective. Where information is lacking in these syntheses, supplementation has been made from results from individual studies or results from other forest ecosystems.

Fertilizer and forest greenhouse gas balance

Forest greenhouse gas balance

Greenhouse gas balance in the forest is dominated by two large flows, carbon dioxide uptake through photosynthesis in trees and soil vegetation and carbon dioxide emissions through respiration (Figure 2). Respiration includes both cell respiration of all biomass, but also the carbon dioxide released by decomposition of organic matter and organic carbon in the soil. A small portion of all carbon dioxide absorbed through photosynthesis leads to the sequensation of carbon in trees and plants.

When old leaves, needles, branches or roots die, they end up in and on the ground and contribute to the build-up of the soil's coal supply. When decomposing old and older coal into the soil, most of it is released as carbon dioxide. A small part of the ground coal can be dissolved in water and can leave the forest to surrounding water.

In addition to carbon dioxide, nitrous oxide and methane are also included in the forest's greenhouse gas balance. Both of these flows are normally very small in solid forests, where there is often a small uptake of methane. The methane discharge, on the other hand, can be large from ditches and wetlands, and for nitrous oxide the discharge is large on ditched peatlands.

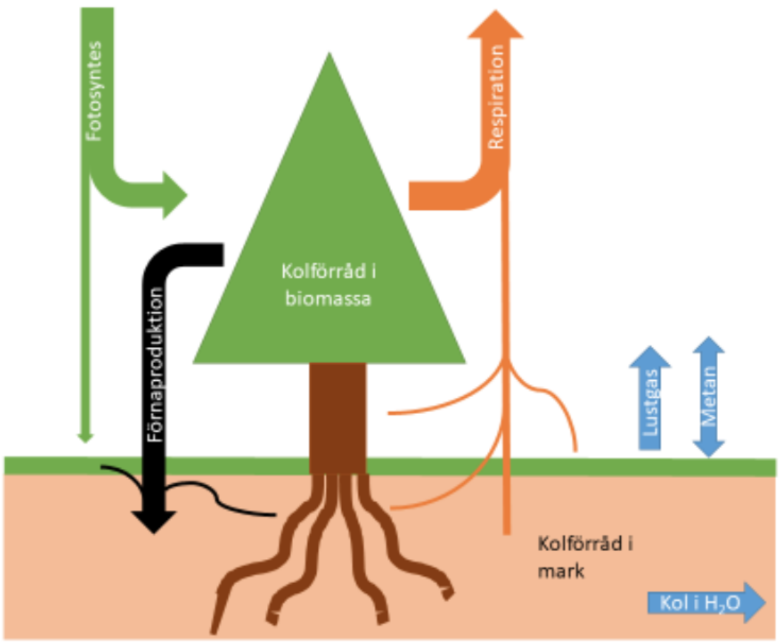

Figure 2. Schematic view of the forest greenhouse gas balance.

When fertilizing forests, all these flows are affected by greenhouse gases and it is the net balance that determines how great the climate benefit will be. Forest fertilization increases the forest's coal supply in both biomass and soil.

Forest fertilization with nitrogen increases biomass production in ecosystems where nitrogen is a limiting growth factor (Tamm 1991). In principle, all Swedish forest on land is limited by nitrogen (Tamm 1991, Nohrstedt 2001). The production potential has been estimated to be two to three times higher than current production if neither nitrogen nor other nutrients restricted growth (Bergh et al. 2005). The production-enhancing effect of nitrogen fertilization is well-established in a number of studies and synthesis reports (Nohrstedt 2001, Pettersson & Högberg 2004, Hyvönen et al, 2008, Hedwall et al. 2014). When the trees gain increased access with nitrogen, they respond by increasing the leaf area. With a larger leaf/needle area, more sunlight can be used and thus more carbon dioxide is absorbed (Hedwall ml 2014). In addition, nitrogen fertilization leads to more efficient photosynthesis in the leaves or barrels (Roberntz & Stockfors 1198). Each tree needle or leaf can thus absorb a little more carbon dioxide when fertilized. The increased production after a round of nitrogen fertilizer usually persists for 7-10 years (Pettersson, 1994; Pettersson and Högbom 2004).

Forest fertilization not only increases the carbon supply of biomass but also the soil's coal supply (Johnson 1992; de Wit & Kvindesland 1999, Johnson & Curtis 2001, Freeman et al. 2005, Hyvönen et al. 2007). This is partly due to the fact that increased growth leads to an increase in litter production and thus an increased supply of coal to the soil, but partly because the degradation of organic material in the soil is reduced (Ågren & Folkesson 2012).

Results from a study of 15 long-term fertilization experiments with recurrent fertilizer donations in Sweden and Finland showed that 25 ± 5 kg of carbon per added kg of nitrogen was bound into the tree biomass and an additional 11 ± 2 kg in the soil (Hyvönen et al. 2008). This corresponds to about 14 tonnes of carbon dioxide per hectare in biomass and another 6 tonnes in the soil at a normal fertilizer rate of 150 kg/hectare. That study further showed that if the fertilizer also contained phosphorus and potassium (NPK), as much as 38 kg of carbon was absorbed per added kg of nitrogen. For a normal fertilizer yield, this corresponds to 21 tonnes of carbon dioxide per hectare. The effect was greatest if nitrogen was added in small doses rather than in large doses.

In conventional forest fertilization of nitrogen limited stocks, a normal fertilizer yield of 150 kg/ha gives an increased stand growth corresponding to about 15 m3 ha-1 (Petterson 1994, Nohrstedt 2001, Pettersson & Högbom 2004). This corresponds to 11 tonnes of carbon dioxide. In addition to growth in stem, there is also increased growth in roots, branches and needles. Since these parts make up about half of a tree's total biomass (see Marklund 1988, Petersson & Ståhl 2006, cf. Björheden 2019), we can expect to be as much bound in there as in the trunk's biomass. This means that a total of about 22 tonnes of carbon dioxide is bound per hectare in the biomass.

Expected production after fertilization for a single forest stand can be estimated based on factors such as location in the country (latitude, altitude), quality, tree species and added nitrogen (Pettersson 1994ab). Production is between 10-20 m3 ha-1 and in absolute numbers the difference between north and south is small, although the relative is higher in the north.

Generally, a classic fertilizer donor gives…

- ... more production for spruce than pine
- ... more on low site quality than high site quality
- … more at higher altitudes than lower

The production of high quality may also be high if other nutrients are added to the fertilizer, together with nitrogen or completely without (Hyvönen et al. 2008, Hedwall et al. 2014). More production in absolute numbers in mature stands than young, but a young is more efficient than the elderly if fertilization is done with more small donors (Hedwall et al. 2014).

Nitrous oxide emissions increase slightly

It is well known from the agricultural context that fertilization leads to increased nitrous oxide emissions, a greenhouse gas that is 298 times as potent as carbon dioxide. Nitrogen is a by-product that is naturally formed during nitrification and denitrification. Nitrification is the aerobic process when ammonium is oxidized to nitrate. During denitrification, nitrate is reduced to nitrogen which is released into the atmosphere. Depending on which microorganisms are involved in the processes, different amounts of nitrous oxide can be emitted.

When it comes to forest fertilization of mineral soils, however, there are no studies showing a significantly increased emission of nitrous oxide (Nohrstedt 2001, Björsne 2018). However, knowledge about nitrous oxide emissions from boreal and hemiboreal forest on solid land for Nordic conditions is very limited (Maljanen et al. 2010). The studies available on these forests show very low emissions of nitrous oxide (Kim & Tanaka 2003, Matson et al. 2009, Ullah et al. 2009, Strömgren et al. 2017, Björsne 2018). Regarding the effect of fertilization, Björsne (2018) showed in his dissertation that there were small differences in nitrous oxide emissions between a forest area that was intensively fertilized with 50-100 kg N per hectare for over twenty years compared to an area that was fertilized. In another ongoing study in which young forest was fertilized every two years, no effect was also seen on nitrous oxide discharge of fertilizer (Bergh et al. 2015).

One reason why nitrous oxide emissions are low in forest ecosystems is that the trees and vegetation are already established and can then absorb nitrogen when available. It should be noted that there are also forests with really high nitrous oxide emissions, especially from forests on fertile ditched peatland or former arable land (Maljanen et al. 2010, Leppelt et al. 2014). This type of forest should not be used for forest fertilization.

Nitrous oxide emissions in Sweden caused by forest fertilization were estimated to be 59 tonnes of carbon dioxide equivalents in 2017 (Swedish Environmental Protection Agency 2019a). Sweden's total emissions of nitrous oxide (including LULUCF) amounted to 6 million

tonnes, of which the agricultural sector accounted for 78% of emissions. For forest fertilization, the emissions were based on a template that 1% of the nitrogen supplied by fertilizer is then emitted to the air as nitrous oxide (Naturvårdsverket 2019 b). This emission factor is taken from the IPCC guidelines for national greenhouse gas inventory (IPCC 2016). It is based solely on studies of fertilization of arable land and it is therefore likely that it is set too high for forest fertilization of Swedish forests carried out in accordance with the recommendations of the Swedish Forest Agency. Even if we use that emission factor, a normal fertilizer supply of 150 kg of nitrogen per hectare would result in 1.5 kg of nitrogen being released in the form of 2.4 kg of nitrous oxide. In terms of carbon dioxide equivalents, this corresponds to 0.7 tonnes of carbon dioxide equivalents per hectare.
The forest's methane balance is affected, but negligible for the entire greenhouse gas balance.

In addition to carbon dioxide and nitrous oxide, there is also the greenhouse gas methane involved in greenhouse gas balance in the forest. It is also significantly more potent than carbon dioxide where 1 kg of methane corresponds to 34 kg of carbon dioxide equivalents over a 100-year perspective. It is mainly from wetlands and wet peatlands that the emissions of methane can be significant. On drained mineral soils, however, methane is oxidized and a small uptake occurs. Fertilization has been shown to reduce the oxidation of methane and thus reduce the uptake or increase of emissions (LeMer & Roger 2001, Liu & Greaver 2009, Aronson & Helliker 2010, Gundersen et al. 2012, Shresta et al. 2015, Högberg et al. 2014) . In a study from four spruce stands and one beech stand, the uptake of methane decreased by the equivalent of 16-50 kg of carbon dioxide equivalents per hectare per year when fertilizing between 35-50 kg N (Gundersen et al. 2012). These levels are negligible in comparison with the levels of uptake and emissions of the greenhouse gases carbon dioxide and nitrous oxide. There are also studies that indicate that there are only initial effects and that the effect is missing or opposite in the longer term (Nohrstedt 2001).

Greenhouse gas emissions caused by the production and spreading of the fertilizer
Yara states that the fertilizers they produce, on average, emit 3.65 kg of carbon dioxide equivalent per kg of nitrogen (Yara, 2019). This included everything from extraction of raw materials to the final product. None of their fertilizers exceeded 4.0 kg of carbon dioxide equivalent per kg of nitrogen. When fertilizing with 150 kg N per hectare, this results in a total emission corresponding to a maximum of 600 kg of carbon dioxide per hectare or 548 kg if one uses an average fertilizer.

Carbon dioxide emissions caused by fuel consumption when spreading forest manure were estimated to be a total of 790 tonnes of carbon dioxide in Sweden in 2014 (Björheden 2019). As this is spread over a total of 24,000 hectares, the average emissions are 33 kg per hectare.

The substitution effect contributes to increased carbon sink
In addition to the binding of carbon dioxide in the wood of the trees in the forest, there is also a further climate benefit from the fact that the wood will in future be tied into different wood products or can be used to replace fossil products. The magnitude of this substitution effect depends on how the wood is used. In a report on opportunities for intensive cultivation at

national level, the substitution effect was stated to be 600 - 800 kg of carbon dioxide per m3 of solid wood (Larsson et al., 2009).

This would correspond to an additional carbon dioxide uptake of about 11 tonnes per hectare if we expect increased stand growth of 15 m3. This is in the same order of magnitude as the amount of carbon dioxide that is bound into the log.
In our calculations for carbon offsetting, we have not calculated the effects of substitution, since it is largely affected by which products the timber is expected to replace in the future. This effect thus becomes an additional bonus.

Greenhouse gas budget for fertilizing an average forest
Fertilization at one time with 150 kg of nitrogen per hectare in an average forest gives a sink in soil and biomass corresponding to about 28 tonnes of carbon dioxide per hectare (Table 1). Depending on the choice of stand, it may vary between 21-35 tonnes. The emissions caused by the production of fertilizers, the spread of fertilizers, the impact on methane production and nitrous oxide production correspond to about 1,3 tonnes. A fertilizer donation thus gives a net absorption corresponding to 26,7 tonnes of carbon dioxide per hectare. In addition, we can expect a substitution effect that results in a total climate benefit of 37 tonnes per hectare.

Table 1. Absorption and emissions of greenhouse gases in carbon dioxide equivalents as a consequence of a fertilizer supply of 150 kg of nitrogen/ha. For supporting documents and assumptions, see text.

Factor	Sequestration (ton/ha)	Emissons (ton/ha)	References
Increased stem growth	11,0		(15 m3 stem) Pettersson, 1994
Increase growth in neddles, roots and branches	11,0		Half the total biomass growth of a tree Marklund 1988, Petersson & Ståhl 2006 (cf. Björheden 2019)
Binding i soil (litter, organic debris)	6,05		Hyvönen et al. 2008
Manufacture of the Nitrogen fertiliser		0,548	Yara, 2019
Execution of forest fertilization		0,033	Björheden 2019
Nitrous oxide		0,7	NIR sub 2019 Annex
Methane (decrease in uptake)		0,05	Gundersen m fl 2012
TOTAL	28,1	1,33	
Net sequestration CO2e (ton/ha)	26,7		ton CO2e/ha

“50% growth in the rest of the tree” in the table above with the support of allometric functions from Marklund 1988, Petersson & Ståhl 2006 (cf. Björheden 2019). When it comes to changing the allocation of growth between above-ground biomass and roots due to fertilization, there is mainly research on plantlets.

Other environmental effects

Nitrogen leaching

Fertilization increases the risk of nitrogen leakage which can lead to eutrophication of water. As the northern forests are severely limited by nitrogen, nitrogen is immediately absorbed by the growing forest, which makes the leakage even from fertilized forest very low (Nohrstedt 2001, Hedwall et al. 2014). A prerequisite is that fertilization is done during the part of the year when the roots are active.

If forest fertilization is done according to the recommendations of the Forest Board, at the right time and with protection zones towards water and wetlands, the risk of significant leakage is low. The leakage has also been found to be low in experimental forests that have been intensively fertilized at levels well above the Forest Board's regulations (Hedwall et al. 2013). The first practical forest fertilization attempts were made with aircraft and helicopters and without water protection zones. In these experiments, about 5% of the nitrogen released leaked (Nohrstedt 2001).

At final harvest, when there are no longer any growing trees, the nitrogen leakage usually increases. As soon as soil vegetation has been established, the leakage returns to low levels again. For a fertilized stock, there is a risk of increased nitrogen leakage at final harvest (Nohrstedt 2001, Högberg et al. 2014). This increase has been especially evident when stocks were fertilized with between 700-1000 kg of nitrogen/ha, which is considerably more than what the National Forest Board recommends. One way to further reduce the risk of nitrogen leakage is to also harvest the logging residues (GROT) at final harvest.

Acidification

Fertilization with ammonium nitrate alone has an initial acidifying effect on soil and water (Nohrstedt 2001). The acidifying effect is transient. Conventional forest fertilizers, in addition to ammonium nitrate, also contain the mineral dolomite which reduces soil acidification.

Rejuvenation of the next stand

No negative effect has been observed on rejuvenation results on subsequent forest generation after fertilization in the previous population (Nohrstedt 2001, Johansson et al. 2013).

Biodiversity

Increased nutritional access affects forest ecosystems in several ways and can therefore affect species composition and ecosystem functions. In fertilization, species found in fertile populations become more common. The magnitude of the changes will depend on the species composition at the original state and the stock's fertility (Hedwall et al. 2014). The consequences are greatest in intensive fertilization.

The boreal forests are characterized by being generally poor in species and dominated by a few species. If fertilization in southern ecosystems can lead to fewer species, fertilization in these forests can rather provide increased species richness (Hedwall et al. 2014).

The increased production at fertilization means that the forest closes faster. The amount of light that reaches the ground is thereby reduced and intensive fertilization can therefore lead to the soil vegetation being completely out competed. If the forest becomes more open and at final harvest, the soil vegetation returns, but with a shift towards plants commonly found in more fertile populations (Hedwall et al. 2014).

For conventional forest fertilization, however, the effect on soil vegetation is low and barely visible after ten years (Hedwall et al. 2014). Mosses and lichens are declining, and for these species groups it may take longer to recover (Strengbom et al. 2001). Also, the biomass of fungi that lives in symbiosis with trees (ectomycorrhizas) decreases during fertilization. This is an effect of the trees sending less carbon to the roots. The effect is transient and the mycorrhizal recovers when the effect of the fertilizer decreases.
The soil fauna decreases after fertilization, which is why fertilization leads to reduced degradation and storage of coal in the soil. This reduction is also expected to be transient and that the soil fauna will recover as the effect of fertilization has subsided.

Fertilization for carbon offsetting is only executed in younger well managed forests with trivial species composition. It will be done with disposable donors that are repeated a maximum of three times during a rotation. A fertilization in this way, in these forests, is expected to have little effect on the species composition of plants. Fertilization for carbon offsetting is not carried out in forest ecosystems with particularly sensitive, valuable and vulnerable species.

There are few studies on effects on larger fauna, but these indicate that (Nohrstedt 2001, Hedwall et al. 2014):

- Fertilizer does not provide toxic levels of nitrate in vegetation grazed by herbivores.
- Reindeer avoids grazing where UREA has been spread.
- Chickens do not pick up the fertilizer granules

Choice of technology for fertilizer systems, timing, forest stands and care demanding patches (written by The Forest Solution)

The fertilizer used for carbon sequestration is Skog-Can, which is a coarse-grained nitrogen fertilizer especially adapted for boreal forest. It contains equal parts of nitrate and ammonium nitrogen, dolomite lime and 0.2% boron (B). Its base effect is neutral. In addition to nitrogen, it also contains lime to compensate for the natural acidifying effect that all growth has. The micronutrient boron is also added because it is noticed that it can affect annual shoot formation on trees if it is missing.

To make sure the fertiliser is deployed in the right spots in the forest, systems with forwarders with spreaders are used. These run on so-called strip roads in the forest that were used during the previous thinning. With a fan, these can direct fertilizer yield but high precision in the well managed forest stands. Should there be a small care demanding patch / stream etc that is not stated in the map material, it is easy to avoid spreading in its vicinity with this technique. Spreading with helicopters with GPS can have the same level of accuracy in terms of where the yield is spread.

The fertilization takes place during the growing season, usually April-September, so that the nutrients are immediately absorbed by the trees.

This fertilization will occur on solid land, usually moraine. Peatlands are not relevant. The typical forest is a coniferous forest that emerged after harvesting in the late 60s and up to the 90s. These forests today consist of fairly well-managed populations of pine/spruce forests or coniferous forests with elements of deciduous trees. Smaller areas of care-demanding patches inside or in connection with these are often apparent and considerations have been taken during the earlier thinning. If there is further consideration, the tractor driver can easily adjust the spread so that these environments are not adversely affected.

What does the Swedish law say?

All measures of forest fertilization is subject to consultation in accordance with Chapter 12, Section 6 of the Environmental Code. Consultation takes place with the Swedish Forest Agency. The consultation states when, where, how and what considerations are taken in the action.

More facts at Skogforsk (the Forestry Research Institute of Sweden) is the central research body for the Swedish forestry sector, and is financed jointly by the government and the members of the Institute.
https://www.skogforsk.se/kunskap/kunskapsbanken/#query=skogsg%C3%B6dsling&page=2

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This is a compilation of research concerning all aspects of this method of carbon sequestration

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English translation by The Forest Solution. Swedish original on www.theforestsolution.se

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