Master Thesis

Life cycle assessment of forest operations - a comparison of Austria and New Zealand

submitted by

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Abstract

Climate change is the most pressing issue human kind is facing today (UN, 2017). Forests and wood are claimed to mitigate climate change while providing fuel, energy, and material (Klein *et al.*, 2015). However, the actual contribution of forests to mitigation and buffering is difficult to assess, and the negative environmental impact of using wood and managing forests has not been assessed sufficiently yet. This life cycle assessment (LCA) provides a framework for studying the environmental impacts of wood production in Austria and in New Zealand with six case studies. The most common commercial tree species, norway spruce for Austria and radiata pine for New Zealand were chosen for the assessment. Different approaches of forest management are compared, as well as forest operations in flat and in steep terrain, and two different harvesting schemes: patch-cut and clearcutting. The assessed system starts at the production of seedlings, considers stand establishment and planting, thinning operations, harvesting, processing, and loading, transport of wood, and ends at the gate of a sawmill, pulpmill or energy plant. The functional unit is 1 m^3 of fresh wood. The overall GWP (global warming potential) was found to be between 10 kg CO_2-equivalents/m^3 and 26 kg CO_2-equivalents/m^3, the FTAP (freshwater and terrestrial acidification potential) was on average 0.08 kg SO_2-equivalents/m^3, the TEP (terrestrial eutrophication potential) 0.24 kg PO_4-equivalents/m^3 and the POFP (photochemical oxidant formation potential) 0.15 kg NMVOC/m^3. It was found that the wheel-based system in Austria had the smallest, and cable-based harvesting had the highest impact in all categories. In New Zealand, harvesting in both terrains had similar impacts to timber harvesting in steep terrain in Austria. The most crucial factors for the difference between the scenarios and the impact in general are transport distances and final harvest. The comparison of two countries on different hemispheres with different approaches to forestry has never been done before, neither has a consideration of forest operations in different terrain, with different harvesting schemes been conducted before.

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List of Abbreviations and Explanation of Terms Used in the Thesis

Forestry	The science, business, and art of creating, conserving, and managing forest and forest lands for the continuing use of their resources, materials, and other forest products (Forest Operations Research, no date).
Forest management	The practical application of scientific, economic, and social principles to the administration and working of a specific forest area for specified objectives (Forest Operations Research, no date)
Forest operations	Any activity that enhances and/or recovers forest growth or harvest yield, such as site preparation, planting, thinning, fertilization, and harvesting (Forest Operations Research, no date)
1 m^3	One cubic meter of wood without interspace between logs or wood pieces
Log	Tree that is delimbed, topped, and cut to length with bark
Sawn wood	Wood of higher quality that is sawed, and used as construction wood, for furniture or flooring
Pulpwood	Wood with lower quality that is used for particleboard, fiberboard, and paper
Energy wood	Wood of low quality that is burned and used to produce heat or electricity or both
Rotation period	The period of time from the planting of seedlings until the trees are harvested
Thinning	Cutting slower growing or crippled trees, or less favored trees in general, to give more promising trees room to grow (BFW, 2014).
Pruning	Cutting the bottom or unfavored branches to increase wood quality
Clear-cutting	Removal of all trees in an area of forest (Merriam-Webster, no date)
Patch-cut	Form of selective harvesting where a stripe of trees is cut and the forest regenerates naturally (Oregon Forest Institute, 2021)
Log truck	Trucks for log transport. In Austria log trucks are lorries with a crane that loads the logs up on itself. In New Zealand they are loaded by a separate machine
Forest road	Non-paved road that is used for forestry purposes

1. Introduction

Wood is among the most versatile raw materials available on industrial scales (Klein *et al.*, 2015) and a significant material and energy input into a biobased economy (Verkerk *et al.*, 2021). In order to determine the effects of timber production on climate change and the environment, emissions and impacts must be measured. Wood is a renewable resource, and sequestrates carbon as it grows, therefore it is commonly claimed to be a carbon neutral material. However, the production chain of timber cannot be considered as carbon dioxide (CO_2) neutral but as a net emission source, as there are several stages in its life cycle that consume fossil fuels (Klein *et al.*, 2015). However the contribution is small compared to all similar materials like steel, concrete, or plastics (Ecoinvent, 2011b; Ecoinvent, 2011a; Ecoinvent, 2011f). Forestry not only emits carbon, but also nitrogen oxides with fertilization, and non-methane volatile carbons (NMVOC) are emitted by chainsaws, which cause other negative impacts on the environment.

Therefore, the main objective of this study is to quantify the environmental impacts of forest operations from the upbringing of seedlings to the delivery of logs to the gate in Austria and in New Zealand. The difference between mountain forestry and forest operations in flat-terrain is evaluated in this study, as well as differences between the harvesting methods clear-cutting and patch-cut and their resulting different forms of regeneration.

To fulfill that objective, a life cycle assessment of forest operations was conducted for six case study scenarios in Austria and in New Zealand. Norway spruce (*Picea abies Karst.*) and Radiata pine (*Pinus radiata Don*) were chosen as tree species for Austria and for New Zealand respectively. Firstly, it is expected that the system in New Zealand, with large scale plantations, spraying herbicides by helicopter, and heavy machinery, has a higher impact than operations in Austria. Also, it is anticipated that operations in steep-terrain with smaller diameters and more difficult working conditions take longer and that therefore the impact is higher than in flat-terrain. Patch-cut with natural regeneration is expected to have a smaller impact than the production, transport, and planting of seedlings. Lastly, it is expected that the transport of logs to a sawmill, pulpmill or energy plant contributes significantly to the environmental impact in both countries.

A life cycle assessment (LCA) is a tool and a method for measuring environmental impacts (ISO, 2006). The number of LCA studies about forestry has been increasing in the last 20 years (Klein *et al.*, 2015), but there is still a multitude of research gaps that need to be filled. Firstly, there is a general lack of LCA studies about countries outside of Europe and North America.

Secondly, there are few studies that consider different harvesting methods associated with different terrain, and no study that compares them. Lastly, there are no studies that compared different harvesting schemes and the resulting differences between planting of seedlings and natural regeneration.

This thesis starts with providing general information about wood and life cycle assessment, followed by a description of the literature background. Then, the life cycle inventory is conducted, including a detailed description of the processes and steps of forest operations of the scenarios. The methods and assumption for the impact assessment are presented. Then, the results of the impact assessment are shown and for every scenario and also for every impact category, followed by a sensitivity analysis of the results. Lastly, the results are discussed and compared with literature.

This research deepens the knowledge and measurability of forest operations in Austria and in New Zealand. Combined with extensive future research, the actual effects and potentials of global forestry could be assessed to review the possibilities to mitigate climate change.

2. State of the Art

This chapter starts with an explanation of the importance of wood and the wood industry, globally and for Austria and New Zealand. Then an examination of all relevant studies for the topic of the present study are presented.

2.1 Importance of Forests and the Wood Industry

Forests cover 31% of the total global land area (FAO, 2020b). Approximately half of that area is still relatively intact and the ecological processes are not significantly disturbed (FAO, 2020b). Even though forests are not distributed equally across the world, and only ten countries hold 66% of the forest area, wood and wood products are used in every country (FAO, 2020b). Crang *et al*. (2018) confirm in their book that wood is the most extensively utilized plant product in the world and the FAO (2010) adds that based on weight, the consumption of wood by far exceeds that of other renewable materials. Especially in less-developed countries, more than half of roundwood production is consumed as fuel (FAO, 2010). Additionally, 90% of people living in poverty at least partly depend on forests for their livelihoods. In the developed world only 21% of the removed biomass is used directly for energy production (FAO, 2020b). Besides providing heat, wood has many desirable qualities and properties. By some estimates, 10,000 different products are made from wood today (Tsoumis, 2020). It is used amongst many applications as building material, for furniture, paper, and for chemicals. It is strong in relation to its weight; it has desirable acoustic properties, and it is capable of insulating heat and electricity. Also, it is easily workable and commonly considered aesthetically pleasing (Tsoumis, 2020).

Wood consumption has been increasing globally over the past decades (FAO, 2010). Between 1970 and 1995 the wood consumption of developing countries grew faster than their GDP (FAO, 2010), and between 2014 and 2018 the global roundwood and industrial wood removals increased by 9% (FAO, 2018). The use of wood-based panels, paper and cardboard increased the most between 1970 and 1994, as the consumption tripled in Asian countries (FAO, 2010). However, this trend has slowed down significantly in the last few years. Wood-panels production and consumption increased by 3% in the Asian-pacific and paper production stagnated between 2014 and 2018 (FAO, 2018). The trends show that the consumption per person is expected to rise the most in the less-developed countries until it reaches the level of the developed world (FAO, 2010).

Increased consumption of wood products results in the depletion of forest area and can also lead to deforestation. Since 1990, 420 million hectares of forest have been lost through deforestation (FAO, 2020a). However, the key driver for deforestation today is the conversion of forests into agricultural land where log extraction is only secondary (FAO, 2020c). Forestry is estimated to produce 2% of the world's gross domestic product (GDP) and 3% of the world's international trade (FAO, 2010), which shows it to be of significant economic importance. Also, wood processing, transportation, and trade provides jobs and income for people around the globe (FAO, 2010).

Austria is a country with a long history of forestry and a sense for longevity of systems, as well as possessing a strong connection to tradition. With a drastic increase in wood demand in Austria with the uprising of the mining industry in the 15th century, deforestation became an issue, and therefore a law for forest conservation was enacted in 1853 (proHolz Austria, 2013a). Norway spruce occurs naturally in Austria, but has been planted and managed extensively after wide areas had been cut in the 17th and 18th century (Kone, 2017). Today, the Austrian wood industry generates €11.3 billion gross annual income (WKO, 2021b) and accounted for 1.8% of the GDP in 2012 (Forest Based Sector, 2012). 5.9 million m^3 of softwood were exported in 2018, while wood with a worth of €4.73 billion was imported (Association of the Austrian Wood Industries, 2019). Norway spruce is the most important tree species in Austria, and 61% of the total commercial forest resources are Norway spruce trees (BFW, 2013).

In New Zealand wood plantation is compared to forest management in Austria a relatively new system. Kaingaroa forest is one of the oldest and largest softwood plantation in New Zealand and it was established as late as 1901 (Timberlands, 2018). Incentivized by the government, there were two planting waves, in the 1930s-1960s, which means that most plantations are in their second to third rotation (FAO, 2013). In New Zealand plantations are run efficiency-oriented, with rotation periods of 25-30 years (NZFOA, 2020), compared to rotations of around 100 years in Austria, and with a high machine input. New Zealand's forest industry generates NZ$6.9 billion gross annual income, which equals €4 billion, and contributes 1.6% of the GDP (Ministry for Primary Industries, 2018). The amount of wood exported is 60% of the total log input from the forestry sector (NZFOA, 2020), which provides 1.1% of the world's supply of industrial wood (Ministry for Primary Industries, 2018). Also, wood is the third most important export good after meat and dairy (Ministry for Primary Industries, 2018). Radiata pine is the main commercial tree species in New Zealand; 90% of all planted trees in New Zealand are radiata pine trees and 99.5% of them are from plantations (NZFOA, 2020).

These differences between the countries; their location, their views with regards to wood production, and history of forestry makes the comparison both interesting and valuable.

2.2 Life Cycle Assessment Studies about Wood Production

This section establishes the available studies and knowledge about LCA of wood and the forestry sector. While life cycle assessments are becoming more popular in the forestry sector, there are, as of yet, not many studies that assess forest operations with a life cycle approach. In their review, Klein *et al*. (2015) found only 26 life cycle assessment studies about forestry in Europe and in the United States. A review by Engelbrecht *et al*., (2018) found 35 papers concerning environmental aspects in general in New Zealand. Of these, 14 were LCA, 13 carbon footprints and 8 water footprints. The LCA studies in their review were about dairy, wool, and apples and the only two of them that could be connected to wood pertain to construction and multi-story-buildings. For Austria, there is one review by Ladenika *et al*. (2018) about the availability of LCA in Austria. They found 15 studies that were about LCA, none of them concerned forestry, but rather energy production, construction, wastewater treatment and food.

In the process of research for this study, 21 studies were found that covered LCA of forestry mostly in Europe and in North America. However, none of them compared Austria or New Zealand with another country; likewise, there are no studies comparing mountain forestry with forestry in flat terrain, nor any comparing different harvesting schemes or different silvicultural treatments. These are the research gaps that will be addressed by this study.

Klein *et al*., (2015) reviewed various studies that were also used in this assessment. Apart from that, Google Scholar offered 150,000 results using the key words “impact assessment forestry” from the year 2015 till now. To narrow and define the scope, this study focusses on the environmental impact assessment or life cycle assessment of forestry, forest management, or forest operations. This means that studies about biomethane, biofuels, short rotation forestry for bioenergy use, studies about indicators or methodological approaches, risk assessment, community forestry, particleboard or other processed wood, studies focusing solely on economic factors, studies on reforestation as well as studies about the forestry sector or wood industry in general were not considered.

The remaining pertinent 21 studies found with Google Scholar and Klein *et al.*, (2015), can be categorized into 4 sections for this review: biomass or bioenergy, climate change, forest operations, and specific tree species.

2.2.1 Biomass and Bioenergy

LCA is often carried out for bioenergy and biomass uses, because there is a great interest in more sustainable energy sources. Therefore, Pieratti *et al*., (2020) assessed the environmental impacts of 18 biomass plants in the Alpine region. They focused their study on sawmills, biomass-plants, and forest owners, and on specific characteristics like ash yield, wood chips quality, harvest volumes, and electric power production, which means that forest operations themselves played a subordinate role in their study. Pieratti *et al*. (2020) found that the transport phase and wood processing are most important in the forest-wood supply chain.

Laschi *et al*. (2016) considered forest management in their assessment of the environmental performance of wood pellets. The cradle of their study is the extraction of material. It can be argued that the operations before extraction are important, but they concluded that forest operations contributed less than 2% of the environmental impact, compared to the production of pellets.

Valente *et al*. (2011a) only considered the forest supply chain in their assessment of bioenergy from mountain forests in Norway. Their system starts at the stand establishment and ends at the factory gate. In their assessment thinnings are not conducted, but in order to produce low quality wood for bioenergy thinnings may not be necessary. Even though their study is conducted in the mountains, they chose harvester and forwarder as harvesting machines. They found that transport and bundling of the biomass material contributed most to the GHG emissions. Valente *et al*. (2011a) only considered CO_2 emissions, while Pieratti *et al*. (2020) and Laschi *et al*. (2016) also assessed other impacts like eutrophication, acidification or land occupation.

Pyörälä *et al*. (2012) also only considered carbon emissions in their assessment of the effect of forest management on biomass production in spruce stands. They found that fertilizing the stands would increase productivity and therefore increase the carbon neutrality of wood production. They conclude that the production of timber and biomass could be increased simultaneously with increasing the carbon stock in the forest. Here it should be argued that even though fertilizing might increase growth, it also contributes to eutrophication of water and soil. Also, it is not necessarily the case that by increasing productivity, carbon is built up in forest biomass, and there is no agreed upon method to measure carbon uptake in a forest ecosystem (Klein *et al.*, 2015).

Alam *et al*. (2011) like Pyörälä *et al*. (2012) only chose carbon emissions as the impact category in their assessment of energy wood production depending on stand density and thinning regimes in boreal ecosystems. They conclude that by increasing extraction volume during thinnings, more energy wood is produced during thinnings and at the final harvest, and therefore the overall carbon is reduced.

However, as argued before, extracting more does not necessarily mean that carbon stocks increase. There is a limited amount of biomass that can grow on an area (Meyer, Nagel and Feldmann, 2021), and even if it can be increased short-term, the soil may be depleted over time.

2.2.2 Climate Change

Most life cycle assessment studies found for this study focus on climate change, and among those, many calculated the carbon sequestration possibilities of forest management. Saud *et al*. (2013) analyzed the forest carbon balance and emissions from mechanized and manual harvesting operations in West Virginia. They suggest that by increasing harvesting intensity, the total carbon stock in the forest increases without an increase in emissions from harvesting operations. They also found that natural regeneration has no fossil fuel consumption. Lastly, they conclude that mechanized harvesting causes higher emissions than manual harvesting by chainsaw and cable skidders, but compared to the carbon stored in the timber, the harvesting system only makes a small difference.

Instead of harvesting systems, White *et al*. (2005) assessed the carbon budget of wood products from harvesting, to product use, until disposal. They found that dimensional lumber and oriented strand board (OSB) products are both net carbon sources, but the total forest carbon cycle still sequestrates more carbon per m^2 per year than is emitted in the following production chain and use phase of the products.

Kilpeläinen *et al*. (2011) developed a tool to measure and quantify the net carbon exchange in forest production. The uptake of carbon into the wood biomass is weighed against carbon released by decomposition, emissions from forest management and carbon released by combustion of biomass. They found that the emissions caused by forest management were significantly smaller than the total ecosystem fluxes and carbon released by decomposition.

Klein *et al*. (2013) also found that the amount of carbon sequestrated exceeded the emissions of forest management practices. They compared the carbon potential of unmanaged forests with managed forests of different tree species and found that spruce offered higher benefits in relation to climate change than other tree species because of its fast growth. In their study they also found that the extent of possible mitigation highly depends on which substitution effects are also considered in the assessment. That is the reason why unmanaged stands were shown in their study to have a smaller potential for climate change mitigation. They admit themselves that the dimensions of substitution effects are still uncertain and that there is a substantial lack of data.

Karjalainen and Asikainen (1996) examined the GHG emissions from the use of primary energy in forest operations. The conclusion which is most relevant for this study is that they found that transport comprises 57% of the total impact of forest operations.

2.2.3 Forest Operations

On the topic of forest operations, González-García *et al*. (2009) compared the environmental impacts of forest operations in Spain and in Sweden with regards to pulpwood production. They found that even though the countries and systems are different, the results are similar, with wood transport and harvesting operations contributing the most, which coincides with the results of the present study.

A different study by Gonzales-Garcia *et al*. (2014) examines the environmental impact of different pulpwood production systems in Europe with different levels of intensity and biomass yield. They likewise concluded that in all systems, harvesting and forwarding could be identified as the main contributors to the environmental impact.

The major influence of transport, as well as harvesting, was also confirmed by Michelsen *et al* (2008) in their study of the impact of wood production in Norway, from seedling production to a factory gate.

Proto *et al*. (2017) assessed 12 impact categories in their study about three different logging systems for roundwood and energy wood production of chestnut trees. They compared logging systems by tractor, skidder and cable yarder and only assessed harvesting operations. They conclude that the cable yarder had the highest impact, while the tractor and skidder performed similarly. However, in the present study the use of skidders or tractors in the steep terrain is not an option. Also, they calculated substitution effects, which was not considered in this study.

2.2.4 Tree Species

The fourth thematic sub-group are LCA studies that examined one singular tree species or compared two tree species with each other, which resembles the method of the present study most closely.

Sonne (2006) studied the direct and indirect GHG emissions of Douglas-fir in the US. They examined a wide range of different management regimes and concluded that harvesting contributed most. They advised against using fertilizers and against slash burning on site because both cause high emissions.

Fertilizing is, however, a common practice in pine production in Brazil (Ferro *et al*. 2018). In this study, they identified and quantified the environmental impacts of industrial pine production in Brazil. They also concluded that harvesting contributed most to the impact of forest operations without transport. Soil preparation also had a high impact, because of the application of fertilizers and pesticides.

González-García *et al*. (2013a) and González-García *et al*. (2013b) are two studies about the influence of management practices on Douglas-fir production in France and in Germany respectively. In France, they assessed a harvested volume of 2200 m^3 per hectare and in Germany 1000 m^3. They compared extensive and intensive management scenarios. The intensive system entailed fertilizing, short rotations, and seven thinning operations, while the extensive system was not fertilized, the rotations were longer and only five thinnings were conducted. Both scenarios in their study are more intensive than in the present study. In both studies they found that stand establishment and tending, thinnings and logging contribute to the environmental impact of forest operations. In the extensive and in the intensive scenario they found that biomass productivity does not compensate the environmental impact. This is contrary to other studies (White *et al*. 2005; Saud *et al*. 2013; Kilpeläinen *et al*. 2011; Pyörälä *et al*. 2012) that claim that more carbon is sequestrated during the growth period of wood and the impact is therefore outweighed. Contrary to the studies just mentioned, González-García *et al*. (2013a;2013b) assessed 15 impact categories, which could be the reason why they found that increasing biomass does not compensate the environmental impact of forest operations.

England *et al*. (2013) again only considered carbon, but they assessed radiata pine and therefore their study was relevant for this assessment. They compared native hardwood forests with forest plantations in Australia from the upbringing of seedlings to the gate of a processing facility. In their study, however, burning and fire plays a critical role, and in New Zealand burning of slash is usually not practiced. Additionally, they did not mention the distance the logs are transported, which is crucial for a comparison.

Dias and Arroja (2012) compared eucalypt with maritime pine production in Portugal along with different management intensities for both species. The machines used as well as the impact categories are the same as in this study. They found that the logging stage, as well as fertilization play a major role in all impact categories.

Most studies place their focus on wood as a material or an energy source, and regard forest management as a subordinate element in the production chain.

This may partly be explained by the fact that forest operations differ highly between countries, regions and even within one company or establishment. This is because the trees differ in rate of growth in different regions, and emissions depend highly on management practices. Forest operations are often less important in the production chain because they are less energy intensive than the succeeding process steps and are therefore considered to cause less environmental impact. A report from McCallum (2009) from the Nelson forest in New Zealand found that forest operations (stand establishment, harvest and logging) account for 30% of the total impact, while more than double (62%) of the total CO_2 emissions is caused by log transport (McCallum, 2009). Even though forest management is often less relevant in LCA studies, it is still important to take it into account, especially since forests could be a crucial element in climate change mitigation in the future (Kilpeläinen *et al.*, 2011).

2.3.5 Summary

The most important contributor to the environmental impact of forestry that can be concluded from the studies above is burning of fuel in machinery. Transport and heavy machinery need most fuel, which makes them most responsible for the impact measured by the impact categories chosen by these studies (Klein *et al.*, 2015).

The literature review shows that further assessment of the impact of forestry in general is necessary. Mountain harvesting has not been assessed yet and more importantly not compared to ground-based harvesting. Also, different harvesting schemes have not been considered yet. More importantly there were no studies found that assessed forestry outside of Europe and North America. A life cycle assessment is a fitting tool to measure the environmental impact of forest operations in Austria and in New Zealand including the possibility to model different harvesting methods and schemes.

3. Methods

The environmental impact of forestry needs to be measured to assess the possibilities to mitigate climate change and to assess the potential negative impacts of forestry. This chapter will outline the possibilities to measure environmental impact, an introduction of the method of LCA, a description of the case studies, an explanation of the flow charts and process steps for the case studies and scenarios, a depiction of impact assessment method and methods for data collection and handling, a list and explanation of all assumptions taken for the assessment, and lastly a description of methods for interpreting the results.

3.1 Assessment of Environmental Impact of Forest Operations

“Environmental impact refers to the direct effect of socio-economic activities and natural events on the components of the environment” (OECD, 1997). There are two main methods to assess environmental impacts: an environmental impact assessment (EIA) and a life cycle assessment (LCA).

An EIA measures the actual impacts of an object located at a given site in a given context. An LCA on the other hand assesses the non-site specific potential environmental impacts associated with a product over its entire life cycle, or parts of it (Crawley and Aho, 1999). An EIA is usually applied to assess a specific factory or a company. An LCA is used to measure products or services, over their entire life cycle or parts of it. In this case study the emissions of a specific site could not be measured, the assessment includes transport to a different site and a long time span is considered, which is why an LCA was used to determine the environmental impact of forestry.

3.2 Life Cycle Assessment

The ISO 14040 defines LCA as “a technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. LCA studies quantify the environmental aspects and potential impacts throughout a product’s life (i.e. ‘cradle-to-grave’) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.”(ISO, 2006, p.14).

Even though there are other definitions of an LCA, the ISO norm is the one that is used in literature, in practice and in scientific articles (Klein *et al*., 2015; Valente *et al*., 2011a; González-García *et al*., 2013b; Heinimann, 2012).

Life cycle assessment emerged in the packaging industry in 1984 (Klöpffer and Grahl, 2009), but today is used in almost every industry branch, for products as well as companies (Pieratti *et al*., 2020; Hasler et al., 2001; Saha, 2014; England *et al*., 2013). In 1994, the International Organization for Standardization defined the basis of norms for life cycle assessments (Klöpffer and Grahl, 2009). Soon after, the paper industry conducted LCA and with that forestry, as the resource producer was assessed as well (Seppälä *et al*., 1998; Guinée *et al*.; 1993, Granath and Stroemdahl, 1994). Figure 1 shows the development of the number of LCA studies since 2000.

The upswing of LCA started in 2005, congruent with a growing interest in renewable energy sources, and they have been increasing in number until 2013 (Klein *et al.*, 2015). It can be assumed that the numbers of LCA studies have increased continuously since then.

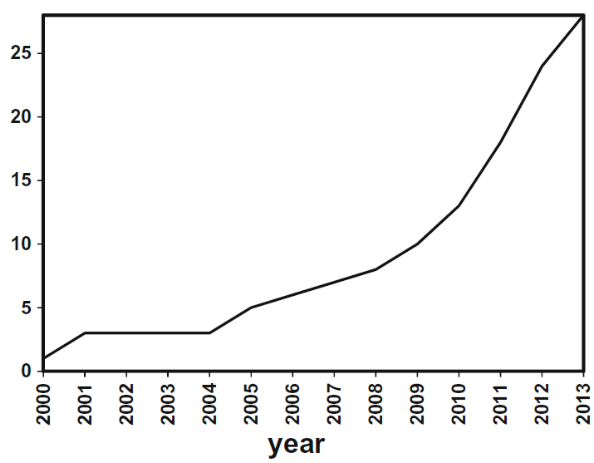


Figure 1: Cumulative number of LCA studies for forest production since 2000 (Klein et al., 2015)

The four main phases of a life cycle assessment are: the definition of goal and scope, the inventory analysis, the impact assessment, and an interpretation of each phase (Figure 2). This interpretation and revision of every step makes an LCA an iterative process.

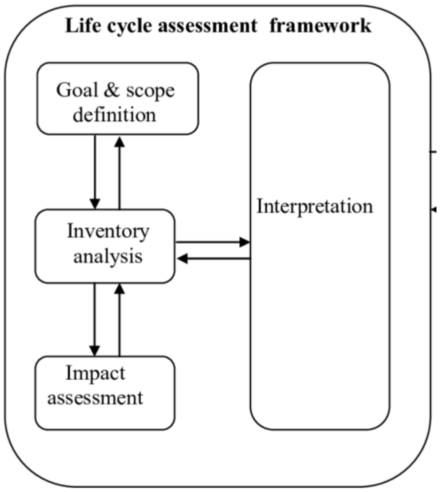


Figure 2: Framework of an LCA (ISO 14040, p.16)

The definition of the goal and scope of the study is the first and most important phase. According to the ISO 14044 “the goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application. Due to the iterative nature of LCA, the scope may have to be refined during the study” (ISO, 2006, Section 4.2.1). The scope of the study describes the assessed product system and defines its border to its environment. The assessed product system is defined for each study and does not have to cover the entire life cycle of a product. The product system is usually shown with a flow chart, where all inputs and outputs of the system, as well as processes, process steps and their interrelations are shown. Ideally the inputs and outputs of the system are elementary flows.

The definition of the functional unit is part of the goal and scope definition. It is a key aspect of a life cycle assessment and should be defined from the start. The whole system is measured by this unit. For example, in this study, the functional unit is 1 m^3 of wood and the environmental impact is indicated per m^3 wood that is produced. The functional unit is used as a unit for comparison within the study as well as with other studies. It is also needed as a unit of reference to all input and output flows of the system (Klöpffer and Grahl, 2009).

The inventory analysis entails the collection of data, calculation of data, and the allocation of flows and emissions. Here, all inputs and outputs of a product are gathered, sorted, and clustered, and converted to correspond to the functional unit ($1m^3$), and are quantified over its life cycle. Inputs and outputs in this context are product-, material-, and energy flows that can be connected to the individual process steps of the product. This is also the part of the LCA that requires the most time and effort (Klöpffer and Grahl, 2009).

The impact assessment connects the inputs and outputs from the inventory analysis to actual and potential environmental impacts and quantifies them. The inventory analysis only lists data about resource use, energy use, and mass flows. In the impact assessment these data are structured, visualized and a value is attached to them, which is the environmental impact. The impact assessment also makes products comparable to each other, at least within the impact categories.

The categories chosen for the present study were identified by (Klein *et al.*, 2015) as the most relevant impact categories for forestry and were also used by (González-García, Krowas, *et al.*, 2013, Dias and Arroja, 2012, Michelsen, Solli and Strømman, 2008, González-García, Bonnesoeur, *et al.*, 2013, Ferro *et al.*, 2018). For the impact assessment firstly, impact categories, and impact factors are set. The impacts from the inventory analysis are assigned to impact categories (Klöpffer and Grahl, 2009). Possible impact categories concern climate change, ecosystems, and human health. According to the ISO 14040, impact categories can be freely chosen; however, they are supposed to represent the most relevant environmental impacts (ISO, 2006,§4.4.2.3). For example, by burning fuels gases like CO_2 and NO_x are emitted. CO_2 is assigned to the impact category climate change, and NO_x to eutrophication. The impact factor converts the amount of CO_2, NO_x, and all other impacting gases and substances into the impact categories. In this study the impact categories are global warming potential, freshwater and terrestrial acidification, freshwater eutrophication, terrestrial eutrophication, and photochemical oxidation formation potential to demonstrate the environmental impact of forest operations (Table 1). The value of the impact categories demonstrates the impact.

Table 1: Impact categories, their unit and description

Impact category	Unit	Description
Global warming potential (GWP)	kg CO_2-equivalents	Measures the energy absorbed by 1 kilogram of a gas over a given period of time compared to 1 kilogram of CO_2. The larger the GWP, the more a gas potentially contributes to global warming (US EPA, 2016)
Freshwater and terrestrial acidification potential (FTAP)	kg SO_2-equivalents	Measures the change in acidity in the soil and in freshwater (González-García, Krowas, *et al.*, 2013). It is based on the contributions of SO_2, NOx, HCl, NH_3, and HF to the potential acid deposition and their potential to form H+ ions (Azapagic, Emsley and Hamerton, 2003)

Freshwater eutrophication potential (FEP)	kg PO_4-equivalents	Measures the nutrient enrichment of the aquatic environment as a result of human activities (González-García, Krowas, *et al.*, 2013).
Terrestrial eutrophication potential (TEP)	kg PO_4-equivalents	Measures the nutrient enrichment of the terrestrial environment (González-García, Krowas, *et al.*, 2013).
Photochemical oxidant formation potential (POFP)	kg NMVOC-equivalents (Non-methane volatile organic compounds)	Measures the amount of air pollutants that are formed by sunlight and oxides of nitrogen and hydrocarbons (González-García, Krowas, *et al.*, 2013).

Evaluation and interpretation of the results is the last phase of the life cycle assessment. The results of the inventory analysis and the impact assessment are compared and interpreted, and subsequently evaluated based on how well those results fit together with the initial goals of the study (Klöpffer and Grahl, 2009).

3.3 Description of Goal & Scope

The first and most important phase of an LCA is the description of the goal and scope. The goal of this study is to assess the potential environmental impacts that occur with the production of 1m^3 of wood in a typical forest in Austria and in New Zealand with state-of-the-art harvesting systems.

The scope of the study are 6 forest sites in Austria and in New Zealand. In each of those sites the impacts will be measured on the basis of one hectare managed over a rotation. This means that all activities are measured per hectare, treatments and operations are in most cases related to operating hours. These were all normalized to a m^3, based on the volume harvested. The reason why all forest were measured per hectare is that operations are usually conducted to produce significantly more than one m^3 of wood. The assessed system starts at the upbringing of seedlings, includes all process steps that are undertaken in one rotation period, and ends at the gate of a wood processing plant. The assessment period is as long as the rotation period of the respective tree species; 100 years for Austria and 28 years for New Zealand. Thereby, all relevant steps and impacts are included.

The definition of the functional unit is an essential part of the definition of goal and scope. The functional unit used in this study is defined as 1 m^3 of green wood with bark that is harvested and transported to a local sawmill, pulpmill, or energy plant. 1 m^3 of green, unprocessed spruce wood weighs 950kg and 1 m^3 of radiata pine green and unprocessed wood weighs 1000kg.

This functional unit was chosen because it was found to be commonly used in related studies. Also, m^3 is the most typical unit to describe forest production (Klein *et al.*, 2015).

3.3.1 Description of Case studies and Scenarios

Six scenarios were chosen to assess different harvesting methods on different terrain in Austria and New Zealand. The chosen tree species are Norway spruce (*Picea abies*) and radiata pine (*Pinus radiata*), since they are commercially the most important tree species in Austria and New Zealand respectively. From these trees, round timber, pulpwood, and energy wood is produced. In both countries, forests are managed in flat as well as mountain areas. Therefore, different harvesting methods and equipment are employed depending on the different requirements. In flat terrain (under 20% steepness), harvesters and forwarders are commonly used.

Most forestry in Austria small-scale and is often conducted by farmers themselves. 19% of felling in Austria is conducted by a harvester and 80% by chainsaw. 23% of logging are conducted by forwarder, 35% by cable yarder, and the remaining 42% by farm tractor (Kühmaier *et al.*, 2019). In Austria the rotation period is usually 100 years. On one hectare between 400 and 600 stems are harvested, which equals 600 m^3 and 800 m^3.

In New Zealand, 63% of final harvest operations are ground-based. 57% of them conduct felling mechanically, most commonly with a modified excavator with a felling head, and the most common machine for extraction is a skidder either with a grapple or chokers (NZ Farm Forestry, 2016). 53% of the harvested trees are processed mechanically and 21% are loaded by front end loader, while 79% are loaded by knuckle-boom loaders (Visser, Spinelli and Magagnotti, 2010). In New Zealand the rotation period is between 25 and 35 years. On one hectare about 400 trees are harvested, which equals around 700 m^3 (NZFOA, 2019).

Table 2 shows a summary of the scenarios chosen for the present thesis. Scenarios 1-4 represent Austria, while Scenarios 5 and 6 represent New Zealand. Scenarios 1 and 2 are in flat terrain, therefore the machines used are harvester and forwarder. The difference between the first two scenarios is the harvesting scheme, clearcutting and patch-cut. Scenarios 3 and 4 are in steep-terrain, therefore the trees are harvested by chainsaw and cable yarder. The system of clearcutting and patch-cut is also applied in those two scenarios. In Scenarios 5 and 6, in New Zealand on the other hand, clearcutting is the harvesting method. Scenario 5 is in flat terrain, and feller-buncher and skidders are used, while in Scenario 6 in steep terrain chainsaw and cable yarders are used.

Table 2: Summary of Scenarios 1-6

	Country	Tree species	Harvesting scheme	Terrain	Harvesting system
Scenario 1	Austria	Norway Spruce	Clearcutting	Flat (20%)	Harvester-Forwarder
Scenario 2	Austria	Norway Spruce	Patch-cut	Flat (20%)	Harvester-Forwarder
Scenario 3	Austria	Norway Spruce	Clearcutting	Steep (70%)	Chainsaw-Cable Yarder
Scenario 4	Austria	Norway Spruce	Patch-cut	Steep (70%)	Chainsaw-Cable Yarder
Scenario 5	New Zealand	Radiata Pine	Clearcutting	Flat (20%)	Feller-Buncher Skidder
Scenario 6	New Zealand	Radiata Pine	Clearcutting	Steep (70%)	Chainsaw-Cable Yarder

3.3.1 General Information about Spruce Production in Austria

47% of Austria is covered with forest, which results in a forested area of 3.2 million ha. 80% of that area is managed, while the other 20% are called “protection forest”. However, the term ‘protection’ refers rather to human protection from avalanches, wind or erosion than wildlife (BFW, 2016). The average volume harvested per year in the last 5 years in Austria is 17.86 million m^3 (without bark) (BMLRT, 2020).

Norway spruce (Picea abies), from now on “spruce”, is the main and most important tree species in Austria for wood production. It is abundant in 86% of all stands, both as their main tree species as well as mixed with others. 38% of Austria's forests are spruce monocultures, both naturally and as a result of silvicultural management. Its occurs naturally at an altitude of 500 to 2000m, but nowadays it is grown in many parts of Austria outside of its natural habitat (LK Österreich, 2015). Forest ownership and management is usually practiced by one person or a family and is mostly on a small scale. 54% of the forest area is owned privately with an area smaller than 200 ha (proHolz, 2013).

Spruce is a rather undemanding tree species and grows on various soils with different pH values (Leitgeb *et al.*, 2013). It is only sensitive to water stress because of its shallow root system (LK Österreich, 2015), wherefore it needs at least 600mm of precipitation per year and between 300mm and 350mm of rain in the growing season (Leitgeb *et al.*, 2013).

Spruce is often used as building material, owing to its high stability and flexibility. Additionally, it is easy to glue and process and it is considerably lightweight, which is why it is widely used for roof frameworks. Also, the wood is quite cheap and has other beneficial properties to use it as middle-layer for flooring, for example. (LWF, 2017). As sawn wood it can be used for furniture, but it also finds use in the paper and pulp industry (BFW, 2013). Sawn wood in Austria is produced from at least 18 cm in diameter, with average lengths of 4 m. Smaller diameters are used for paper or energy wood.

Natural regeneration works in many regions and spruce seedlings are less prone to deer and other animals (LWF, 2020). The establishment of a stand is quite easy, and tending is less work intensive than other species Thus, until recently, spruce has been easy to grow and maintain with high yields and low risks. Now, however, climate change poses a direct threat to future stands. With the temperature rising, and more unstable weather conditions, drought stress increases. This makes the trees more vulnerable to windblow, snow damages and pests. Bark beetles have always endangered large areas of spruce plantations, and more vulnerable stands are even more likely to suffer from bark beetle outbreaks (LWF, 2020).

3.3.2 Description of Austrian Scenarios 1-4

Scenarios 1 and 2 are located at the "Stift Zwettl" in Lower Austria (48° 37′ 1″ N, 15° 12′ 0″) (Spot 1 on Map 1). The annual rainfall is 700mm and the mean annual temperature is 7°. The soil is brown soil. The average steepness of the area is 20% and the altitude is 500 meters. The area also falls within the natural growing area of spruce. The managed forest encompasses 1200ha, which is quite large for Austrian standards (proHolz Austria, 2013b).

Map 1: Map of Location Scenarios 1-4. Scenarios 1 and 2 are at spot 1 and Scenarios 3 and 4 on spot number 3.

Scenario 1 represents spruce forestry as a monoculture in flat terrain and clearcutting as harvesting method, while in Scenario 2 the harvesting scheme is patch-cut. Patch-cut means that instead of harvesting the area all at once, only a strip is cut (Figure 3). This enables light to reach the forest floor and underneath the remaining canopy natural regeneration emerges. As soon as the small trees have a height of about one meter the remaining canopy is harvested. In practice, for efficiency reasons the strips are 50 meters wide, which means that an area of one hectare is harvested twice. The time difference between these final harvests is usually 10 years.

Figure 3: Types of harvesting schemes (Oregon Forest Resource Institute, 2021)

Scenarios 3 and 4 are located on steep terrain in the Lehrforst Rosalia (47° 45′ N, 16° 15′ O), also in Lower Austria (Spot 3 on Map 1). The annual rainfall is 700-900mm per year and the mean annual temperature is 6,5° (BOKU, 2018). The most common soil type is podzolic- brown soil. The altitude is between 300 and 750m and the average steepness is around 40%. The harvesting area of both Scenarios 3 and 4 lies at 500m and has a steepness of 70%. This forest was chosen because it is fit for steep terrain harvesting operations, and because it is also in the natural growing area of spruce. Additionally, the forest belongs to the University of Natural Resources and Life Sciences Vienna, which provided full data access. The difference between Scenarios 3 and 4 is the harvesting scheme, with clearcutting and patch-cut respectively. In steep terrain, cable yarding is the usual practice since it is too steep for wheeled or tracked machinery.

3.3.3 General Information about Radiata Pine in New Zealand

New Zealand's forests cover 38% of the total land area, of which 80% are native forests, which are for the most part on conservation land (Ministry for Primary Industries, 2020). The remaining 20% are large-scale, industrialized forest plantations where mainly exotic pine trees are grown (NZ wood, 2020). Pine, more precisely *Pinus radiata*, accounts for 90% of the trees in these plantations (Forest Owners Association, 2020a). Pinus radiata is the world's most extensively planted exotic softwood, because of its durability and fast growth. In New Zealand it reaches its target growth at the age of 25-35 years (Ministry for Primary Industries, 2015).

Radiata pine needs at least 600-750mm of annual rainfall, and the optimum is at 1500-2000mm. Additionally, dry summers are preferred, but severe drought can cause stress. Minimum temperatures are between -12° and -14° in winter. If the climate allows it, the trees can grow throughout the year (FAO, 2013). Ambient field temperatures of 10-24° give the best diameter growth (FAO, 2013). The mean annual temperature of New Zealand lies between 12° and 15° (NIWA, 2010), and is therefore optimal. Pinus radiata grows on almost all soils from recently formed sand-dunes and volcanic soils to older leached red earths and podzols (Scion, 2017). The highest productivity is reached under mild conditions and with a deep pumice soil (Forestenterprises, 2018), and soils that are well-drained with high biological activity (FAO, 2013). Ideally up to 840 m^3 can be harvested on 1 ha after 28 years (Forestenterprises, 2018).

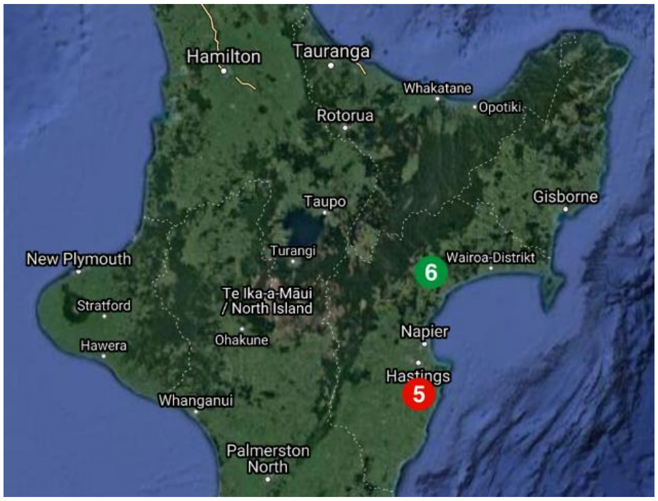
Originally, radiata pine comes from California, where it naturally covers an area of about 10 000 ha. Today, there are 4 million ha of radiata plantations worldwide and New Zealand alone accounts for 1.5 million ha of them. 90% of the plantation land is privately owned but the trees are managed or owned by management companies. The largest plantations are in the center of the north island, where the production is in the hands of a few large growers who manage the majority of the plantation area (FAO, 2013). In 2019, a total of 35.9 million m^3 of wood was harvested in New Zealand. 40% of logs are processed in New Zealand, the rest is shipped as logs, chips or other processed forms to mostly China, Australia, Japan, South Korea, India and to the United States (Forest Owners Association, 2020a).

The pine trees can be used for various purposes. The top 5 meters have little value and are often left in the forest. The next 8 meters are used as pulpwood for paper, medium-density-fiberboard, or particleboard. The bulk of the tree is used for sawlogs, which are put to a variety of construction uses. The pruned butt of the tree yields clear timber for furniture, house building and beam construction (Forestenterprises, 2018). About 85% of New Zealand's wood production produces high value logs, sawlogs and peelers (Forest Owners Association, 2020a).

3.3.4 Description of Scenarios 5 and 6

Scenario 5 is in New Zealand, on the north island in Hawke's Bay (Spot 5 on Map 2), Hastings District (39°49'20,9''S 176°50'40,5''E) (Spot 5 on Map 2). The forest area is about 8 km^2. Hawke's Bay is generally less prone to high wind speeds than other areas in New Zealand (Chapell, 2011), which is beneficial for pine production, since wind break is one of the biggest threats (FAO, 2013). The annual rainfall is about 800mm. The mean annual temperature is 13.5° with a mean temperature in summer of 20° and in winter 3-5° (Chapell, 2011).

The soil is pallic soil (Scion, 2017) and the elevation is about 100m (Topographic Map, no date). At the end of the rotation period the area is clear-felled with wheeled machinery.



Map 2: Map of location Scenarios 5 and 6 (Google Maps, 2021)

Scenario 6 is close to Kotemaori on the north island in Hawke's Bay (Spot 6 on Map 2), Wairoa District. The forest area is about 9.2 km^2. The coordinates are 39°03'47.7"S 176°55'60.0"E (Spot 6 on Map 2). The climate conditions are similar to Scenario 5 however the annual rainfall is 470mm. The elevation is about 450m, and the slope steepness is about 60% (Topographic Map, no date), and therefore mountain harvesting techniques are applied. In Scenario 6 the harvesting method is also clear-felling.

3.4 Inventory Analysis- Collection of Primary and Secondary Data

The easily and open accessible data availability for forest management and forestry is generally quite limited (Klein *et al.*, 2013). One of the reasons for that is that forest management is highly dependent on the species, forest management practice, the location, and the stand. All operations are usually adapted to the conditions of the stand. The data that is available is either exceedingly general or very specific. There is more data available for New Zealand than there is for Austria because forest management in New Zealand is conducted by a few large companies and there is greater involvement by the government and official research facilities. Even so, specific data on duration, machines and transport distances is not available in both countries.

According to Klöpffer and Grahl (2009) the collection of data is the most difficult and time-consuming part of a life cycle assessment, especially because specific data about forestry are scarce, and mostly only known by forest owners and managers.

Therefore, primary data were obtained with the help of three experts, two in Austria and one in New Zealand. The experts from Austria both manage large forest areas and have more than 40 years of experience in their field. In New Zealand, the expert is a harvesting and engineering coordinator for the 16th largest forest ownership and management company in New Zealand. All specific data and information about specific processes and operations that are conducted, as well as machine productivity, which machines specifically are used, working hours, volume harvested during thinnings and final harvest, tree diameter, and in Austria some information about biodiversity were all obtained by these experts.

For general information about forestry, there are official sites from the Austrian and the New Zealand government. New Zealand provides a 'Facts and Figures' document on forestry every year, where stocking numbers and age, as well as volumes harvested, ownership of the forests and export data are made available (Forest Owners Association, 2020a). For Austria various leaflets from the government, more specifically the chamber of agriculture, were examined for data about, for example, spruce in general, thinning operations, or harvesting. For scientific papers and LCA studies, Google Scholar and BOKU:Lit search were used. Other data like the weight of machines, their size, production site or their fuel use, were taken off their manufacturers' websites. Transport distances were calculated using Google maps. Data for the impact assessment derives from Ecoinvent, which is the largest environmental data base worldwide.

3.5 Life Cycle Inventory of Wood Production in Austria and New Zealand

The inventory analysis starts with the creation of a flow chart depicting the processes of the production chain. In this case, from the upbringing of the seedlings to the gate of a sawmill, pulpmill or energy wood factory. The flow chart is divided into four process stages: planting, thinning, harvest, and transport (Figure 4). Planting starts with the upbringing of seedlings and includes site preparation and spraying, mowing, and finally, planting of the seedlings. It ends with planted seedlings or with seedlings of a height of 1 m when the regeneration occurred naturally. All tending steps that are taken between planting and final harvest are called 'thinning'. Even though the extraction of materials in a thinning process is a harvesting operation, it is called 'thinning' in this study to distinguish from the final harvest. Between two and four thinning operations and pruning comprise this stage. The final harvesting operation encompasses such steps as site preparation, transport of machinery, felling the trees, delimbing, cut-to-length, topping and extracting them. Finally, 'transport' is the transport of the felled and processed logs to the plant gate. Furthermore, the transport of workers from and to the forest, production of machinery, as well as constructing forest roads are also considered in the assessment.

3.5.1 Inventory Analysis of the Austrian Case Study

The inventory analysis of an LCA starts with a flow chart of all inputs and outputs of the wood production system (Figure 4).

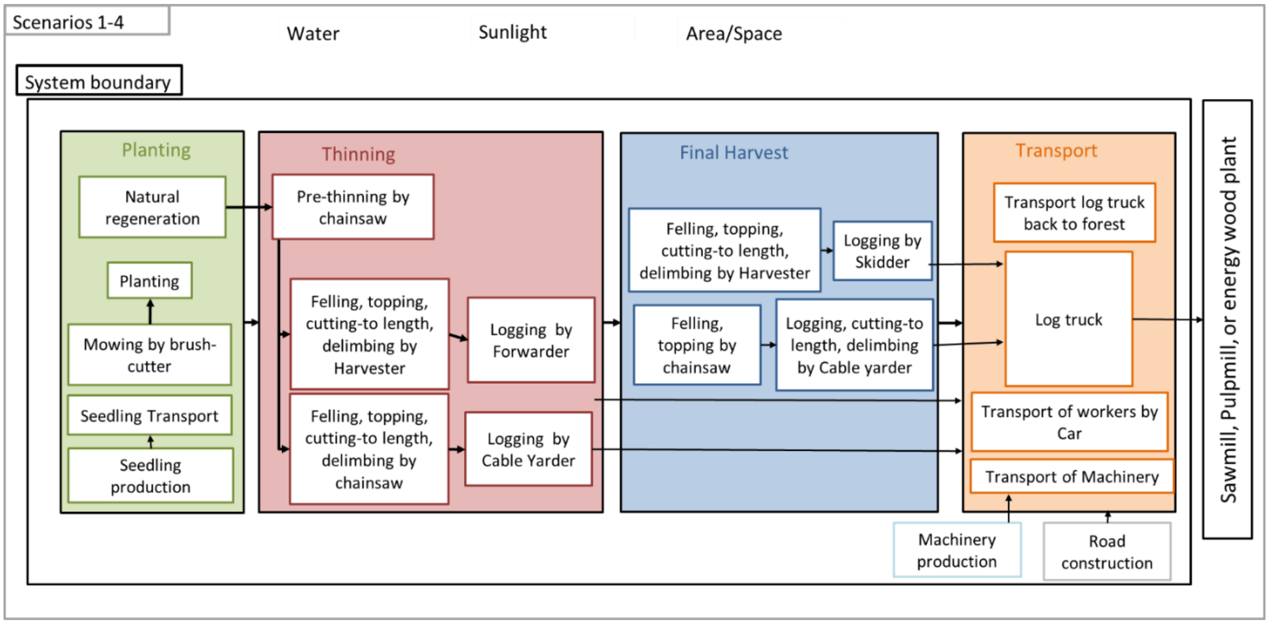


Figure 4: Flow chart of the wood production system of all scenarios in Austria.

In Scenarios 1-4 in Austria, the process starts with the stage of planting. There are two options, either the forest is planted with seedlings from a tree nursery, or it regenerates naturally. In the first option, the seedlings are produced and transported and then planted on the area that was mowed. If the forest regenerates naturally, no action is undertaken in the stage of planting, but in the stage of 'thinning', pre-thinnings are conducted. In natural regeneration a large number of seedlings emerge, and they stand closely together. In order to ensure good growth and wood quality they need to be thinned. Those 'pre-thinnings' are undertaken twice and after that the trees are arranged about as closely together as the planted seedlings in the other scenarios. These pre-thinnings are conducted by chainsaw and the cut material is left in the forest to protect the seedlings and to provide nutrients.

Thinning is ideally done every 5-10 years, but it is also common practice to only thin twice in one rotation period. In steep terrain, thinning is done with a chainsaw and the trees are transported by a cable yarder to the forest road, where the trees are further processed by chainsaw. In flat terrain, a harvester cuts and delimbs the trees and a forwarder loads the trees up and transports them to the forest road.

The harvester and forwarder drive on so-called “skid trails”. The “skid trails” are cut at the beginning of every harvesting operation. The machines drive only on those skid trails, so that the forest soil is impacted as little as possible (DeArmond, Ferraz and Higuchi, 2021) while also making harvesting clearer and well arranged. From the forest road the trees are brought to a sawmill, pulpmill, and energy plant by log trucks.

When the trees have reached their optimum size after 100 years, they are harvested. This happens by harvester and forwarder in flat terrain, and by chainsaw and a cable yarder in steep terrain. The trees are picked up by a log truck from the forest road and transported and sold to a sawmill, a pulpmill, or an energy plant. The assessment ends with the arrival of the trees at the gate.

3.5.1.1 Description of Forest Operation Processes in Scenarios 1 and 2

In Scenario 1, after a clearcutting, the soil is either bare or vegetated with non-wood plants at the beginning of the rotation period. After the area has been mowed with a brush cutter, 3000 seedlings are planted on one hectare. The seedlings are grown in Ottenstein, which is 17 km away from Stift Zwettl. The seedlings are brought to the forest by a small truck, with a net weight of 1,5 tons. The seedlings are bare rooted, and they are planted with a combination of machine and manual work. The machine is a “hole-maker”, which is a forwarder, John Deere 1110D, with a special hole-making appliance. The machine creates holes in rows, 4-5 rows at a time. A worker is assigned to each row to place the plants in the hole, drag soil into the hole with their shoe and press the soil around the seedling. That way, 30-40 plants are planted per person per hour. Consequently, it takes 15-20 hours to plant one hectare. The area is mowed once a year for the following three years, until the seedlings are no longer suppressed by weeds.

In Scenario 2 natural regeneration takes place instead of planting. The trees from the previous rotation were harvested as a patch-cut, in strips with a width of 50 m, so that light reaches the forest floor and regeneration is allowed to occur naturally. Therefore, no action has to be taken in the first stage of planting. However, because a large number of seedlings start growing at the same time, they stand significantly closer together than if they had been planted, with approximately one tree per 10 cm^2, which equals 10,000 seedlings per ha. In order to ensure good growing conditions for the trees and a certain quality of the wood, the trees are thinned after 5-10 years, or when they are 2-3 m high. They are thinned again at the height of 5 m, which results in a stand density of 2000-3000 small trees. Both of those thinnings are conducted by chainsaw. The trees cut during these “pre-thinnings” have too small of a diameter to be of enough value for sale; additionally, they can provide nutrients for the remaining trees when left in the forest.

This marks the beginning of the stage ‘thinning’, which is the same for both scenarios. Four thinnings are conducted in one rotation period. The first thinning is undertaken at the age of 20-30 years, when the diameter at breast height (DBH) of the trees is between 15 and 20cm, then when they are 30-40 years, 40-50 and 50-60 years old. In Scenario 2, thinning is also undertaken four times. Because the trees in the rotation before were harvested in a patch-cut, there are two different age classes on one hectare with about 10 years in between them. Thinning is still conducted for the full hectare, and trees of different age and therefore of different diameter are extracted at the same time. The first thinning in both scenarios is done with a smaller harvester, John Deere 1070G (17.8t tons), and between 50 m^3 and $80m^3$ are extracted per hectare. The second and all following thinnings are done with a larger harvester, John Deere 1270G (20.6 tons). The second thinning yields $50\text{-}80m^3$ and the third and fourth $50\text{-}100m^3$ per hectare. In all thinnings, the trees are subsequently logged with a smaller forwarder, a John Deere 1110D (12.8 tons). In every thinning about 1/3 of the stems are extracted and at the age of 60 there should be between 400 and 600 trees standing on one hectare, with at least 200 of them of high quality and a diameter of 50 to 65cm. About 40 years later, the rotation period ends with the final harvest.

The harvesting method in Scenario 1 is clearcutting, whereby the whole area is harvested at the same time. The harvester, John Deere 1270G, drives on the skid trails and cuts the trees. It also cuts off the top, delimbs the trees, cuts them to length and puts them along the skid trails. Simultaneously, a forwarder (John Deere 1510G) loads up the logs, extracts them to the forest road and stacks the logs. Instead of clear-cutting, patch-cut is applied in Scenario 2, where only half of the area is harvested, followed by the other half 5-10 years later. The harvesting machines are the same as in Scenario 1. In both scenarios the volume of the harvest amounts to $600m^3$ per ha. Lastly, in both scenarios, the logs are picked up by trucks and brought to sawmills, pulpwood factory and energy wood plant nearby.

3.5.1.2 Description of Forest Operation Processes in Scenarios 3 and 4

Scenarios 3 and 4 represent forest operations in steep terrain in Austria. In Scenario 3 the harvesting method is clear-cutting. Like in Scenario 1, the area is prepared by mowing to get rid of shrubs so that the seedlings can grow. The seedlings come from Arndorf, which is 177km away from the Lehrforst Rosalia, Forchtenstein. 2500 seedlings are planted per hectare by hand, which takes one worker between 166 and 250 hours. Conversely, in Scenario 4, the harvesting scheme is patch-cutting, like in Scenario 2. Therefore, no seedlings are planted since the forest regenerates naturally. Also like in Scenario 2, two pre-thinnings are conducted by chainsaw. ‘Thinning’ (after the pre-thinnings of Scenario 4) is the same for both scenarios and the area is thinned twice. Once, between 25-40 years of age and with a diameter of 12-15cm, $50\text{-}80m^3$ are harvested per hectare. The second time with 35-55 years, with a diameter of 15 30cm, where 50-100m^3 are extracted. In Scenario 4 the hectare is, like in Scenario 2, thinned at once with different tree sizes in it.

The trees are cut during both thinnings in both scenarios with a chainsaw, and they are logged with a Koller 300 mobile yarder. The yarder is essentially an appliance for a tractor, consisting of a tower with a winch and steel ropes. Two or more ropes, the guylines, hold the machine in place. The skyline leads downhill until the end of the yarding line and is fixed there (Visser and Harrill, 2017). The main line is the line that runs from the tower to the carriage and pulls the carriage uphill (Figure 5) (US forest service, 1997). The carriage has chokers to which the trees are fixed by hand and then pulled upwards (Koller, 2005). At the top of the cable corridor, the trees are unhooked, afterwards delimbed and cut to length by chainsaw.

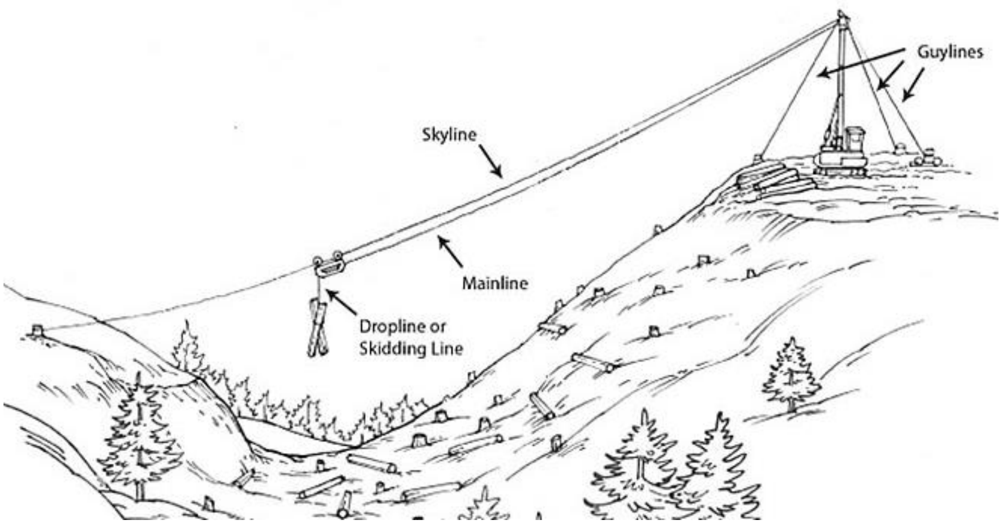


Figure 5: Cable yarder scheme, (US Forest Service, 1997)

Final harvesting is conducted in a similar way. The trees are cut with a chainsaw, and they are logged with a mountain harvester (Mounty 4000). This is a cable yarder combined with a harvester head mounted on a truck. The trees are cut, and the top is cut off in the forest, then they are fixed to the chokers and hauled uphill. At the top the trees are delimbed and cut to length with the harvester head and stacked (Raab *et al.*, 2002). From there they are loaded onto trucks and sold. Per hectare about 600 m^3 are harvested. In Scenario 3 the complete area is harvested, while in Scenario 4 only half of it is cut, followed by the other half 5 to 10 years later.

3.5.2 Inventory Analysis of the New Zealand Case Study

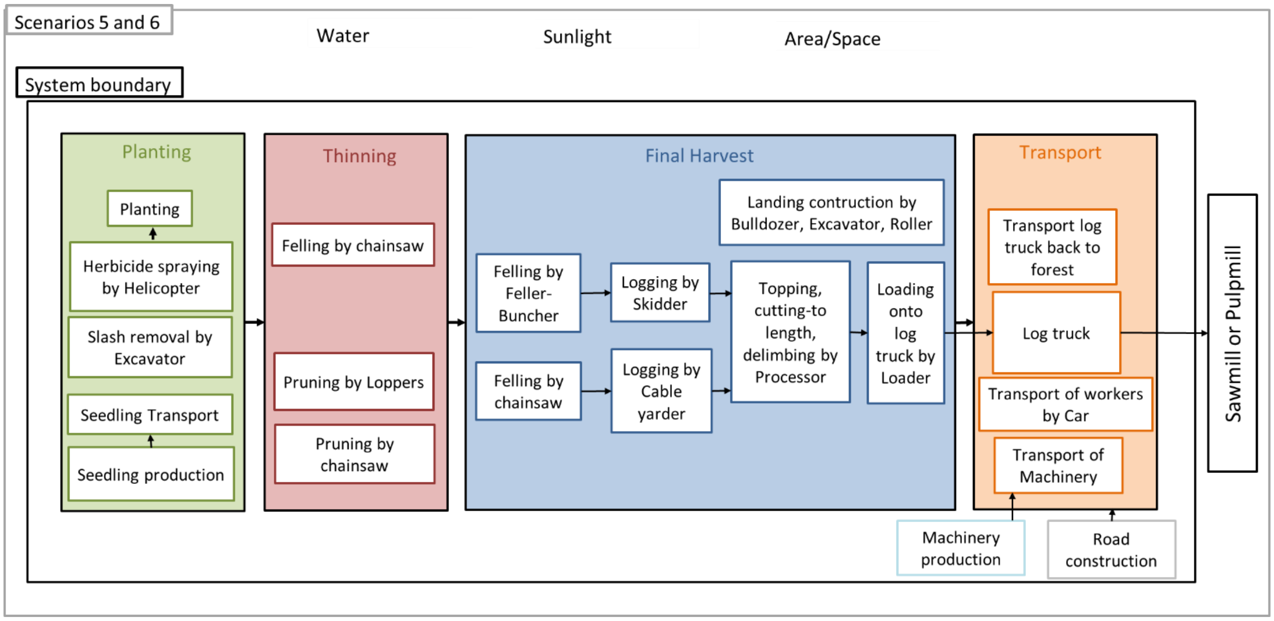


Figure 6: Flow chart of the wood production system of all scenarios in New Zealand

The assessment in New Zealand starts with the production of seedlings. In New Zealand, natural regeneration does not exist as a concept in this form of wood plantation. The trees are an exotic species that is managed like an agricultural crop with exact silvicultural regimes of spacing and timing of treatments. The trees are bred and improved for specific traits like fast and strong growth, disease resistance and improved wood qualities. The seedlings are grown in tree nurseries from specific seeds (Forestenterprises, 2018). Before planting, the area is prepared by removing slash and by spraying herbicides, after which planting is done manually (NZ Farm Forestry, 2007).

The stage of 'thinning' in this case study includes pruning and thinning to waste. Pruning is the removal of lower branches to produce a knot free stem, which is of higher quality and value (NZ Farm Forestry, 2005). Thinning to waste means that the cut material is left in the forest. Thinning and pruning is done three times in the 28 years of a rotation period in this case study. For this study it was assumed that thinning and pruning are undertaken simultaneously to increase efficiency. The material from thinnings and prunings are left in the forest (NZ Farm Forestry, 2007).

Harvest operations start with the construction of a landing, a place where the logs are processed, sorted, stacked, and picked up by trucks. Ground-based harvesting is conducted with a combination of a feller-buncher, skidder and processor. On steep terrain the system consists of a chainsaw, cable yarder and processor. From the landing site the logs are picked up by trucks and brought to a port, sawmill, or pulpwood factory (Figure 6).

3.5.2.1 Description of Forest Operation Processes in Scenario 5

Prior to planting, the forest is made accessible by removing vegetation and slash with a small excavator Komatsu PC55MR-5. Thereby, planting is facilitated, and workers can reach the area by pick-up truck. Also, the area is sprayed with a mixture of 3.3kg/ha Glyphosate and 0.115 kg/ha Metsulfuron before planting (Rolando and Harnett, 2015). The helicopter used for spraying is the Eurocopter AS350 B3. Then, 833 bare-rooted seedlings are planted manually. A hole is made with a spade, the tree is put in, soil is dragged into the hole with a shoe, the tree is lifted up lightly, so that the soil around the roots is loosened and all roots are pointing down, then the soil is firmed around the tree (NZ Farm Forestry, 2007). Planting time is usually in winter between May and August (Forestenterprises, 2018) That way, 115 seedlings are planted per worker per hour. The bare-rooted seedlings are transported 126 km (Google Maps, 2021) from the nursery in Woodsville to the forest by heavy truck. A few months after the seedlings are planted, they are sprayed again with a mixture of 7kg/ha Hexazinone and 1.75 kg/ha Terbuthylazine by helicopter. The workers drive to the forest site together in a ute, which is a pick-up truck.

The regime of thinning and pruning that is applied for this case study in the stage of 'thinning' starts at the age of 3-4 years when trees are about 5m high. They are pruned up to the height of 2-2,5m and thinned to 700 stems per ha. At the age of 4-6 years the trees are pruned again. At 6-8 years, or 8-18 months after the second pruning, the trees are thinned a second time, resulting in 380 trees per hectare (Forecaster Calculator, 2021). The trees are also pruned again to reach a target branch-free stem of 6,5m. The chainsaw used for thinning is the Shindaiwa 362Ts. It takes 11.25 hours for one worker to thin one hectare. The first pruning is done with loppers, and for the second and third pruning a small chainsaw Echo CS2511TES is used. The first prune takes 1.5 hours for one hectare and the following two, 2.25 hours. On one hectare, around 30 trees are pruned. In this case no production thinning is done and all the material is left in the forest.

The harvesting operations start with building a landing. The landing is 4000 m^2 wide (NZ Farm Forestry, 2016) and built for the harvest of 8.5 hectares. The area is cleared from all plants and the topsoil (Forest Owners Association, 2020b) and with a large CAT D7 bulldozer, an CAT 326 excavator and a CAT 825K sheepfoot roller the landing is created. It takes between 5 and 7 workdays to build a landing of 2400m^2. The workers and all machinery are brought from Napier to the forest site. After the landing is constructed, final harvesting starts. The trees are cut with a John Deere 959M feller buncher. This machine cuts the tree and lays it down in a bunch or one tree at a time. From there a John Deere 648L skidder, grapples the trees and extracts them to the landing.

There the trees are processed into logs, which means that they are delimbed, topped and cut to length with a CAT 548 processor. They are stacked and sorted to between 7 and 16 log sorts (Raymond, 2016). These are customized to the buyer and are therefore picked up by different companies and trucks according to the order. The logs are loaded onto truck with a CAT 982M front-end loader. From there they are brought to a sawmill in Napier, or a pulpmill in Auckland.

3.5.2.2 Description of Forest Operation Processes in Scenario 6

Planting and the scheme of growth and maintenance is the same as in Scenario 5. The landing is likewise built with the same machines as in Scenario 5, and it also takes the same amount of time. The difference lies in harvesting itself. Since the terrain has a steepness of 60%, ground-based harvesting is no longer possible. Therefore, the trees are cut manually with a chainsaw, Husqvarna 572XP G. The whole trees are logged with a Madill 124 swingyarder. The Madill 124 has grapples, so multiple trees are carried at the same time. Using a grapple increases the productivity compared to chokers (Raymond, 2016). Since there are no trees on the landing to fix the yarder to, it is anchored with a bulldozer, CAT D7, and an excavator, CAT 326. The processor and the loader are the same as in Scenario 5. Scenario 6 also ends at the gate of a sawmill or a pulpmill.

3.6 Assumption for the Inventory analysis and Methods for the Impact Assessment

The forest operation processes are established and with all assumptions that were taken for them, the inventory analysis of the LCA is complete. In the following impact assessment, every action and stage of forest operations are combined with an impact factor to assess the environmental impact.

In this section for every stage the assumptions are listed and explained, they were taken mostly because the information was not given or specified by the experts. Since most values were given in ranges, the average was taken. Also, all values were converted to correspond to either per hectare or per m^3. The stages of forest operations are planting, thinning, final harvest, transport, and workers. Also, the methods for the impact assessment are presented for every stage. In the impact assessment every input from the inventory analysis is multiplied with the according impact factor and is then demonstrated with the impact categories. The inputs are machines, seedlings, herbicides, and lorries of different sizes. The impact of the production of all inputs is given as an impact factor by Ecoinvent.

The impact factor is different for every machine, material and substance, and also for every impact category. In Ecoinvent transport is measured in ton*kilometers, therefore all transport distances, combined with the transported loads were converted into ton*kilometers.

The machines are not only produced and transported, but also their operation is considered. The impact factor provided by Ecoinvent for one hour of machine operation is multiplied by the hours needed for the operation per hectare. Finally, the impact of every input is summed up for every stage.

3.6.1 General Assumptions

Firstly, it is assumed that the chosen scenarios are representative for the assessed countries. Secondly, it was assumed that one m^3 of green spruce wood weighs 950kg. This number derives from the experts and from grey literature (Baumeister, 2021). The weight of green wood varies highly between stands and trees mainly because of varying water contents. The weight of radiata pine wood also varies highly, but on average 1 m^3 of green pine wood weighs 1 ton (Moreno Chan, Raymond and Walker, 2010).

Knowing the weight is important to determine the efficiency of logging and the environmental impact of the logs' transport, and to enable comparisons between the scenarios and countries. It is also assumed that all machines are running with full capacity and that they are state-of-the-art.

The location of the forests in Austria were determined by the managed area of the experts. In New Zealand the location was chosen considering the area the expert from New Zealand operates in. This was correlated with the topography, to find a flat area for Scenario 5 and a mountainous area for Scenario 6.

For all scenarios, it was assumed that the forests were established before the assessment period started, and therefore there is no aspect of land transformation from grassland or field to forestland to be considered. Also, the influence on soil and nutrient balances are not considered for the assessment, not because they are assumed as irrelevant but because of a lack of data. Furthermore, assessing net carbon sequestration is beyond the scope of this study because there is no agreed upon method yet to calculate sequestration (Klein *et al.*, 2015).

The data from the inventory analysis is combined with data and parameters from Ecoinvent to conduct the impact assessment. Ecoinvent provides data about the impact of products, energy sources, resources, machines, their production and use, chemicals, industrial process steps, and transport. Not only data of the impact is offered, but also parameters for their calculation.

These parameters are impact factors that are specific for every product, resource, energy source,… and they allocate a value to one unit of the assessed e.g., product. Multiplied with the number of units, the result is the impact.

3.6.2 Assumptions and Methods for ‘Planting’

Firstly, it was assumed that the seedlings are produced in an unheated greenhouse. Therefore, their impact is smaller compared to a heated greenhouse, which is usually heated with diesel (Ecoinvent, 2002b). Secondly, it is assumed that one spruce or pine seedling weighs 0.2kg. This number was already researched and calculated by Kühmaier *et al*. (2019) and is also in accordance with Ecoinvent (2002). The weight of the seedlings is important for their transport’s impact. The seedlings are transported in Austria with a small lorry, and for that the “lorry 3.5-7.5t” was chosen. This is the smallest lorry available in Ecoinvent, and since 2000 seedlings are brought to the forest, this type of lorry would be able to carry the necessary weight. In New Zealand the seedlings are transported with a large lorry with a gross weight of 16-32 tons The distance the seedlings are transported was approximated by route distances from Google Maps. For Austria the name of the tree nursery was given by the experts. In New Zealand it was assumed that the nursery is located in Woodsville, which is 120 km closer than the next tree nursery in Cambridge. The impact of the seedlings ($Impact_{seedlings}$) was calculated as follows:

$$Impact_{seedlings} = (Number_{seedlings} * Impact\ factor_{seedling}) + (Transport_{tkm} * Impact\ factor_{Transport})$$

The impact of the seedlings production, which is the number of seedlings ($Number_{seedlings}$) multiplied by the impact of one seedling ($Impact\ factor_{seedling}$), is added to the seedlings’ transport. The impact of the seedlings’ transport is calculated by multiplying the transport in ton*kilometers ($Transport_{tkm}$), which is the weight of the seedlings multiplied by the kilometers they are transported, multiplied by the transport impact factor ($Impact\ factor_{Transport}$) from Ecoinvent for a 1 tkm of a small lorry.

In Austria the area is mowed once before and three to five times after planting. It was assumed that the brush-cutter is similar to a chainsaw and has therefore the same weight, fuel use and emissions. This is due to the fact that there is no data available for another machine besides a chainsaw in Ecoinvent. The working hours for mowing with the brush-cutter and early thinnings were given by the experts and the average number was taken from that.

The impact of the brush-cutter ($Impact_{mowing}$) was calculated as follows:

$$Impact_{mowing} = Working\ hours_{mowing} * Impact\ factor_{power\ sawing}$$

Where *Working hours* $_{mowing}$ is the hours required to mow one hectare and the according Impact factor for mowing is *Impact factor* $_{power\ sawing}$

In New Zealand the site is prepared with a small excavator before planting to remove slash and to make the area accessible to the workers. It was assumed that the excavator used is a Komatsu excavator PC 55MR-5 with a weight of 6.5 tons. The machine is used for 4-6 hours, 5 hours on average. Komatsu was assumed to have a manufacturing plant in New Zealand; therefore, the machine is transported 400 km from Auckland to Napier. It was assumed that every operation starts in Napier, where the forest management firm is located. The area is sprayed twice with herbicides, once before and once post planting. The impact of the herbicides was calculated by multiplying the amount with the according impact factor. While Ecoinvent offers an impact factor for Glyphosate, the impact factor “pesticide unspecified” was used for Metsulfuron. Terbuthylazine and Hexazinone are quite similar and chemically close to Triazine, so the impact factor for “market triazine” was used for both chemicals.

Spraying is done by helicopter. It was assumed that the helicopter is a AS 350 B3. The helicopter's weight is given by the manufacturer Eurocopter. Eurocopter produces in Brisbane, Australia. The manufacturer also states that the average fuel use is 180l of kerosene per hour (AvBuyer, 2016). The conversion factor of liter kerosene into kg was given by Ecoinvent (1990) and is 0,817kg/l. To determine the productivity of the helicopter, the travelling speed is essential. Qiu *et al*. (2013) found that the optimum speed for spraying is 50km/h, or 13.9 m/s. It was calculated how long it takes for the helicopter to fly 100m, this was converted into hours, because every operation in this assessment is calculated per hour, and multiplied by 10, because the helicopter has to fly 10 times across the area to spray it. It was thus concluded that it takes 1.2 minutes to spray one hectare by helicopter.

In Scenario 1 the seedlings are planted mechanically with a forwarder. It was assumed that it is the same type of machine that is used in thinning operations later. In Scenarios 2 and 4 it was assumed that natural regeneration takes place, and no planting is needed. In Scenarios 3, 5 and 6, the seedlings are planted manually. The duration of planting was given by the experts. Also, it was assumed that no herbicides and fertilizers are used in the forest in Austria. In New Zealand the seedlings are planted manually. The average worker plants 115 seedlings per hour, therefore it only takes 7,5 hours to plant a hectare. In steep terrain planting takes 20% longer according to the experts. Herbicides are sprayed in the stage of planting, but it was assumed that no fertilizer is applied.

3.6.3 Assumptions and Methods for 'Thinning'

Thinning includes pre-thinnings that are conducted in Austria in Scenarios 2 and 4, thinning in Scenarios 1-4 as well as thinning and pruning in New Zealand. The pre-thinnings in Scenarios 2 and 4 must be done to reduce the number of trees in the first 15 years after natural regeneration to ensure high quality and growth. The weight of the chainsaws for the pre-thinning is assumed as an average number from different producers, because the type and brand of the chainsaw was not given by the experts. It is assumed that it is a chainsaw of average size and a gross weight of 7,5kg (Stihl, no date). The working hours for the pre-thinnings per hectare were given as between 15-20 hours and 40-50 hours, from that an average was taken. From those two operations, no material is sold, therefore their impact was divided by the total harvested volume per hectare. The impact of these operations was calculated in the same manner as "mowing".

In New Zealand, in this case study three thinnings and prunings are conducted. The working hours for thinning and pruning were given by the expert. The productivity for thinning is according to the expert between 11.25 and 22.5 hours per ha. For Scenario 5 the topography allows easier access, wherefore it was assumed that thinning takes 11.25 hours. In steep terrain in Scenario 6, thinning takes 22.5 hours. The productivity of the first prune for Scenario 5 was given as nine hectares per worker per day, which is 1.5 hours per ha, the second and third prune take 2.25 hours per hectare. In Scenario 6 pruning takes presumably 20% longer than in Scenario 5, because the terrain is more difficult. A small chainsaw is used for thinnings, the Shindaiwa 362Ts with a weight of 3.6kg is presumed. The first prune is done with loppers, where the weight is assumed to be 1.5 kg. The loppers are assumed to be produced in Auckland. The following prunings are done with a small chainsaw Echo CS2511TES with a weight of 2,5kg. The chainsaws are produced in Japan, so the distance from Tokyo to Auckland by ship and then the distance from Auckland to Napier was assessed. The machines are assumed to be transported together with the workers to the forest site, since they take them with them in the pick-up truck. There is no production thinning in this case study in New Zealand, therefore all cut material is left in the forest.

In Austria, four thinnings are conducted in Scenarios 1 and 2 and two thinnings in Scenarios 3 and 4. For the thinnings the experts gave a range of 50-80m^3 of extracted material per thinning operation. It was assumed that only 50 m^3 are extracted during every thinning operation. With extracting less during thinnings, more can be harvested during final harvest, and it was assumed that forestry is performed to produce high quality logs and therefore the focus lies on the final harvest.

In Scenarios 1 and 2 thinning is done by harvester and forwarder, and Scenarios 3 and 4 by chainsaw and cable yarders. In order to calculate the impact, the productivity is determined first.

The impact of the machines themselves is measured in machine hours. Working hours is the reciprocal of the productivity and the productivity of harvesting ($Productivity_{Harvester}$) is calculated as follows (Gurdet, 2008):

$$Productivity_{Harvester} = -3,87+11,43*Volume_{Tree}^{0,25}-3,5*HK_1^{0,4}+10,06*Volume_{Tree}^{0,25}*HK_1^{0,4}+0,52*HK_2$$

HK1 and HK2 are technology factors. For the first two thinnings HK1 and HK2 are 2.99 and -0.57 respectively and for the other two and final harvesting HK1 and HK2 are 5.23 and -0.18 respectively (Gurdet, 2008). $Volume_{Tree}$ is calculated as follows:

$$Volume_{Tree} = Tree\ diameter^2/1000$$

The $Volume_{Tree}$ (Gurdet, 2008) is calculated in m^3 and the tree DBH is given in cm.

The productivity of the forwarder ($Productivity_{forwarder}$) is calculated as follows (Gurdet, 2008):

$$Productivity_{forwarder} = 60/\ (1.3*(0.511*Volume_{Log}^{-0.2}+((0.023*Forwarding\ distance+0.24*Volume_{Forwarder})/Volume_{Forwarder})+0.8145)$$

The volume of a log is smaller than of a tree and is calculated as follows (Gurdet, 2008):

$$Volume_{Log} = 0,008+0,1987*Volume_{Tree}^{0,7}$$

The forwarding distance was given by the experts as 100 meters, from the forest to the forest road. The volume of the forwarder load ($Volume_{Forwarder}$) was estimated by dividing the carrying capacity of the forwarder, which is 12 tons, by 950kg which is the wood's weight per m^3.

$$Productivity_{cable\ yarder} = (14.46-2.68*Volume_{Log}^{-0.5}+(1/distance)*628.12+(Volume_{Log}^{-0.5}/distance)*(-178.63)+Lateral\ yarding\ distance*(-0.078))/1.11$$

The calculation of the volume of a log is explained above. The *distance* means the distance the logs are extracted by the cable yarder and was estimated as 100m. Lateral yarding distance is the distance the trees are dragged until they are in the cable corridor, from where they are pulled upwards. In Scenario 3 the cable yarder is put up twice to harvest the area, and therefore the distance between the two lines is 33.3m, from that the average lateral yarding distance is 16.6m. In Scenario 4 the hectare is harvested twice, each time a strip of 50m width.

The cable yarder is established in the middle of that, and so the average lateral yarding distance was assumed as 12.5m.

The productivity of a chainsaw for thinning and harvesting operations (*Productivity* $_{chainsaw}$) is calculated as follows (Gurdet, 2008):

$$Productivity_{chainsaw} = 1/((1,35/Volume_{Tree}) * (3,3229+5,6851*(Volume_{Tree}^{0,7})+0,1087*(Volume_{Tree}^{0,7})* Branch_{\%} -1,7506*(Volume_{Tree}^{0,7})*1)/60)$$ (Gurdet, 2008)

The branch percentage ($Branch_{\%}$) depends on the number and diameter of the tree's branches. This is important because processing by chainsaw takes longer the more branches there are. The assumed percentage of 50% was the average of values given by Sperrer (2009) and Albrecht (2018).

The productivity of the machines is crucial for measuring the environmental impact of wood production because the machines have high fuel emissions, which contribute to all impact categories. The higher the productivity, the lower is the impact of the operation per m^3. All data was calculated per hectare and divided by the harvested volume in that stage, 100 m^3 in Scenarios 3 and 4, and 200 m^3 in Scenarios 1 and 2.

In Scenarios 2 and 4, with patch-cut, the productivity is lower than with clearcutting, because the trees are of different age and have therefore smaller diameters. It was assumed that in patch-cut the trees are on average 5 years younger. One half of the hectare is harvested, and the other half 10 years later, therefore during thinnings, there is that same age difference, which is on average 5 years. For the thinning operations in Scenarios 2 and 4, the diameter of trees 5 years younger, with the according diameter was used for the calculations than the point in time of the thinnings would suggest. For example, in Scenario 2 the first thinning is at the age of 20-30 years, from that the average is 25 years, but because the trees are on average 5 years younger, the diameter used is from the age of 20.

With the machines' productivity calculated, the impact of the machine and the impact of using it is calculated.

$$Impact_{machine} = Transport_{Production\text{-}tkm} * Impact\ factor_{Transport} + Working\ hours * Impact\ factor_{machine\ use} + [Transport_{machine\ tkm} * Impact\ factor_{Transport}]$$

Firstly, the machines are transported from their factory to the forest site. This is always done by a "lorry 16-32tons". This category was chosen because their gross vehicle weight suffices to carry the machines. If machines are built overseas, then they are also transported by ship or ferry. The transport distances were approximated from Google Maps. The transport ($Transport_{Production\ tkm}$) is measured in weight of the machine in tons multiplied by the kilometers it is transported (ton*km). These ton*km are multiplied by the impact factor for a lorry 16-32 tons ($Impact\ factor_{Transport}$).

The impact of the machines' transport to the forest site is added to the impact of the machines' use. The impact of the machines' use is the working hours (*Working hours*) the machine takes to work on one hectare multiplied by the impact factors for the machines' use (*Impact factor $_{Machine\ use}$*) from Ecoinvent.

Since the machines examined in Ecoinvent differ from the machines used in the scenarios, they are adjusted accordingly. In Austria the fuel use of the machines was given by the experts, so the number of the impact factor was divided by the fuel use from Ecoinvent and multiplied by the fuel use of the machine used in the scenarios. If the fuel use was not available, the machines were adjusted by their weight. The weight was found at websites of the manufacturers.

The impact category 'machine use' usually includes the machines' transport between forest sites. Large machines, like felling and logging machines, are transported between stands. Based on Ecoinvent (2012) these machines travel, mounted on trucks, for 25 km daily. For Austria and for New Zealand these 25 km daily are used for the machines' transport. For bulldozers, excavators, rollers, and loaders there is no specific category in Ecoinvent. Therefore, the category 'machine operation, diesel' is used. For those machines the daily transport is not included. Only in those cases the transport of 25km per working day is added (*[Transport $_{machine\ tkm}$ * Impact factor $_{Transport}$]*). Small machines like chainsaws and brush-cutters are transported together with the forest crew, and therefore their daily transport is not considered.

For all transports the impact category of "market transport" was chosen, because market includes the production and transport of the trucks themselves, in addition to the transport of the goods, logs, or machines that the trucks are transporting (Ecoinvent, 2013a). Also, EURO 6 was used, which is the most recent norm for fuel emissions (WKO, 2020).

3.6.4 Assumptions and Methods for 'Final Harvest'

In Austria it was assumed that 600 m^3 are harvested per hectare at the end of the rotation period. It was also assumed that the DBH in Scenarios 1 and 2 is 50cm and in 3 and 4, 20% less, 39cm, because the trees grow slower in steep terrain. Then the harvested volume was calculated by multiplying the number of trees harvested on 1 ha with the diameters harvested. The resulting harvested volume is similar to the assumed harvested volume, but not the same.

To calculate the machines' productivity the formulae from above were used. In the stage of final harvest, the harvester has a productivity of 28 m^3/hour and the forwarder 25.6 m^3/hour. Harvesters and forwarders from John Deere are produced in Finland and are therefore transported by lorry and by ferry.

In Scenarios 3 and 4 the cable yarder for the final harvest also processes the logs, and it has a different productivity (17 m^3/hour) than the cable yarder in the thinning operations. The cable yarder is produced in Austria and its productivity is calculated as follows (Gurdet, 2008):

$$Productivity_{\text{cable yarder with processor}} = 0.8*(-22{,}7713+41{,}8961*Volume_{Tree}^{0.15}-0{,}0046*distance-0.0897*Incline)$$

The volume of the trees (*Volume* $_{Tree}$) was calculated the same way as above, and the logging distance (*distance*) was also estimated as 100m. The *Incline* was assumed to be 60%. In the case of ground-based harvesting, the forwarder brings the logs to the forest road. From the forest road the logs are picked up by trucks.

In New Zealand the first step in the harvest operation is the construction of a landing. One landing is built to keep and process on average 6000 m^3 of wood, which equals 8.5 hectares. Therefore, the working hours, and subsequently the impact was divided by 8.5. Building a landing usually takes between 5 and 7 days, with a daily working time of 10 hours. Since there was no further information on the duration of the machine use, it was assumed that each machine works for the same amount of time, for 21 hours. The machines from CAT are produced in Portland, USA.

In New Zealand it was assumed that 700 m^3 are harvested per hectare. Final harvesting starts after the landing is built. The trees are cut with a feller buncher. It was assumed that the feller buncher used is the John Deere 843L which is a large sized feller buncher, suitable to cut the large diameters the trees have.

The trees are then logged with a skidder, assumed to be the John Deere 648L. The productivity of the feller buncher was assessed by applying the formula from Brown *et al*. (2013). The average tree volume is assumed to be 1.8m^3. This number is an average from Forest Owners Association (2020a) and Berry (2019).
The dissertation by Brown *et al*. (2013) says that productivity is volume per time and the time the feller buncher needs to move to the tree is between 12.2 and 79.4 seconds. The time to fell the tree is between 6.2 and 47.75 seconds. The minimum and maximum productivity was calculated and the average between them was taken. The minimum was with a move-to-tree time of 70 seconds and cut-tree time of 15 seconds. The maximum was 30 seconds and 10 seconds. The average productivity of the feller buncher was calculated as 119 m^3/h. The productivity of the skidder was calculated with a formula from Gurdet (2008).

$$Productivity\ Skidder = (1254 - 1{,}33 * Skid_{distance} + (22{,}4 * (Volume_{Log}^{0{,}8}) * (Bunch^{0{,}8}))) * 0{,}02832$$

The skid distance ($Skid_{distance}$) was assumed to be 200 meters. The volume of the log ($Volume_{Log}$) is 1.8m^3 (NZFOA, 2019) minus 13%, which is the volume of the bark, because the formula calculates the productivity without bark. The *Bunch* is the number of trees that is transported at the same time, and it was estimated that 5 trees fit into the grapple at the same time. This number is based on grapple sizes and the carrying capacity of the machine. The productivity of the skidder was calculated as 31.27m^3/hour. The expert states that a skidder skids 500 tons of trees per day, which equals 55.5m^3/hour. Since the calculations are done for a case study, the numbers from the expert are used, and are reviewed later in the sensitivity analysis.

In steep terrain felling is done manually by chainsaw, with a tree volume of 1.8m^3 and an assumed branch percentage of 50%. For logging a cable yarder is used. The swing yarder Madill 124 is the most common yarder in New Zealand and was therefore chosen for the assessment. The productivity of the yarder was given by the expert as 38.8m^3/hour.

The productivity of the processor was calculated the same way as the feller buncher, because the formula provided in the model from Gurdet (2008) gave numbers too low to be representative for the highly efficient and advanced system in New Zealand. The dissertation from Berry (2019) assessed the average productivity as 62m^3 per hour. This number was used for the sensitivity analysis. The expert states that the productivity of the processor is 38.8 m^3/hour.

The productivity of the loader, which puts the logs onto trucks, was also applied from Akay *et al*. (2020). The productivity is again volume per time and the volume of one tree is 1.8m^3 (NZFOA, 2019).

The time the loader moves to the wood was estimated as 20 seconds, the logs are loaded for 5.5 seconds, the loader drives to the truck for 20 seconds, unloads for 7 seconds and an additional delay of 10.83 seconds is added.

The productivity of the loader according to these calculations is 102 m^3/hour and it is reviewed in the sensitivity analysis. According to the expert in New Zealand the productivity of the loader is 33.3 tons/hour. The impact of the 'machines use' is explained in the chapter above in 3.6.3.

In steep terrain harvesting operations, one additional bulldozer and excavator are needed to anchor the cable yarder. For them the transport was considered, but no additional environmental impact, because it was assumed that the machines are only used for their weight.

By loading the logs all process steps in the forest are done, and transport to a sawmill, pulpmill, or energy wood plant starts.

3.6.5 Methods and Assumptions for Timber transport

The timber truck was assumed in all scenarios to have a net weight of 14 tons. This is based on an average of various timber trucks that are commonly used (Autoline, 2021). With the net weight of the trucks considered, a maximum of 30 tons of wood can be transported, which is between 30 and 40 m^3. Also, the maximum gross weight for trucks without a special approval for road use in Austria and in New Zealand is 44 tons (WKO, 2021b and NZ Transport Agency, 2016). The distance to the sawmill and all other distances were approximated with Google Maps.

In Scenarios 1 and 2 the distance to the sawmill is 19km, 20km to the pulpmill and 3.4km to the energy plant. In Scenarios 3 and 4 the distances are 123, 127 and 18.5km. In Scenarios 5 and 6 the wood is transported for 47.9 km to the closest sawmill and presumably 455 km to a pulpmill in Auckland.

Transport is calculated in ton*kilometers. Therefore, firstly the ratio between the two or three log sorts is needed. For New Zealand the ratio of sawlogs to pulpwood was calculated with data from Forest Owners Association (2020a), where it says that from a 2.3m^3 log, 0.31m^3 is a pulplog, which is 13%. In New Zealand the logs go either to a sawmill or into plywood or paper, but it is not used for energy purposes directly.

In Austria the ratio was given by the experts. In the first thinning it is assumed, based on expert opinion, that 80% of the harvest is pulplogs is, 10% are sawlogs and 10% energy wood. In the second thinning there are 70% pulplogs, 20% sawlogs and 10% energy wood. In Scenarios 1 and 2 there are two more thinnings where the ratio was assumed as 60% pulplogs, 30% sawlogs, and 10% energy wood, and 50% pulplogs, 40% sawlogs and 10% energy wood.

The weight of the logs that are transported were calculated as follows:

$$Weight_{\text{Logs transported}} = \text{Share of log sort} * m^3/ha_{\text{harvested}} * Weight_{\text{tons per } m^3}$$

The logs that are transported are distinguished between the log products because they travel different distances. These log products, or log sorts are sawlog, pulplog, energy log. The amount of a log product (*Share of log sort*) that is harvested on one hectare ($m^3/ha_{harvested}$) is multiplied by its weight per m^3 ($Weight_{\text{tons per } m^3}$). In Austria the weight per m^3 is 0.95 tons, in New Zealand it is 1 ton.

The kilometers that the logs are transported was assessed by calculating the number of tours the trucks take to transport all logs to their destination. The number of tours was calculated by dividing the tons to be transported by 30 tons, which a truck can load at once, and that number rounded up to the nearest integer.

The ton*kilometers the wood is transported was calculated by multiplying the number of tours with the tons transported and with the distance to the mill or plant. It was also assumed that the trucks drive back empty. Instead of calculating their impact by ton*km, it was calculated per km. The impact of the trucks driving back is the number of tours multiplied by the kilometers per tour.

The kilometers to the plants were researched on Google Maps. For New Zealand it was not considered that most logs are not processed in New Zealand but shipped as whole logs to another country (Forest Owners Association, 2020a). It was assumed that all logs produced in Scenarios 5 and 6 are processed in New Zealand.

$$Impact_{Log\ Transport} = Ton*km*Factor_{Lorry<32t} + km*Impact\ factor_{Lorry<32t}$$

The ton*kilometers of the logs was calculated by multiplying the weight of the logs transported with the distance to the sawmill, pulpmill, or energy plant, which is between 3.4 and 400 km. The impact factor “Lorry<32 tons” was used because the maximum gross vehicle weight is 44 tons, and large lorries are needed for log transport. Added to that is the impact of the lorry driving back. The impact category for the ‘lorry driving back’ was calculated per km, because the lorry drives back empty. The impact was calculated for every log sort for every thinning and final harvest operation. In the end they were summed up to calculate the total impact of the logs’ transport.

3.6.6 Methods and Assumptions for Workers and their Transport

Workers are also considered in the calculations, but only the impact of their transport and not their food or other impacts from their housing or upbringing. In Austria they each drive by car to the forest site, and it was given by the experts that they drive 65 kilometers every day. In New Zealand they commute together in a pick-up truck from Napier to the forest site, which is 47.9km in Scenario 5 and 71.1km in Scenario 6. Transport is calculated in Ecoinvent in Person*kilometers.
Therefore, the number of workers in each stage for the full operation per hectare was assessed. In Austria a working day is assumed to be 8 hours long, in New Zealand it is 9 hours.

For every action the working days were calculated by dividing the working hours per hectare by hours per working day and rounded up. Within the stages the working days were summed up, and that represents the number of workers needed per stage. It was assumed that only one worker is needed to operate a ground-based machine or a chainsaw. It was assumed, however that one cable yarder has a team of three workers. It was not considered that planners, managers, or forest owners are also present during harvesting, thinning, or planting operations. Then the number of workers was multiplied by the kilometers they drive per working day. That way the person*kilometers per stage were calculated.

3.7 Impact Assessment -Datasets and Impact Factors

The impact assessment method determines the value of the impact factors. For this study the second version of the environmental footprint (EF 2.0) was used. The impact categories of the EF 2.0 were developed for the product environmental footprint (PEF). The PEF is the framework by the EU as a revised form of life cycle assessment and it is supposed to be the standard for all environmental declarations in the future (Lehmann, Bach and Finkbeiner, 2015). Currently the ISO 14040 is the only standardized method to assess a range of potential environmental impacts of products and services. According to the ISO 14040, impact categories can be chosen freely, but they should represent the relevant impacts. Klein *et al*. (2015) found that global warming potential, freshwater and terrestrial acidification, freshwater eutrophication, and photochemical ozone formation are the most relevant impact categories for forestry and therefore they were used in the assessment.

The impact factors are taken from Ecoinvent, and how the impact was calculated was explained in chapter 3.5. Table 3 shows the data sets that were used for the impact assessment. The values for the impact factors for every dataset used in the impact assessment are presented in the Appendix.

Table 3:Impact categories, application, and source

Name of Dataset in Ecoinvent	Application	Source
Tree seedling production in unheated greenhouse	Seedlings, Spruce and Pine	(Ecoinvent, 2002a)
Transport, freight lorry 3.5-7.5 metric tons, EURO 6	Lorry for transporting seedlings in Austria	(Ecoinvent, 2013b)
Transport, freight lorry 16-32 metric ton, EURO 6	Transport seedlings in New Zealand Transport machines	(Ecoinvent, 2013c)
Market transport, freight lorry >32 tons [tkm]	Log transport	(Ecoinvent, 2013a)

Transport, freight lorry >32 tons [km]	Truck driving back	(UBA, 2012)
Transport, freight, sea, ferry	Transport machines to Austria	(Ecoinvent, 2012n)
Transport, freight, sea, ship	Transport machines to New Zealand	(Ecoinvent, 2012g)
Power sawing, without catalytic converter	Brush-cutter, and chainsaw	(Ecoinvent, 2012i)
Power saw production	Brush-cutter, and chainsaw	(Ecoinvent, 2011h)
Transport passenger car, diesel	Transport of workers	(Ecoinvent, 2012h)
Harvesting, forestry harvester	Harvester John Deere: 1070G, 1270G	(Ecoinvent, 2012f)
Forestry harvester production	Harvester John Deere: 1070G, 1270G	(Ecoinvent, 2012c)
Forwarding, forwarder	Forwarder John Deere 1110D, 1510G	(Ecoinvent, 2012e)
Production forwarder	Forwarder John Deere 1110D, 1510G	(Ecoinvent, 2012d)
Yarding and processing, mobile yarder on truck	Mounty 4000 cable yarder	(Ecoinvent, 2012o)
Mobile yarder on truck, production	Mounty 4000 cable yarder	(Ecoinvent, 2012a)
Machine operation, diesel, _= 18.64 kW and _ 74.57 kW, high load factor_	Small excavator Komatsu PC55MR	(Ecoinvent, 2014a)
Machine operation, diesel, _= 74.57 kW, high load factor	CAT D7-Bulldozer, CAT 326 Excavator, CAT 825 roller, John Deere 959M Feller-Buncher, CAT 982M Loader	(Ecoinvent, 2014b)
Hydraulic digger production (excavator, feller buncher)	CAT D7-Bulldozer, CAT 326 Excavator, CAT 825 roller, John Deere 959M Feller-Buncher, CAT 982M Loader, CAT 548 Processor	(Ecoinvent, 2001)
Skidding, skidder	John Deere 648L skidder	(Ecoinvent, 2012k)
Skidder production	John Deere 648L skidder	(Ecoinvent, 2012j)
Delimbing, with excavator-based processor	CAT 548 Processor	(Ecoinvent, 2012b)
Yarding, mobile cable yarder on trailer	Madill 124 swing yarder Koller K300	(Ecoinvent, 2012p)
Cable yarder, trailer mounted, production	Madill 124 swing yarder, Koller K300	(Ecoinvent, 2019)

Transport, helicopter	Spraying of herbicide by AS-350 B3 helicopter	(Ecoinvent, 1990)
Production helicopter	Helicopter	(Ecoinvent, 2000)
Market glyphosate	Glyphosate	(Ecoinvent, 2011c)
Market pesticide unspecified	Metsulfuron	(Ecoinvent, 2011e)
Market herbicide triazine	Hexazinone, Terbuthylazine	(Ecoinvent, 2011g)
Gravel crushed	Gravel for forest roads	(Ecoinvent, 2011d)

The environmental impact of machine use, machine transport, log transport, and worker transport is calculated for different impact categories. The impact categories chosen are global warming potential (GWP 100), freshwater and terrestrial acidification potential (AP), freshwater eutrophication potential (FEP), terrestrial eutrophication potential (TEP), and photochemical oxidant formation potential (POFP). The impact was calculated for every action taken in the forest stand in one rotation period on one hectare. Within every stage the impact was divided by the harvested volume, to have the impact per m^3. The impacts of all stages except transport are summed up as an intermediate result at the forest road in Austria and at the landing in New Zealand. After that, the logs' transport is calculated and added to the result “at forest road”, to have the result “at gate”.

3.8 Methods for the Comparison of Scenarios

After calculating the impact for every stage of forest operations and for every scenario, the results are demonstrated visually. The environmental impact of the scenarios is compared and evaluated. Firstly, the scenarios were compared by their total environmental impact in chapter 4.1. Then they are compared by impact category, and the contribution of the individual stages (planting, thinning, harvest, transport, and workers) to the impact is shown in 4.2.

Section 4.3 follows a different approach, and the contribution of the individual forest operation processes are presented for every scenario. These are: machine production, machine transport, machine use, seedling production, log transport, transport of workers, and road construction. These main contributions were determined in the course of the impact assessment and the sensitivity analysis. They show which forestry inputs emit the most and how the systems could be improved. The impact of the production of all machines used in one rotation is summed up for each scenario to assess the impact of the machines production. It was taken into consideration that the machines operate for longer than they are used for the forest operations in this study.

Therefore, the impact of the machines' production was divided by the total life span hours and multiplied by the working hours for the forest operations. Transport of machines entails their transport from the production site to the forest and also transport between forest sites. Also here, it was considered that the machines travel from their production site to Austria or New Zealand for more than just the operations in this study, and the impact of their transport was allocated to the working hours. And 'machine use' means the summed-up operation of all machines used in one rotation period. The production and transport of seedlings, the transport of logs to their destination and the transport of workers, are the same as in the calculations before in chapter 4.2.

3.9 Methods Sensitivity Analysis

The sensitivity analysis tests the results for their accuracy, and the assumptions for their preciseness. In other words, it tests how and if the results change when numbers and assumptions are changed. The sensitivity of all input parameters was tested in the order of the stages, and the actions within the stages. If the result in the end, at the gate, or within the stage changed by at least 5%, it was found significant and is presented below in chapter 4.5. Each parameter was tested individually, and while one parameter was tested, the others remained constant. The following list describes all sensitivity tests that were found significant within the stage or for the final result.

- The sensitivity for increasing the number of seedlings by 1000 or by 400 was tested. This demonstrates how much the impact would increase if the doubled number of seedlings are needed per hectare, because of inefficiency, animals, or frost
- The sensitivity for increasing mowing time by 20 hours and pre-thinnings by 10 hours was tested to see the possible effect in case the use of a chainsaw-like machine takes double the amount of time
- The sensitivity was tested for increasing the working hours of the excavator used in the stage of planting for removing slash and clearing the road by 2 hours
- For New Zealand it was also tested how the results of 'planting' change when the double amount of herbicide is used

- The sensitivity was checked for increasing the amount harvested in one thinning in Scenarios 1-4 from 50 m^3 to 80 m^3, with an accordingly smaller harvest in the end
- It was also investigated how the results are influenced if all thinnings extracted 80 m^3 instead of 50 m^3, and even less could be harvested in the end

- It was tested if the results would improve if instead of four thinnings in Scenarios 1 and 2, only two thinnings were conducted, leaving more to be harvested in the end
- The lateral yarding distance, which is part of the formula for the cable yarder in thinning operations, was doubled in Scenarios 3 and 4
- For thinnings in New Zealand, the sensitivity for an increased duration of thinning operations by 5 hours was tested
- It was tested if the results changed by switching the gasoline chainsaws to electric chainsaws in all scenarios

- The sensitivity was tested for increasing the harvested volume during final harvest by 20%, because of good growth conditions
- The assumptions for machine productivity were compared with literature for Scenarios 5 and 6 and it was tested how the results change if the productivity was assumed according to values offered in scientific papers

- The sensitivity of the weight of spruce per m^3 was tested by reducing it by 20% in Scenarios 1-4
- An increase of the transport distance of logs by 20% was assessed for all scenarios
- A normalization of all transport distances was conducted to highlight the influence of log transport on the result
- The sensitivity was tested for a change of the emission norm of the log trucks

4. Results

This section will first present an overview of the general results for all six scenarios. Scenarios 1-4 are located in Austria and Scenarios 5 and 6 in New Zealand. Scenario 1 represents spruce forestry in flat terrain harvested by clear-cutting. Scenario 2 is also spruce forestry in flat-terrain with patch-cut as harvesting scheme. Scenarios 3 and 4 are in steep terrain, with clearcutting in Scenario 3 and patch-cutting in Scenario 4. Scenario 5 covers radiata pine cultivation in flat terrain and Scenario 6 in steep terrain. Then, the scenarios are compared by each impact category, followed by a demonstration of the contribution of the individual forest operation processes for each scenario. Lastly, a sensitivity analysis checks all assumptions and input data for their influence on the results.

4.1 General Results of the Impact assessment

In the impact assessment the impact of every input, or every operation is calculated. These impacts were summed up per stage and as a final result at the factory gate. Table 4 shows the results for Scenarios 1-6 at the forest road and at the gate for all assessed impact categories.

Table 4: Results Scenarios 1-6, at forest road and gate, for all impact categories

	GWP kg CO_2 -eq/m^3	FTAP kg SO_2-eq/m^3	FEP kg PO_4-eq/m^3	TEP kg PO_4-eq/m^3	POFP kg NMVOC-eq/m^3
Scenario 1 Forest Road	8,63	0,05	0,002	0,18	0,09
Scenario 1 Gate	10,78	0,05	0,002	0,18	0,09
Scenario 2 Forest Road	7,83	0,04	0,002	0,15	0,08
Scenario 2 Gate	10,02	0,05	0,002	0,17	0,09
Scenario 3 Forest Road	12,89	0,05	0,004	0,19	0,18
Scenario 3 Gate	26,68	0,10	0,005	0,30	0,22
Scenario 4 Forest Road	12,43	0,05	0,004	0,19	0,18
Scenario 4 Gate	26,40	0,10	0,005	0,30	0,23
Scenario 5 Forest Road	10,52	0,04	0,001	0,15	0,08
Scenario 5 Gate	24,39	0,09	0,002	0,26	0,12
Scenario 6 Forest Road	13,34	0,06	0,004	0,19	0,16
Scenario 6 Gate	25,12	0,09	0,005	0,29	0,20

The result of the impact assessment is first presented as GWP for all scenarios, then as all other impact categories. Figure 7 shows the global warming potential at the gate in kg CO_2-equivalents per m^3, in Austria and in New Zealand with the Scenarios 1 to 6. The first bar with a black outline is the summed up GWP of each scenario, the following bars show the GWP of the individual stages.

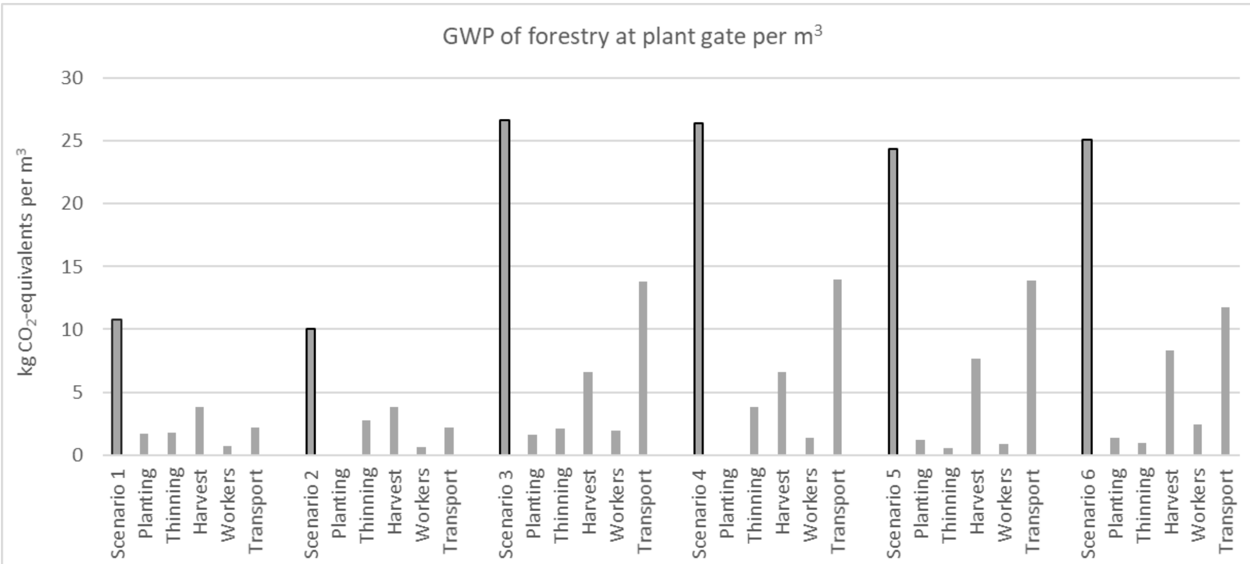


Figure 7: Global warming potential of forest operations at plant gate per m^3

Scenarios 1-6 divided into four process steps: planting (stand establishment and planting), thinning (felling and logging in Austria, only felling in New Zealand), final harvesting (felling, logging, processing, and loading onto trucks), transport of logs from the forest to a processing plant, and transport of workers to and from the forest The overall GWP is between 10 kg CO_2-equivalents per m^3, and 26.6 kg CO_2-equivalents per m^3. This range, especially when comparing Scenarios 1 and 2 to Scenarios 3 to 6, is mainly due to differing harvesting methods, as well as varying transport distances. The transport distances are between 3.4 km and 400 km. It includes the transportation of all log assortments (sawlog, pulplog, energy log) from the forest to the plant.

In Scenarios 1 and 2, due to short transport distances, final harvesting is the most influential factor, whereas it is only the second largest contributor to the environmental impact of forestry in the other scenarios. Final harvesting is more efficient and easier in flat terrain (Scenarios 1 and 2). In New Zealand, all material is extracted during the final harvest, so the entire impact from machinery use is emitted during this step. Final harvesting on steep terrain is more time consuming, which makes the productivity smaller and thus increases the machine time per m^3 of produced wood. Therefore, the environmental impact of harvesting is highest in Scenario 6.

For the same reason, the impact of 'workers' is highest in this scenario as well. In Scenarios 1-4 thinning is also significant. The impact is higher in Scenarios 2 and 4 than in 1 and 2, because the productivity is smaller due to smaller tree diameters with patch-cut. In New Zealand, Scenarios 5 and 6, thinning and pruning are done without extracting any material, which is why the impact of thinning and pruning is rather low.

Figure 8 shows impact categories excluding GWP. It demonstrates all scenarios. The impact values are given in kg of each impact measure per m^3. In all scenarios and in most categories the final harvesting activity has the greatest impact, followed by transport. The TEP of harvest is between 0.087 kg PO_4-eq/m^3 and 0.14 kg PO_4-eq/m^3, and for transport between 0.01 kg PO_4-eq/m^3 and 0.07 kg PO_4-eq/m^3.

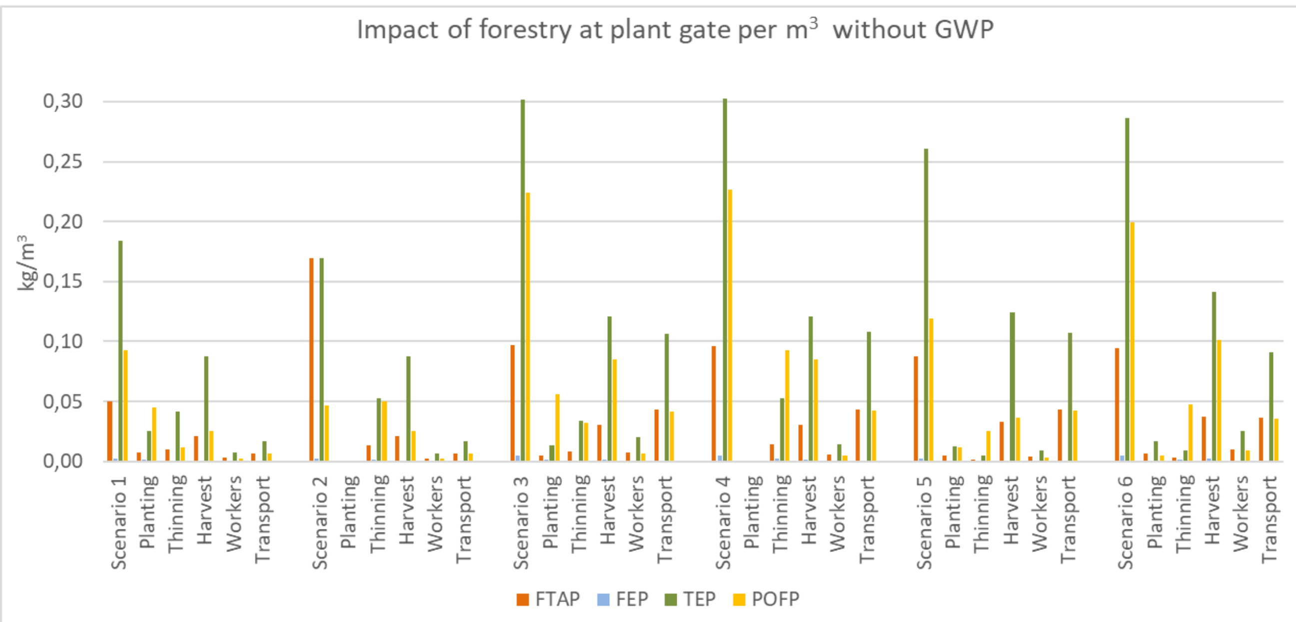


Figure 8: Impact of forest operations per m^3 without GWP ; freshwater and terrestrial acidification potential (FTAP), freshwater eutrophication potential (FEP), terrestrial eutrophication potential (TEP), photochemical oxidant formation potential (POFP). Presented in four operation steps: planting (stand establishment and planting), thinning (felling and logging in Austria, only felling in New Zealand), final harvesting (felling, logging, processing, and loading onto trucks), transport of logs from the forest to a processing plant, and transport of workers to and from the forest.

For POFP, the impact ranges between 0.002 kg NMVOC-eq/m^3 and 0.1 kg NMVOC-eq/m^3. In Scenarios 3, 4 and 6 cable yarders are used for harvesting operations, and therefore the impact is higher because cable yarders have a significantly higher fuel use than ground-based machines used in Scenarios 1, 2 and 5.

The impact is also higher in Scenarios 3, 4, and 6 because the systems are less efficient than ground-based harvesting systems. FTAP is higher in Scenarios 3-6, but still the values are similar in each case. The values are between 0.001 kg SO_2-eq/m^3 and 0.04 kg SO_2-eq/m^3. FEP is between 0.0001 kg PO_4-eq/m^3 and 0.002 kg PO_4-eq/m^3. Overall Scenarios 1 and 2 have the lowest impact in all categories. With the exception of TEP, Scenarios 3 and 4 have the highest impact, and Scenarios 5 and 6 have a smaller impact than 3 and 4, but still significantly higher than 1 and 2.

While Figure 8 offers an overview, it does not show the importance of different categories and does not compare them. One impact category being smaller than the other does not necessarily mean that is it is less important, or less harmful for the environment.

4.2 Comparison of Scenarios by Impact Category

In this section the scenarios are presented by impact category. This makes it easier to compare them. Also, the contribution of the individual stages is shown.

4.2.1 Global Warming Potential (GWP)

GWP is the impact category with the highest numbers in all scenarios and stages and lies between 10 and 26 kg CO_2-eq/m^3.

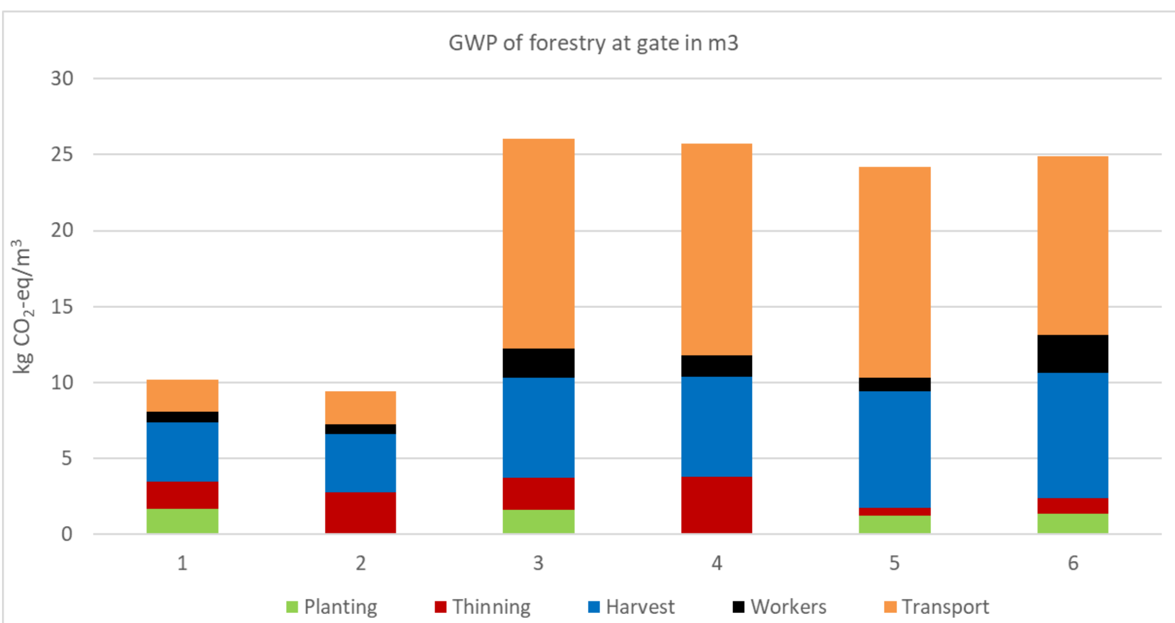


Figure 9: Global warming potential of Scenarios 1-6 at the gate of a sawmill/pulpmill/energy plant per m^3, presented as stages in forest operations: Planting (stand establishment and planting), thinning, final harvest up to loading onto trucks, transport to gate.

Scenarios 1 and 2 have a smaller global warming potential than the other scenarios, with a total GWP of 10.78kg CO_2-eq/m^3 in Scenario 1 and 10.02kg CO_2-eq/m^3 in Scenario 2. One of the reasons for that are the shorter transport distances, that are dependent on the location of the forest and the sawmill, pulpmill or energy wood plant. Transport contributes only 20% to the GWP of Scenarios 1 and 2, compared to 56% in Scenario 5, or 52% in Scenario 3. Also, by harvesting with harvester and forwarder, harvesting has a lower impact than in Scenarios 3 and 4, where harvesting is conducted by chainsaw and cable yarder. Their total GWP is 26.7 kg CO_2-eq/m^3 in Scenario 3 and 26.4kg CO_2-eq/m^3 in Scenario 4 (Figure 9).

Scenario 2 has the smallest impact because in addition to short transport distances, and ground-based harvesting, no mechanical planting is done. Instead, there are two additional pre-thinnings, which is why the stage of thinning is of higher importance than in Scenario 1. The impact of those pre-thinnings has half the GWP than the stage of planting in Scenario 1. Thinning contributes 17% to the total global warming potential in Scenario 1 and planting 16%, while in Scenario 2 thinning has a share of 27.5%. Thinning contributes that much in Scenario 2, because the productivity is smaller, because the trees are on average five years younger in each thinning, and have therefore a smaller diameter than in Scenario 1.

The difference between Scenarios 3 and 4 mirrors that of Scenarios 1 and 2. There is no planting in Scenario 4, but two additional pre-thinnings. Thinning in Scenario 4 contributes 14.5%, while planting in Scenario 3 is 5.6% of the impact and thinning is 7.8%. The overall impact of thinnings is larger in Scenarios 3 and 4 compared to Scenarios 1 and 2 because thinning in steep terrain takes longer and the cable-yarder for extraction has a higher GWP than the forwarder in Scenarios 1 and 2. In Scenarios 1 and 2, apart from pre-thinnings, four thinnings are conducted in which 200m^3 are harvested, while in Scenarios 3 and 4 there are only two, with a harvested volume of 100m^3 per hectare. In Scenarios 5 and 6 the stage of thinning has a small impact because the biomass is left in forest and it is also not, processed, loaded onto trucks and also no material from that stage needs to be transported. The contribution of thinnings is 2% in Scenario 5 and 4% in Scenario 6.

Final harvesting contributes significantly to all scenarios. In Scenarios 3 and 4 final harvesting is responsible for 25% of the total GWP, while it contributes 36% in Scenario 1 and 38% in Scenario 2. The GWP of final harvesting is significantly higher in Scenarios 3 and 4, even though in Scenarios 1-4 the same volume is extracted in this stage. The only difference is the machinery that is used because of different terrain. Cable yarders have a significantly higher environmental impact because they are heavier and need more fuel. Additionally, in steep terrain the tree diameters are smaller, resulting in a lower efficiency of the machines.

In Scenarios 5 and 6 the contribution of harvest is 31% of the overall GWP of 24.5kg CO_2-eq/m^3 and 33% of the total 19.4kg CO_2-eq/m^3 respectively. Here, harvesting has a larger impact than in Scenario 3 and 4 because all the material is extracted in that stage. The contribution is even higher in Scenario 6 because cable extraction and tree-felling by chainsaw takes longer and is therefore more machine intensive than ground-based harvesting in Scenario 5.

Even though the productivity in New Zealand is significantly higher than in Austria, the GWP of harvesting per m^3 is 30% higher in Scenario 5 than in Scenario 1. A ground-based feller-buncher is used in Scenario 5 with a productivity of 119m^3/hour, whereas the harvester in Scenario 1 has a productivity of 28m^3/hour. The reason why the impact is 30% higher is that 100 m^3 more are harvested per hectare in that stage than in Austria. Also, only the feller-buncher has such a high productivity and the skidder has a productivity of 55 m^3/h and the processor 38 m^3/h. Using three machines instead of only two, a harvester and forwarder, makes up the higher impact. Additionally, in New Zealand a loader is used to load the logs onto the log trucks, whereas in Austria the log trucks load themselves. Processors and loaders both are heavy machines with a high fuel use. In Scenario 6 harvesting has 21% more environmental impact than Scenario 3.

Transport of logs to a sawmill, pulpmill or energy wood plant contributes significantly to all scenarios. In Scenarios 1 and 2 transport is responsible for 20% or 22% of the total GWP. In Scenarios 3 and 4 transport accounts for 52% of the impact, in Scenario 5 for 56% and in Scenario 6 for 47%. The GWP of transport is similar in Scenarios 3-5, at about 13kg CO_2-eq/m^{3,} and 11.8kg CO_2-eq/m^3 in Scenario 6. The reason why the impact of Scenarios 3-5 is so similar is that the transport distances are alike. In Scenario 5 the transport distance to the pulpmill is 400km, compared to 127km in Austria. On the other hand, the sawmill in Austria is 123km away from the forest site, and in New Zealand 70km. Additionally, in New Zealand the ratio of sawlogs to pulpwood is larger, so more material is brought to the plant closer to the forest site. And, while the pulpmill is closer in Austria than in New Zealand, the majority of the wood is transported for 123km or 127km, compared to 70km in New Zealand. Transport in Scenario 6 has a smaller impact than in Scenarios 3-5, because the distance is shorter than in Scenario 5. Transport of workers contributes between 4% and 7% of the total GWP. In Austria it was assumed that every worker travels separately to the forest and travels 65km daily. In New Zealand it was assumed that workers live in or close to Napier and drive together to the forest site.

In Scenario 5 the number of times workers are transported is the smallest, while it is the largest in Scenario 6. The number of workers and the amount of time workers are needed mainly depends on terrain. In steep terrain every operation takes longer, and more working days are needed to get them done. Also, cable-crews consist of three workers, while there are only two needed for a harvester and a forwarder, or a feller-buncher and a skidder. In Scenarios 5 and 6 fewer workers are needed for thinning operations, but more machines are operated during harvesting than in Austria. Forestry in steep terrain in Austria was found in this study to have a similar environmental impact to plantation forestry in New Zealand in terms of GWP.

4.2.2 Freshwater and Terrestrial Acidification Potential (FTAP)

The total FTAP for Scenarios 1-6 lies between 0.046 kg SO_2 -eq and 0.097 kg SO_2 -equivalents (Figure 10).

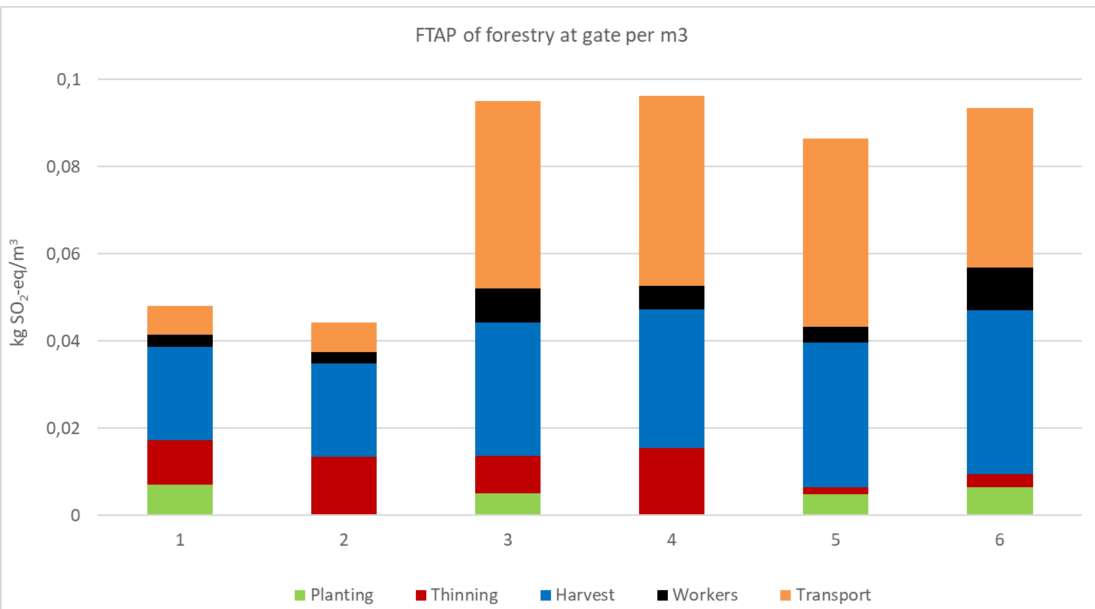


Figure 10: Freshwater and terrestrial acidification potential of Scenarios 1-6 at the gate of a sawmill/pulpmill or energy plant, divided into the main stages of forest operations: planting (site establishment and planting), thinning, final harvest and loading onto trucks, transport of workers from and to the forest and transport to plant gate. FTAP is shown as kg SO_2-equivalents per m^3 wood.

The contribution of the individual stages to the FTAP differs between the scenarios. Scenario 1 has a total impact of 0.05 kg SO_2 -equivalents per m^3. The largest share, 43%, are emitted during final harvest, 20% during thinnings, 14% during planting, 13% during transport and the remaining 5% are emitted by workers' transport. Scenario 2 has the smallest FTAP with 0.046kg SO_2-eq/m^3. From that the largest share is also emitted during final harvesting operations.

Since there is no planting in Scenario 2, the stage of thinning contributes 29% to the impact. In Scenario 3 the trees are again planted artificially, and that contributes 5.7% of the total 0.086kg SO_2-equivalents per m^3. Transport has the largest share of 50% in this scenario, while final harvest has 35%. In Scenario 4 the contribution of harvest and transport is similar to Scenario 3, and the FTAP is highest in this scenario: 0.096kg SO_2-equivalents/m^3. In Scenario 5, harvest produces the largest share of all scenarios, namely 49% and the total FTAP is 0.087 kg SO_2-equivalents/m^3. In Scenario 6 harvest and transport have the same contribution, 39% to the overall 0.094kg SO_2-eq/m^3.

Scenarios 1 and 2 have an overall smaller impact than the other scenarios, because harvesters and forwarders work efficiently and have lower emissions than chainsaws and cable yarders in this case study. Planting has the highest impact in Scenario 1, because that is the only scenario where planting is done mechanically. Thinnings have a significantly smaller impact in New Zealand because it is done by chainsaw and no material is extracted. Workers are assigned higher emissions the more working hours are needed during the operations, and since everything takes longer in steep terrain, the impact is higher in Scenarios 3, 4 and 6.

4.2.3 Freshwater Eutrophication Potential (FEP)

The total FEP for Scenarios 1-6 lies between 0.0022 and 0.0053 kg PO_4-equivalents/m^3.

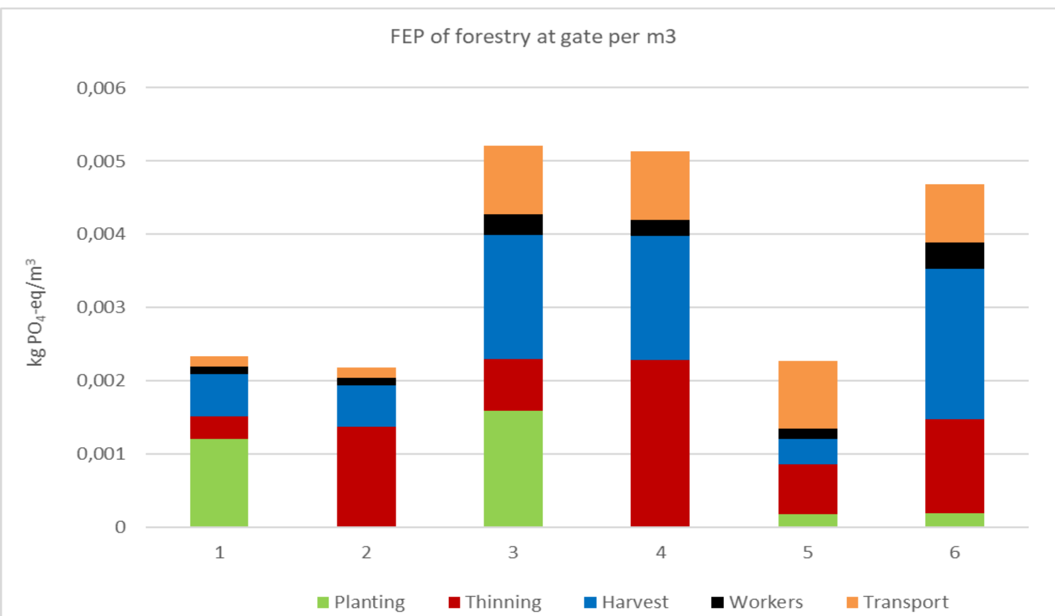


Figure 11: Freshwater eutrophication potential of Scenarios 1-6 at the gate of a sawmill/pulpmill or energy plant, divided into the main stages of forest operations: planting (site establishment and planting), thinning, harvest and loading onto trucks, transport of workers to and from the forest and transport to plant gate. Shown as kg PO_4 -equivalents per m^3 wood.

In Scenario 1 the total FEP is 0.0023 kg PO_4-eq per m^3. From that, 50.5% are emitted during planting, with thinning being the largest contributor in Scenario 2, with 61% of the total 0.0022kg PO_4-eq/m^3. In Scenario 3, 38% of 0.0053 kg PO_4-equivalents/m^3 are emitted during harvesting operations, 35% during planting, and 15% during thinnings. Scenario 4 has the second highest FEP, 0.0049kg PO_4-equivalents/m^3. 43% of them are emitted during thinnings and 32% during harvests. In this category Scenario 5 has a smaller impact than in all the other categories, 0.002 kg PO_4-equivalents are emitted per m^3. From that, the largest portion is contributed during thinning and transportation processes. In Scenario 6, on the other hand, 43.5% are emitted during harvesting and 27.5% during thinnings. Workers also contribute 7% to the impact in Scenario 6, which is more than in the other scenarios (Figure 11).

The freshwater eutrophication potential is generally small for all scenarios, especially compared to the other impact categories. Thinning and harvesting contribute the most. Chainsaws without catalytic converters have higher emissions in this category, while trucks with the current emission norm do not. However, in the burning process of fuels not only CO_2, but also Nitrogen compounds are emitted, which contribute to the eutrophication potential.

4.2.4 Terrestrial Eutrophication Potential (TEP)

The total TEP in Scenarios 1-6 is between 0.16 and 0.29 kg PO_4-equivalents/m^3 (Figure 12).

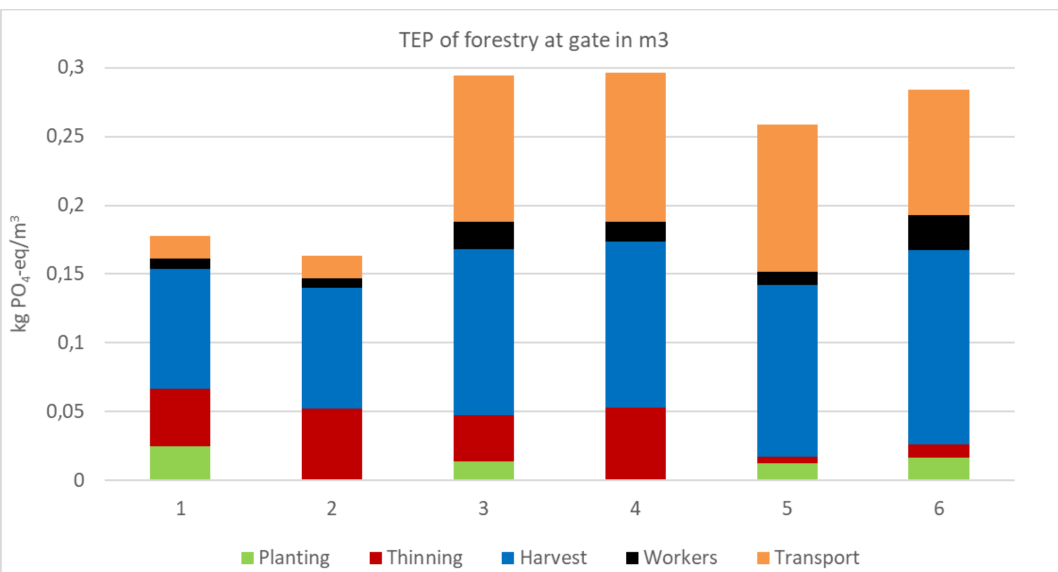


Figure 12: Terrestrial eutrophication potential of Scenarios 1-6 at the gate of a sawmill/pulpmill or energy plant, divided into the main stages of forest operations: planting (site establishment and planting), thinning, harvest and loading onto trucks, transport of workers to and from the forest, and transport to plant gate. Shown as kg PO_4-equivalents per m^3 wood.

In Scenario 1 the total TEP is 0.18 kg PO_4-equivalents, and harvest contributes the most with 47.5%, while planting is responsible for 14% of the impact. In Scenario 2, 51% of the total 0.16kg PO_4-equivalents/m^3 are emitted during final harvesting. Likewise, in Scenario 3, harvesting emits the largest share of the total 0.23 kg PO_4-equivalents per m^3, but in this scenario it is closely followed by 41% that are emitted during transport. Scenario 4 has the highest TEP of 0.29kg SO_2-equivalents/m^3, of which 40% are emitted by harvesting operations, 35.5% by transport and 17% by thinning. The total TEP of Scenario 5 is 0.26 kg PO_4-equivalents/m^3; from that 48% are emitted in final harvesting operations, and 41% in transport. Scenario 6 has the third highest TEP with 0.286 kg PO4-e/m3, where final harvest contributes most, followed by transport, and lastly, workers, who are responsible for 8% of the TEP (Figure 12). Harvest contributes the largest share of the impact in this impact category, which explains why Scenarios 1 and 2 have such high values compared to the other scenarios and the other categories.

4.2.5 Photochemical Oxidant Formation Potential (POFP)

The total POFP lies between 0.084 and 0.22 kg NMVOC-equivalents/m^3.

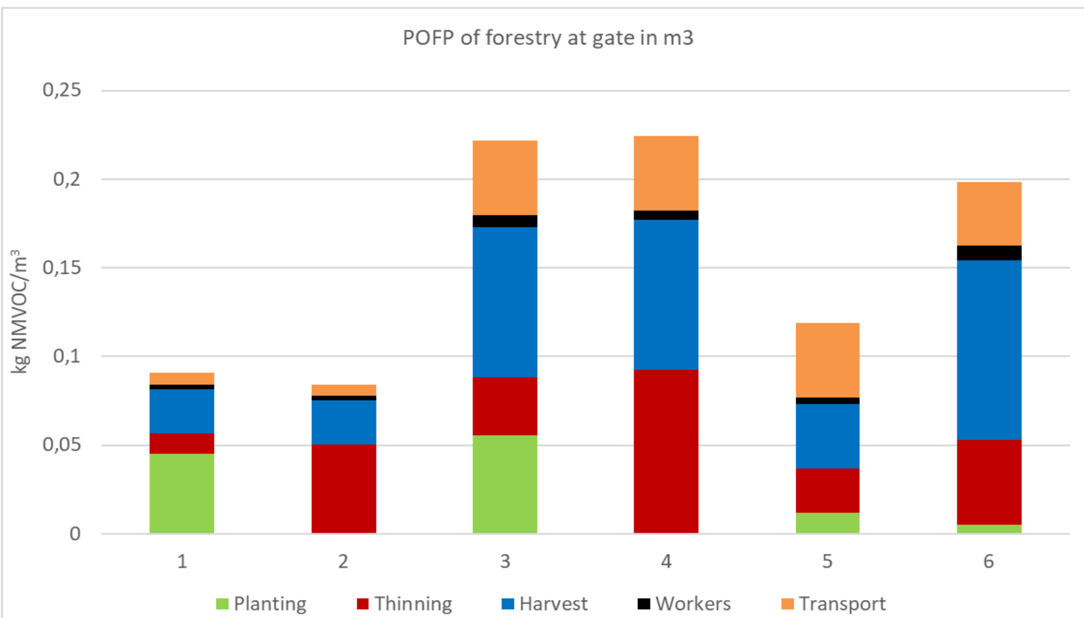


Figure 13: Photochemical oxidant formation potential of Scenarios 1-6 at the gate of a sawmill/pulpmill or energy plant, divided into the main stages of forest operations: planting (site establishment and planting), thinning, harvest and loading onto trucks, transport of workers to and from the forest and transport to plant gate. Shown as kg NMVOC-equivalents per m^3 wood.

The POFP varies between the scenarios and is influenced by harvesting methods, transport distances and machine input (Figure 13).

In Scenario 1 the total POFP is 0.091 kg NMVOC-equivalents per m^3. From that the largest share, 48.8%, are emitted during planting, 13% during thinning and 27% during final harvest. In Scenario 2, 58% of the overall 0.084 kg NMVOC-equivalents/m^3 are emitted during thinning, and 29% during final harvesting operations. In Scenario 3, 0.17 kg NMVOC-equivalents are emitted and from that 49% during final harvest, and 32% during planting. Scenario 4 has the highest POFP of 0.22kg NMVOC-eq/m^3. The largest share, 40%, are emitted during thinning, while 37% are emitted during final harvesting. In Scenario 5 transport contributes the most, with 35% of the total 0.12kg NMVOC-eq/m^3. 31% are contributed by final harvesting and 21% by thinnings. Scenario 6 has a total POFP of 0.199kg NMVOC/m^3. From that 51% of the total POFP are emitted by final harvesting operations, 24% by thinnings, 18% by transport and 4.4% by workers. The use of chainsaws contributes the most to this environmental impact category, because catalysators are not used in chainsaws and therefore photochemical oxidants are not filtered but emitted. This is shown in Scenarios 1 and 3, where the area is mowed four times, which contributes highly in this impact category. In Scenarios 2 and 4 the second pre-thinning contributes most in this category. Scenario 5 emits significantly less than Scenarios 3, 4 and 6, because chainsaws are used little in this scenario, whereas in Scenarios 3, 4 and 6 chainsaws are used for thinning and final harvesting operations. Also, cable yarders emit considerably more in this category than ground-based machines. In Scenarios 1 and 3 the area is mowed four times with a mower, which was assumed to be similar to a chainsaw and to have the same impact, in the stage of planting, which also results in a relatively high impact.

4.3 Contribution of Individual Forest Operation Processes

In this section the impact of forest operations is not shown by impact category, but by the contribution of the individual forest operation processes. Those are: production of machines, transport of machines, machine use, production and transport of seedlings, transport of logs, transport of workers, and road construction and maintenance. The production of the machinery has an impact that was considered above but is shown in this section separately. The impact of the machines' production was calculated by dividing the impact of the production with the machine's lifetime and multiplying it with the working hours per hectare. For the transport of the machines to the forest site it was assumed for Austria that they are transported for 25 km daily.

For New Zealand it was considered that the machines are transported to harvest 8.5 hectares at once and therefore the impact is divided by 8.5. Except for workers and log transport, the environmental impact is demonstrated differently than in the sections before.

Especially the contribution of the machines, the environmental impact of machine operation and transport is made significantly more visible in this section.

4.3.1 Scenario 1

For Scenario 1 the contribution of the individual forest operation processes to GWP is presented in Figure 14.

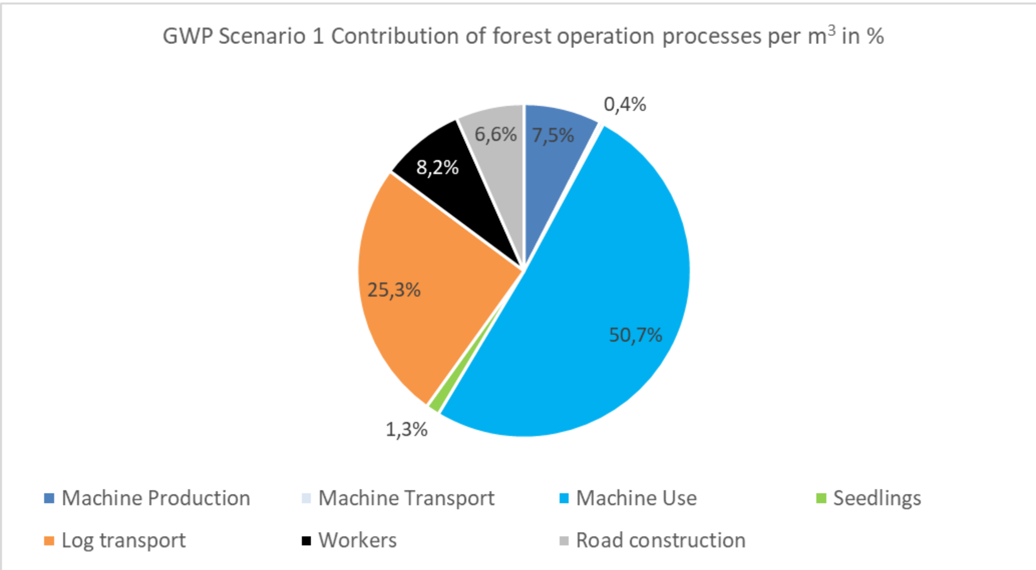


Figure 14: Contribution of forest operation processes to the global warming potential of Scenario 1. Main contributions are machine production (production of all machines used in one rotation period), transport of machines from production site to the forest, use of machine (transport of machines between forest sites, burning of fuels, use of lubricants), production and transport of seedlings, transport of logs from the forest to a sawmill, pulpmill or energy wood plant, transport of workers to and from the forest site and road construction.

Scenario 1 has a total GWP of 10.8 kg CO_2-equivalents per produced m^3. 7.5% of that is emitted by the production of machines. This includes the production of all machines used: chainsaws, harvesters, forwarders, and log trucks. Machine transport is the transport of all machines from their production site to the forest, which only encompasses 0.4% of the entire impact. The impact from the 'machine use', which is the machines' operation, mainly derives from burning fuels. In Scenario 1, 50.7% of the GWP is emitted by machine operation. 1.3% are contributed by the production and transport of seedlings. 25% of the GWP is emitted by the transport of the logs to the plant gate, and 8.2% by the transport of workers to and from the forest site. The remaining 6.6% are emitted by road building and maintenance (Figure 14).

Figure 14 shows that the environmental impact could chiefly be decreased by reducing the impact of machine use. That could be achieved by changing the type of fuel or by increasing efficiency.

However, the actual potential is difficult to assess since the environmental impact of biofuels can vary depending on the assumptions of their LCA. Increasing the efficiency could be done by shortening transport distances, and by improving transport logistics in general.

4.3.2 Scenario 2

For Scenario 2 the contribution of the individual forest operation processes is presented in Figure 15.

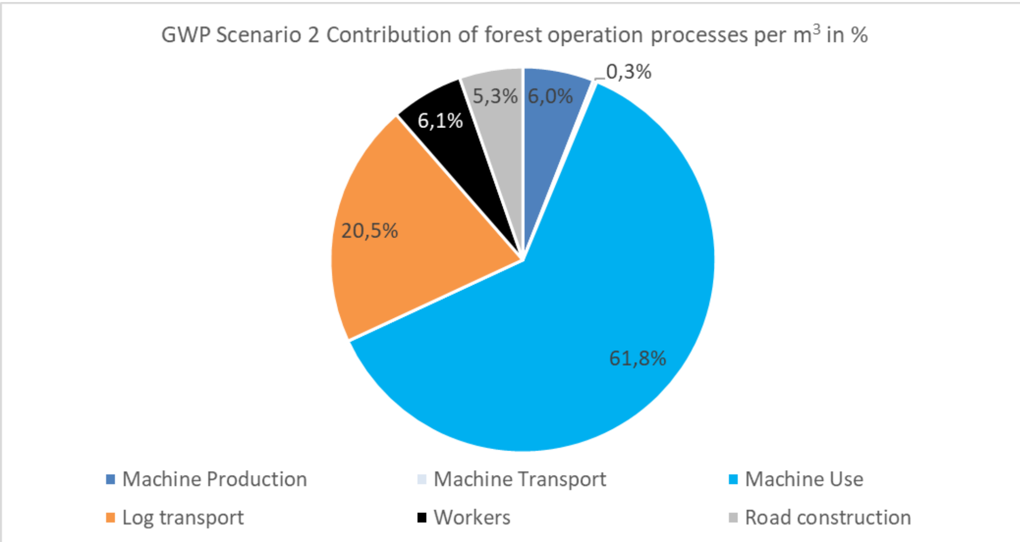


Figure 15: Contribution of forest operation processes to the global warming potential of Scenario 2. Main contributions are machine production (production of all machines used in one rotation period), transport of machines from production site to the forest, use of machine (transport of machines between forest sites, burning of fuels, use of lubricants), transport of logs from the forest to a sawmill, pulpmill or energy wood plant, transport of workers to and from the forest site and road construction.

In Scenario 2, the total GWP per m^3 is 10 kg CO_2-equivalents. The production of all machines used to produce 1 m^3 makes up 6% of the impact. The transport of these machines is 0.3%, while the use of the machines, is 61%. 20.5% of the total impact are emitted by log transport, and 6% by the transport of workers. Road construction is responsible for the remaining 5.3% of the impact (Figure 15).

Therefore, impact reductions should be made, like in Scenario 1, in the section of machine use, for example a different kind of fuel, or by increasing efficiency.

4.3.3 Scenario 3

For Scenario 3 the contribution of the individual forest operation processes is presented in Figure 16.

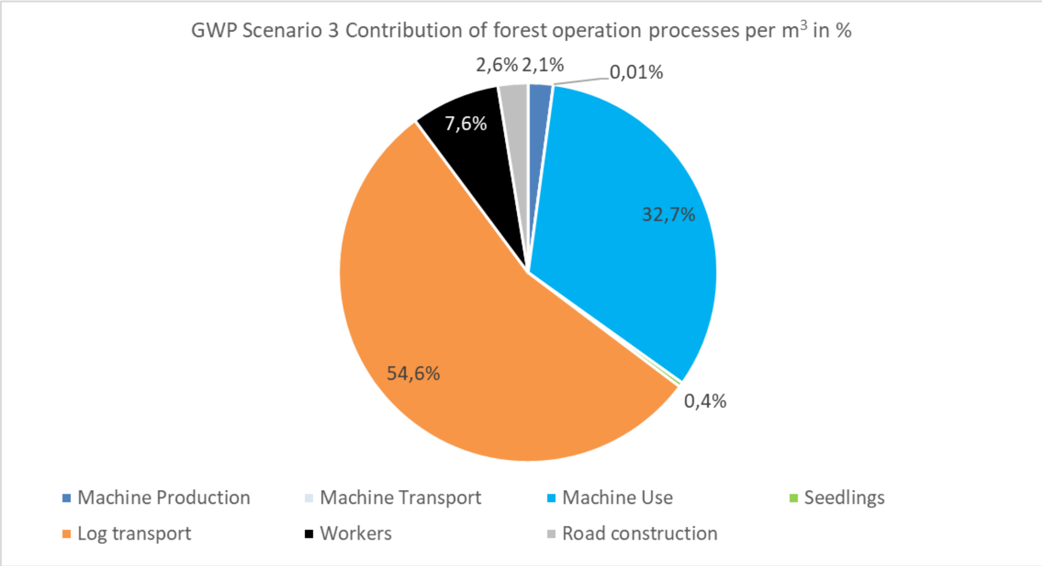


Figure 16: Contribution of forest operation processes to the global warming potential of Scenario 3. Main contributions are machine production (production of all machines used in one rotation period), transport of machines from production site to the forest, use of machine (transport of machines between forest sites, burning of fuels, use of lubricants), transport and production of seedlings, transport of logs from the forest to a sawmill, pulpmill or energy wood plant, transport of workers to and from the forest site and road construction.

The total GWP in Scenario 3 is 26.7kg CO_2-equivalents per m^3. From that, the impact of machine production is 2.1%, and the transport of the machines from their production site to the forest is 0.01%. The use of the machines, which mostly entails burning of fuels, creates 32% of the impact. The transport of the logs to the sawmill/pulpmill/energy plant comprises 54% of the GWP in this scenario. The transport of the workers contributes 7.6% and road construction 2.5% to the impact of forestry in Scenario 3 (Figure 16).

Scenario 3 has the highest GWP of all scenarios. The first reason is that timber harvesting in mountain forests has a higher impact than operations on flat terrain, because it takes longer, tree diameters are smaller, and because cable yarders have a higher fuel consumption per m^3 and per ha than ground-based machines. The second and more important reason is the transport distance, which is six times longer than in the two previous scenarios. This is also the reason why log transport has the largest share. The machines' transport on the other hand still has a small share.

The impact of this scenario could be most efficiently reduced by improving transport logistics of log transport, by electrifying the transport system, by reducing transport distances, or by using a different kind of fuel for the log trucks.

4.3.4 Scenario 4

For Scenario 4 the contribution of the individual forest operation processes is presented in Figure 17.

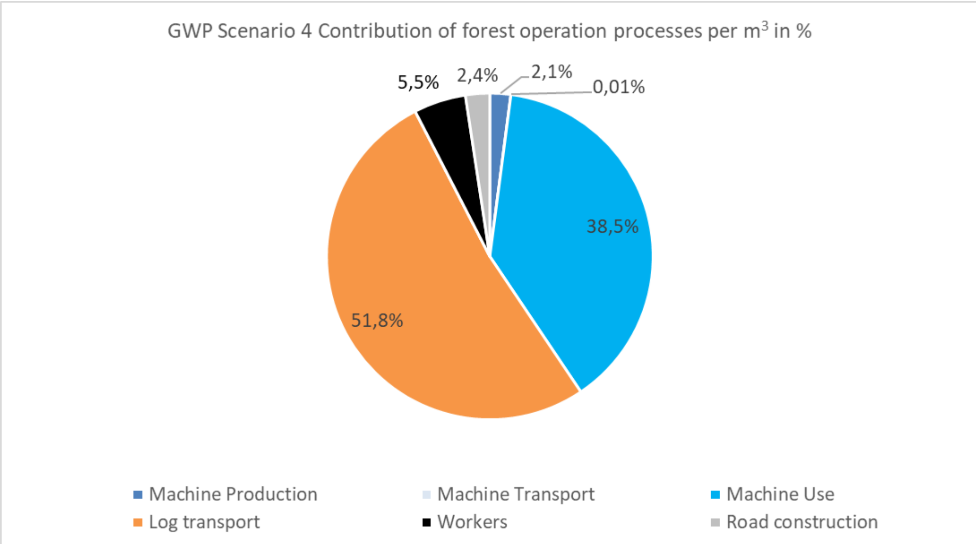


Figure 17: Contribution of forest operation processes to the global warming potential of Scenario 4. Main contributions are machine production (production of all machines used in one rotation period), transport of machines from production site to the forest, use of machine (transport of machines between forest sites, burning of fuels, use of lubricants), transport of logs from the forest to a sawmill, pulpmill or energy wood plant, transport of workers to and from the forest site and road construction.

Scenario 4 has a total GWP of 26.4kg CO_2-equivalents per m^3. From that the production of all machines makes up 2.2% of the impact and 0.01% is the transport of the machines. 41% are emitted by machine use, which mostly entails burning of fuel. The largest share, 55% is the transport of the logs to the gate of a sawmill, pulpmill plant, or an energy plant. 5.5% go to the transport of workers and 2.5% to the construction of roads (Figure 17).

Log transport and operation of the machines contributes most in this scenario, like in the previous scenario. In order to reduce the environmental impact of Scenario 4, log transport should be more efficient and the fuel use of the cable yarder. Log transport logistics could be improved, like in Scenario 3, by increasing the use of railway instead of trucks, or by electrifying the trucks themselves. The cable yarders could be fueled by biofuels, instead of diesel, or by electricity as well.

4.3.5 Scenario 5

For Scenario 5 the contribution of the individual forest operation processes are presented in Figure 18.

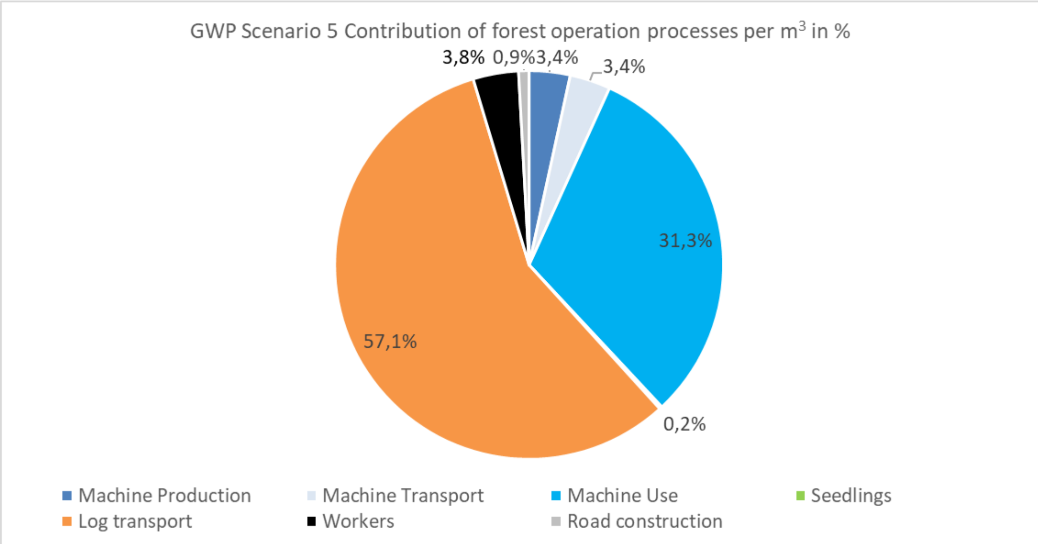


Figure 18: Contribution of forest operation processes to the global warming potential of Scenario 5. Main contributions are machine production (production of all machines used in one rotation period), transport of machines from production site to the forest, use of machine (transport of machines between forest sites, burning of fuels, use of lubricants), production and transport of seedlings, transport of logs from the forest to a sawmill, pulpmill or energy wood plant, transport of workers to and from the forest site and road construction.

The total GWP of Scenario 5 is 24.4kg CO_2-equivalents per m^3. The production of all machines used to produce 1 m^3 contributes 3.4% to the GWP, and their transport to 3.4% as well. The use of the machines makes up 31% of the impact. The production and transport of seedlings is only 0.2% of the GWP. The transport of logs is the biggest share with 57%. The transport of workers is 3.8% and the construction of roads 0.87% (Figure 18).

The transport of machines makes up a larger share in New Zealand than in Austria because they are often produced either overseas or in parts of New Zealand that are significantly further away than factories in Austria. Road construction, on the other hand, contributes less than in Austria because there are fewer roads built in New Zealand per hectare compared to Austria. Therefore, less impact from road building is allocated to one m^3. Transport of logs has a high impact in Scenario 5 because the distances are long. Therefore, reducing the impact in Scenario 5 could be done most efficiently by improving transport logistics, or by changing the fuel used.

4.3.6 Scenario 6

For Scenario 6 the contribution of the individual forest operation processes are presented in Figure 19.

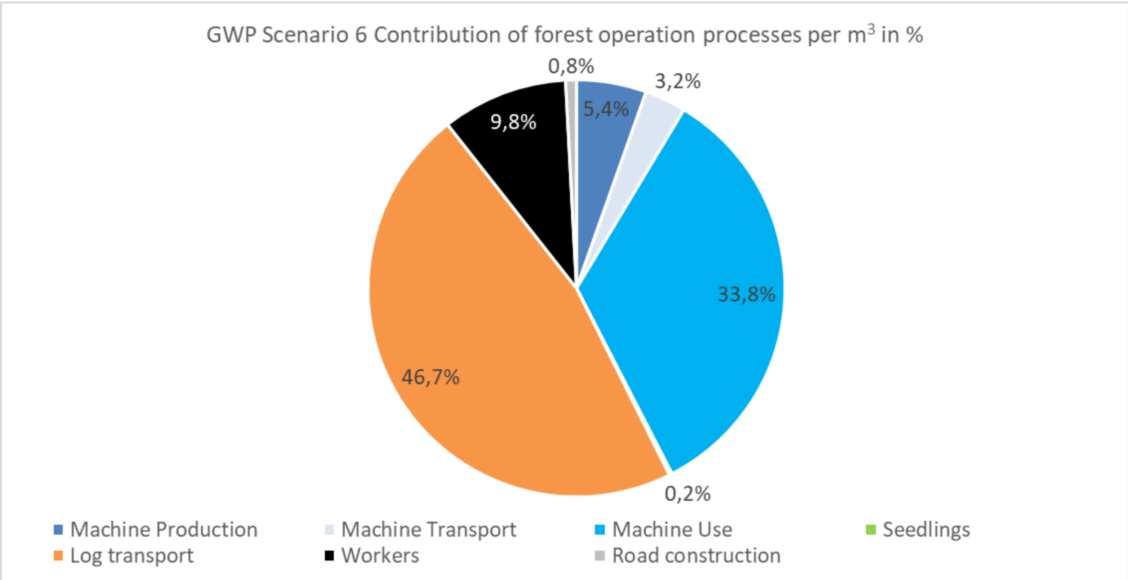


Figure 19: Contribution of forest operation processes to the global warming potential of Scenario 6. Main contributions are machine production (production of all machines used in one rotation period), transport of machines from production site to the forest, use of machine (transport of machines between forest sites, burning of fuels, use of lubricants), production and transport of seedlings, transport of logs from the forest to a sawmill, pulpmill or energy wood plant, transport of workers to and from the forest site and road construction.

The total GWP of Scenario 6 is 25.1kg CO_2-equivalents per m^3. From that the production of all machines is responsible 5.4% of the impact in Scenario 6. The transport of these machines from their factory o the forest is 3.2%. 33% of the GWP are emitted by the use of the machines, which is mostly burning of fuels. The transport of logs contributes 46% of the impact. Workers' transport is 9,7% and road construction accounts for 0.8% of the GWP in Scenario 6 (Figure 19).

Workers have the largest share in this scenario, because all operations take longer in steep terrain and because harvesting by cable yarder needs more workers. This graph shows that reductions of the environmental impact should be done in the section of machine use, or log transport. This could be done by a change of fuel, or increased efficiency.

4.4 Sensitivity Analysis

Input data and factors were tested according to their significance in the previous screening analysis. It was found that transport distance, the wood's weight, as well as machine efficiency influence the results the most. All input data was tested for its sensitivity to the result and the chapter below presents the outcome of all significant input parameters. Parameters were found significant if the result either within the stage or at the end changed by at least 5%.

4.4.1 Result Sensitivity Analysis for 'Planting'

The stage of planting entails the production of seedlings, their transport, soil preparation and planting of seedlings themselves. The sensitivity of all input parameters in the stage of 'Planting' was tested. Below all significant sensitivities are shown.

Firstly, it was tested how the results changed if the double number of seedlings needed to be planted because of loss to animals, frost, or inefficiency. 2000 seedlings are planted per hectare in Scenario 1, and 1500 in Scenario 3, and that number was increased by 1000. In New Zealand 833 seedlings are planted per hectare, and an increase of 400 was tested.

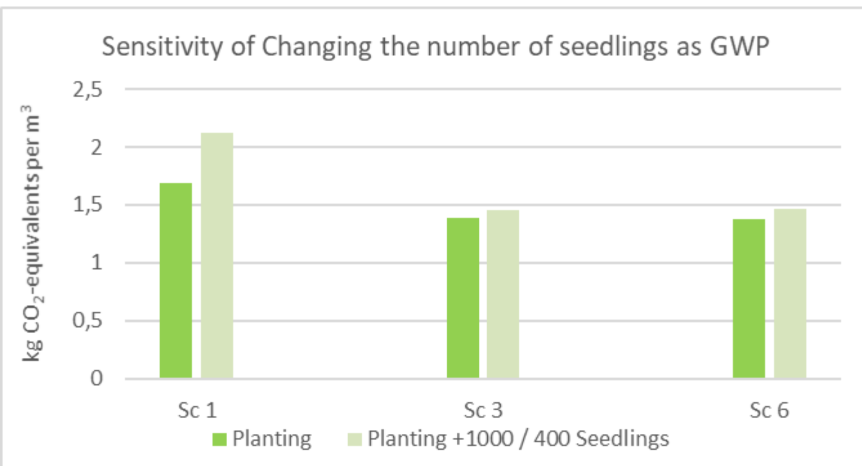


Figure 20: Sensitivity of GWP to an increase of seedlings planted per ha for the Scenarios 1, 3 and 6

Increasing the number of seedlings has a significant influence in Scenarios 1, 3 and 6. In Scenarios 2 and 4 there is no planting done, and it was assumed that natural regeneration works, and in Scenario 5 the influence is under 5% in the stage of planting. The difference is highest in Scenario 1, where it reaches 25%. This is because the seedlings are planted by a forwarder, and an increase of seedlings naturally causes an increase of working hours as well. In the other scenarios, the seedlings are planted manually which results in a GWP impact increase of 4% in Scenario 3, and 6.8% in Scenario 6 (Figure 20).

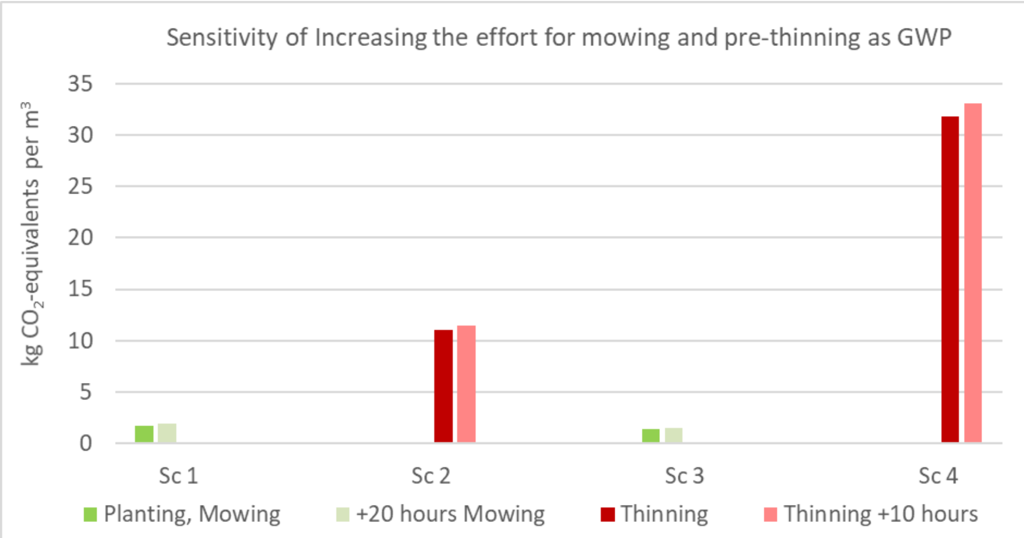


Figure 21: Sensitivity of global warming potential to an increase of time for mowing or pre-thinnings in Scenarios 1-4.

Figure 21 shows the sensitivity of the GWP to an increase of mowing or pre-thinning working hours in Scenarios 1-4. Two sensitivity tests were combined: in Scenarios 1 and 3 the increase of 20 hours of mowing time was tested, while in Scenarios 2 and 4, the number of hours for pre-thinnings was increased by 10 hours. These operations are all conducted by chainsaws, or chainsaw-like machines.

By increasing the time for mowing in Scenario 1, the GWP rises by 13%, and in Scenario 3 by 8.5% at the stage of planting. The increase of mowing by 20 hours would increase the result for the whole supply chain in Scenario 1 by 2% in the impact category GWP.

POFP on the other hand would increase by 12.5% if mowing would take 20 hours longer. This is because chainsaws emit significantly in the category of POFP. If pre-thinnings would take 10 hours longer the GWP of the stage of thinnings would increase in both scenarios by 4%. The POFP would increase by 7% in Scenario 4 and by 11% in Scenario 2. If the working hours were reduced by 10 or 20 hours respectively, the GWP would be smaller by the same amount.

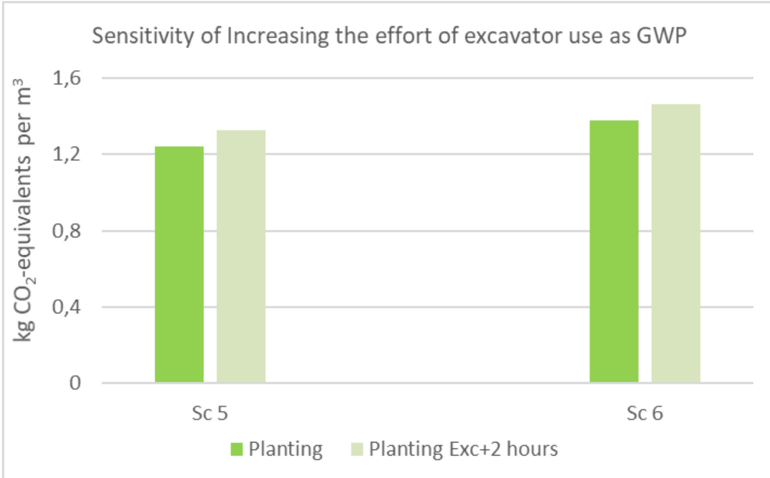


Figure 22: Sensitivity of global warming potential in Scenarios 5 and 6 to an increase of excavator time in the stage of planting.

Figure 22 shows the influence of the hours of excavator use to the global warming potential of 'planting' in New Zealand. A small excavator is used before planting for 5 hours to remove slash from the area as well as to clear the access road. If that excavator were used for 2 hours longer, the GWP would increase by 7% in Scenario 5 and 6% in Scenario 6. The influence on the result for the whole supply chain at the plant gate is under 1%.

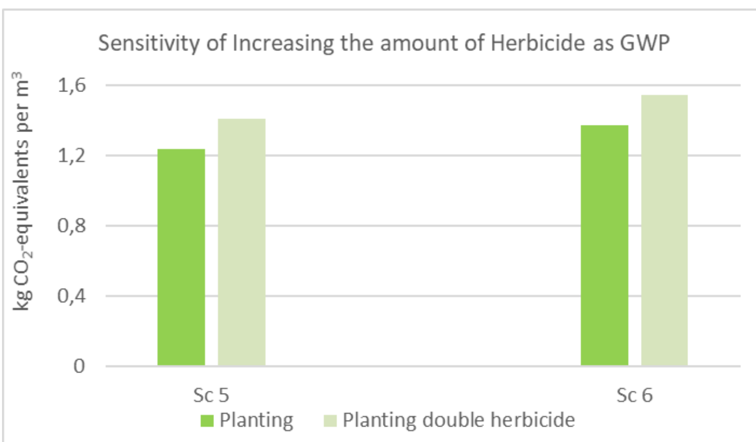


Figure 23: Sensitivity of global warming potential in Scenarios 5 and 6 to an increase of herbicides used in the stage of planting

In Scenarios 5 and 6 herbicides are used to increase growth of young trees by exterminating competing plants. Herbicides not only contribute to toxicity, but they also have a significant GWP. If double the amount of herbicide were used, the GWP would increase by 13% in the stage of planting in both scenarios (Figure 23). However, it is not significant to the result at the plant gate, because the stage of planting contributes only 11% to the overall result.

4.4.2 Results of the Sensitivity Analysis for 'Thinning'

The stage 'Thinning' entails harvesting and forest operations that are conducted before the final harvest: thinning in Austria and thinning and pruning in New Zealand. All input parameters were tested and the significant sensitivities either within in the stage or for the final result are shown below.

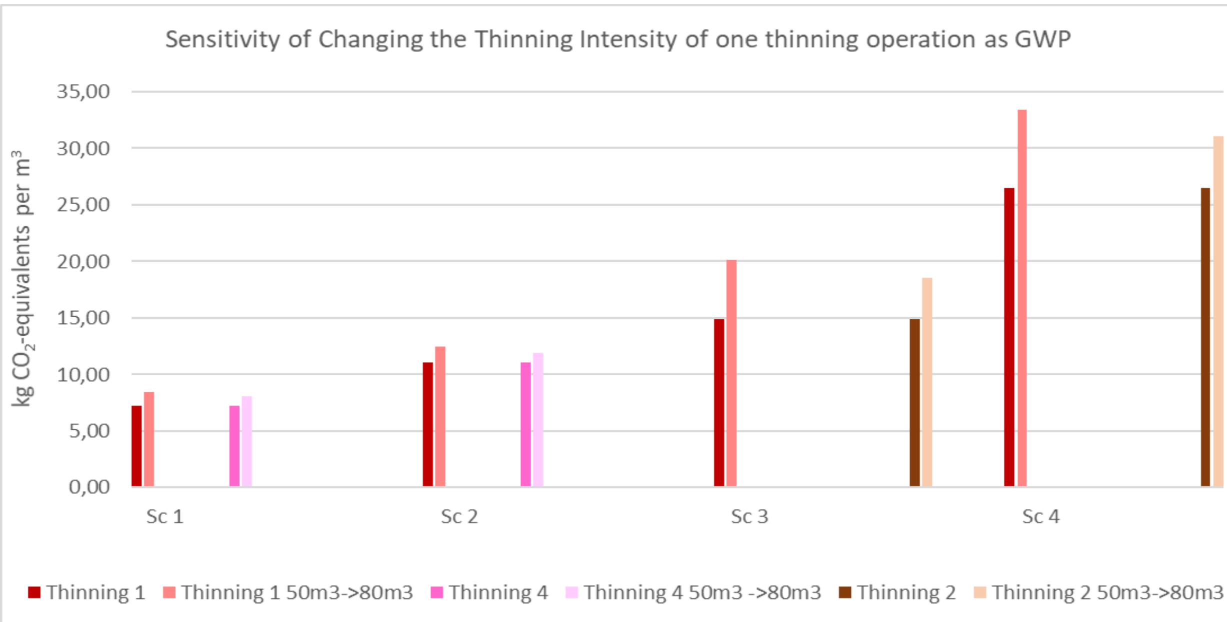


Figure 24: Sensitivity of the global warming potential in Scenarios 1-4 to an increased volume harvested in one thinning from 50m³ to 80m³.

Figure 24 shows the increase of the GWP in the stage of 'Thinning' if the volume harvested were increased from 50 m^3 to 80 m^3 in one thinning in Scenarios 1-4. For Scenarios 1 and 2 the first and fourth thinning are shown, in Scenarios 3 and 4 the first and the second. For every scenario two thinnings are shown, but their harvested volume was changed individually.

According to the forest managers of Scenarios 1-4, the average harvested volume of one thinning per hectare is between 50 m^3 and 80 m^3. For this assessment it was assumed that only 50 m^3 are harvested, so that more is extracted during the final harvest, therefore it was tested how the results would change if the harvested volume in one thinning operation was 80 m^3. The total harvested volume per hectare was assumed constant, which means that if the extracted volume during thinnings increases, it decreases during final harvesting.

In Scenarios 1 and 2 four thinnings are conducted, while in Scenarios 3 and 4 only two. For Scenarios 1 and 2 the first and fourth thinning are shown in figure 24, because the difference between thinning one and two, and three and four is smaller than between the first and last two thinnings. The highest difference is between thinning one and four, which is why those were chosen for the figure.

In Scenario 1 the increase of the GWP is in the first thinning 17%, and in the fourth thinning 12%. The later the thinnings are, the larger is the diameter, the higher is the efficiency of the machines, and the smaller is the difference between 50m^3 and 80 m^3 harvested. In Scenario 2, the GWP increase falls between 8% and 12% for the same reason. In Scenario 3, in the first thinning the GWP potential increases by 35%, and in the second thinning by 24%. In Scenario 4 the increase is 26% in the first and 17% in the second thinning. By increasing the amount harvested in thinnings, 5% less is harvested during the final harvest. That is why the influence on transport is smaller than 1%. Since the increased impact of thinnings more or less outweighs the smaller impact of final harvesting, and there is no change during transport, the result at the plant gate also changes only minimally. This means that if the total harvested volume per hectare is constant, it does not matter at which point in the rotation period it is extracted.

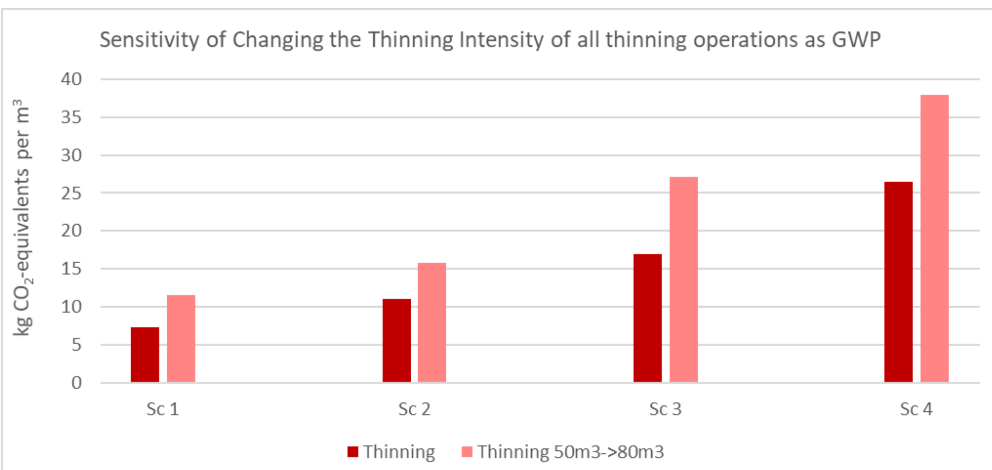


Figure 25: Sensitivity of the global warming potential in Scenarios 1-4 to an increased extraction volume during all thinning operations . The increase is from 50 m^3 to 80 m^3 per ha.

Figure 25 shows the sensitivity of the stage of ‘Thinning’ if both or all thinnings extract 80 m^3 instead of 50 m^3. In Scenarios 1 and 3 the GWP increases by 60%, in Scenario 2 by 43% and in Scenario 4 by 47.5%. By increasing the amount extracted during thinnings, the volume and therefore the impact of final harvest decreases by 20% in Scenarios 1 and 2 and by 10% and in Scenarios 3 and 4.

This difference of the impact of harvest occurs because in Scenarios 1 and 2 there are four thinnings and Scenarios 3 and 4 only two. Like in the sensitivity test above, the impact of transport stays the same and also the result at the gate. That means that from an environmental point of view, it does not matter how much is extracted during thinnings if the total biomass stays the same and the ratio of extraction between thinnings and harvests can vary without changing the result. It was not considered that the yield might change with changing the harvested volume during thinnings.

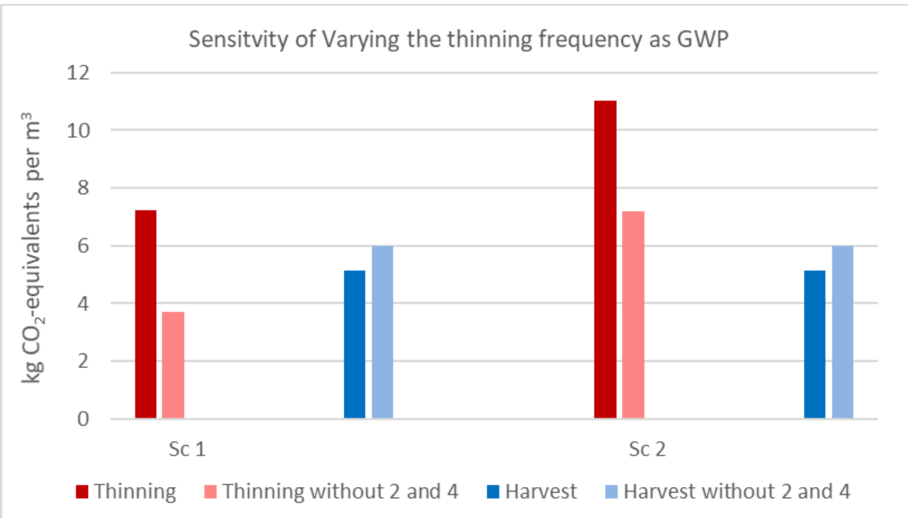


Figure 26: Sensitivity of global warming potential to a decrease of numbers of thinnings in Scenarios 1 and 2. Instead of 4 thinnings only 2 are conducted, in each 50 m^3 are extracted and the volume for final harvesting increases.

Figure 26 shows the influence of a reduction of the number of thinnings on the global warming potential of 'thinning' as well as the influence on 'final harvest'.

In Scenarios 1 and 2 there are 4 thinnings, in Scenarios 3 and 4 there are only two. It was therefore tested what would happen if in Scenarios 1 and 2 there were only two thinnings like in Scenarios 3 and 4. The total volume of harvested wood per hectare remains the same, which means that more m^3 have to be harvested in the end. The amount extracted per thinning remained 50 m^3 and the amount harvested in the final cut is increased to 700 m^3, instead of 600 m^3.

In Scenario 1 the GWP of thinning would decrease by 48.5%, but that of final harvest would increase by 16.6%. In Scenario 2 the GWP would decrease by 34.6%, and final harvest would also increase by 16.6%. Since harvest comprises a larger share of the overall result, leaving out two thinnings would not change the result of the supply chain significantly they would only change by 2.5% in Scenario 1 and 4% in Scenario 2. This proves again that the amount extracted during thinnings makes no difference if the total biomass stays the same.

Economically it would make sense to conduct fewer thinnings, and harvest more with a higher value in the end. However, there is a possibility that the trees may grow slower with fewer thinnings.

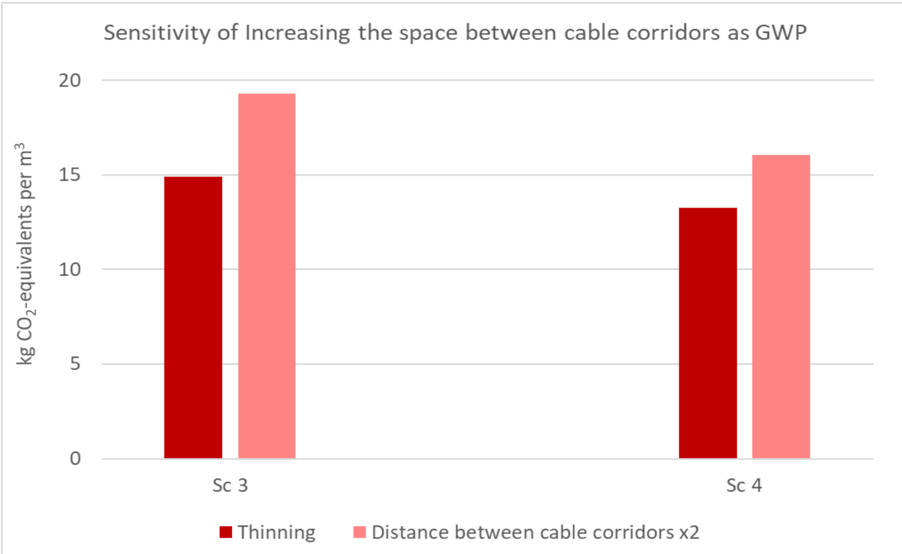


Figure 27: Sensitivity of global warming potential to an increase of the lateral yarding distance to the doubled distance in Scenarios 3 and 4.

The logs have to be pulled by the cable yarder until they are arranged under the cable corridor, from where they are extracted uphill. It was assumed that the lateral yarding distance is 16.6m in Scenario 3 and 12.5m in Scenario 4 because that is the average distance between the trees and the main line. If the lateral yarding distance would be doubled, the productivity of the yarder would decline significantly. This results in the increase of the GWP in the stage of thinning by 29.7% in Scenario 3, and by 21% in Scenario 4 (Figure 27).

This means that it might be better to set up the cable yarder more often to decrease the lateral yarding distance, but to increase efficiency. However, that depends on the time needed for mounting the cable yarder, compared to the increase of efficiency. The lateral yarding distance only has an influence in the stage of thinning because it is not part of the formula of the cable yarder for final harvesting (Chapter 3.6.4).

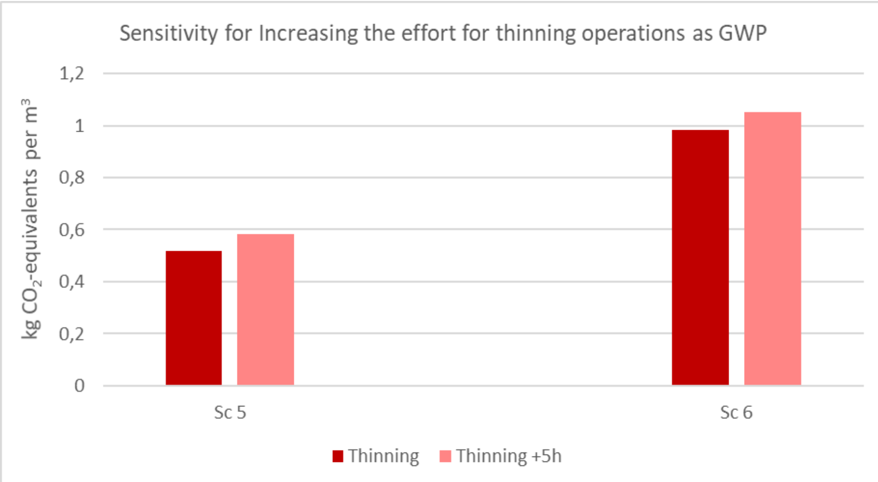


Figure 28: Sensitivity of global warming potential to an increase of thinning working hours in Scenarios 5 and 6.

If thinnings were conducted less efficiently and would thus take 5 hours longer in New Zealand, the GWP would increase by 13% in Scenario 5 and by 6.7% in Scenario 6 respectively. The working hours for thinnings are significant, but do not alter the overall result (Figure 28).

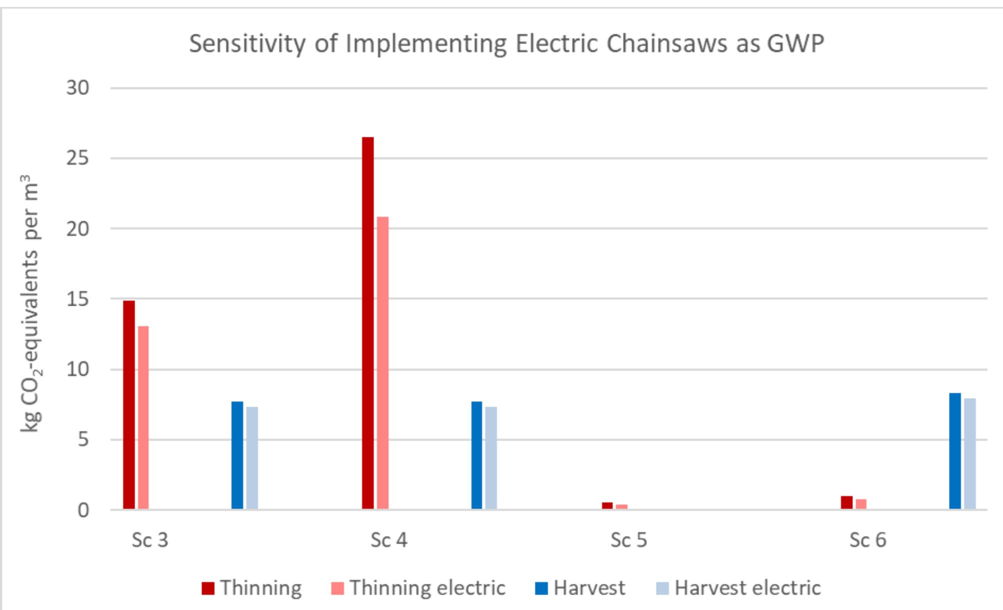


Figure 29: Sensitivity of global warming potential to a change from gasoline fueled chainsaws to electric chainsaws, in Scenarios 3-6, for stages final harvest and thinning.

Figure 29 shows the sensitivity of the stages 'thinning' and 'harvest' if electric chainsaws were used instead of standard fuel chainsaws, in Scenarios 3-6. Since electric chainsaws are used with exceeding frequency, and the trend will most likely continue in the future, testing their influence is of considerable interest (Kühmaier *et al.*, 2019).

In Scenario 3, the GWP would decrease by 12.46% in the stage of thinning, while the FEP would decrease by 49% and the POFP by 39.5%. In the stage of final harvesting the GWP would decrease by 4.7% and the POFP by 17.5%. In Scenario 4 the GWP would decrease by 21.4% in the stage of thinning and by 4.3% in the stage of final harvest. In Scenario 5 the GWP of 'thinning' would decrease by 24.7%, but there is no influence on final harvest because logging and processing is not done by chainsaw in this scenario. In Scenario 6 the GWP of 'thinning' would decrease by 25.9% and of 'harvest' by 4.5%. This means that using electric chainsaws instead of fuel chainsaws could improve the environmental impact of forestry substantially, especially in the category of FEP and POFP.

4.4.3 Result Sensitivity Analysis for 'Final Harvest'

Final Harvest entails site preparation, cutting, topping, delimbing of trees, as well as logging them to a place where the logs are loaded onto trucks. This stage is the highest or second highest contributor to the environmental impact of forest operations. In this section the sensitivities of all significant input parameters of final harvest operations are shown.

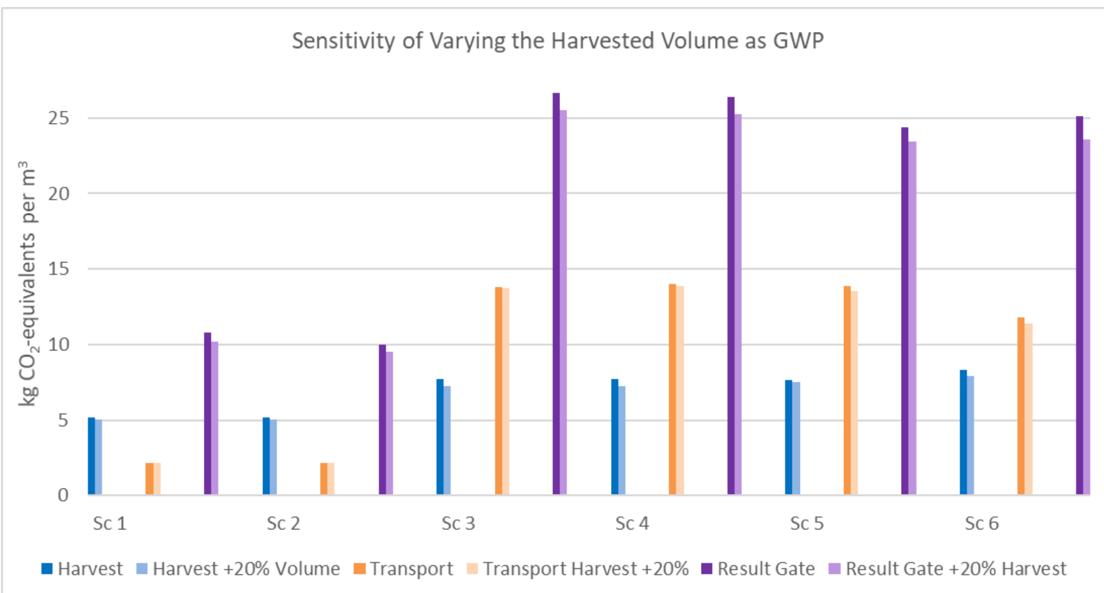


Figure 30: Sensitivity of global warming potential to an increase of harvested volume by 20%, in all scenarios. The affected stages harvest, transport, are shown and the influence on the supply chain at the gate.

Figure 30 shows the influence of an increase of the harvested volume on the global warming potential of harvest, transport, and the overall result. It was tested how the GWP changes if the harvested volume increased because of good weather, soil or other growth enhancing conditions. This resulted in a total harvested volume of 720 m^3 instead of 600 m^3, which means that the impact is divided by 720 m^3.

In Scenario 1 the GWP of harvesting would decrease by 2.7%, while the impact of transport would decrease by 0.24% and the overall result at the gate by 5.3%. The result for Scenario 2 is similar to Scenario 1. In Scenario 3 and 4 this increase in harvested volume would mean a decreased impact of 5.7% during harvest, 0.18% during transport and 4.4% in the overall result. Better conditions would decrease the environmental impact of the harvesting process by 1.6% in Scenario 5 and 6. Transport would also decrease by 2.6%, and the GWP at the plant gate by 4% in Scenario 5 and by 6.2% in Scenario 6. The impact does not change that much in most cases, because if the harvested volume is increased, the input of machines and transport increases as well.

Figures 32 and 33 show the sensitivity of the result of 'final harvest' to varying the productivity of the harvesting machinery. In both figures 'harvest' represents the unchanged result, and each bar to the right of 'harvest' is the result with the changed productivity of that machine. The productivity of machines was identified as an essential parameter for the impact and efficiency of forest operations, and therefore their sensitivity was tested. The productivities of the machines were given by the expert and those values were used for the impact assessment. There are various studies that examined the productivity of similar machines, and it was tested how the results changed if the machines in the present study had the productivities of the machines in those studies. This demonstrates the importance of efficiency in harvesting operations, the importance of data accuracy, as well as possibilities for improvement.

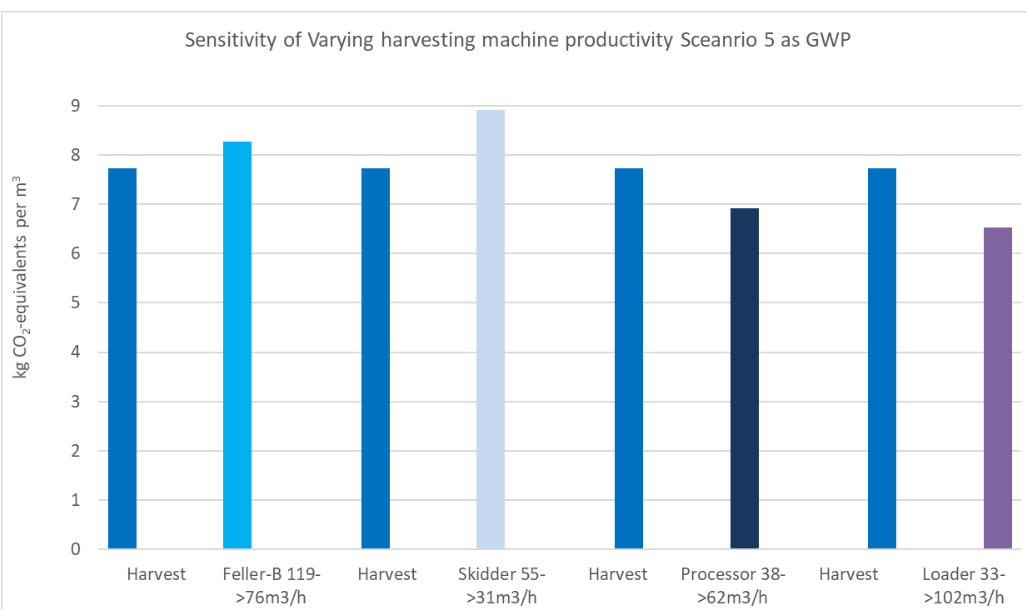


Figure 31: Sensitivity of global warming potential to changed productivities of harvesting machines. Each left bar is the value for harvesting, with the productivity unchanged. Each right bar is the value for harvesting with a changed productivity. The first tested productivity is feller-buncher, then skidder, processor, and loader.

In figure 32 for Scenario 5 the productivity of the feller buncher was calculated from a formula in a study from Bilici *et al*. (2019), and the average of best-case and worst-case outcomes were used for the calculations. For the sensitivity test the worst-case result was taken, which is 76 m^3/hour instead of 119 m^3/hour. This decrease in efficiency would increase the GWP by 7%.

For the skidder's productivity the formula from Gurdet (2008) proposes a productivity of 31 m^3/hour, which is significantly smaller than the 55 m^3/hour suggested by the expert in New Zealand. That change of productivity would result in a GWP increase of 15.3% and the result at the plant gate would also increase by 5%.

The productivity of the processor was increased from 38 m^3/hour to 62 m^3/h. The 62 m^3/hour derive from a dissertation by Berry (2019) where 62 m^3/hour is given as the average productivity of a processor. This increase in productivity would result in a GWP reduced by 9.4%.

The loader's productivity is according to the expert 38 m^3/hour, but Akay *et al*. (2020) calculated an average productivity of 102 m^3/hour. If the productivity was indeed increased to 102 m^3/hour, the GWP would decrease by 14%.

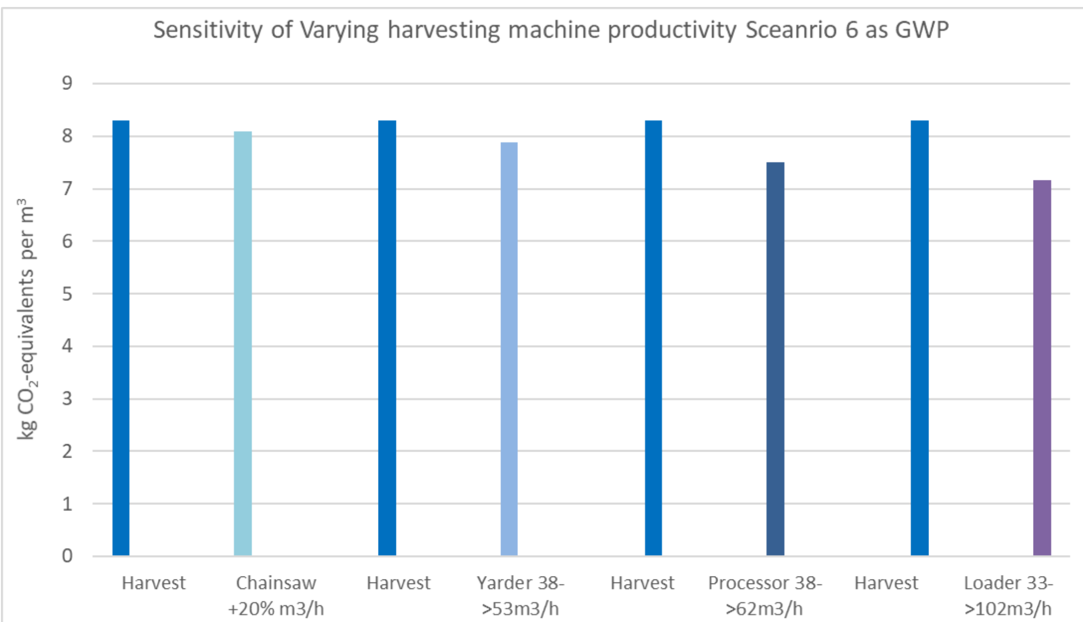


Figure 32: Sensitivity of global warming potential to changed productivities of harvesting machines. Each left bar is the value for harvesting, with the productivity unchanged. Each right bar is the value for harvesting with a changed productivity. The tested machines are chainsaw, cable yarder, processor, and loader.

For Scenario 6 the productivities of a chainsaw, the cable yarder, as well as processor and loader were tested. Increasing the productivity of the chainsaw by 20% in Scenario 6 would result in a decrease of the GWP by 2.6% and of the POFP by 10.5%. After the trees are cut by chainsaws, they are logged by a cable yarder, whose productivity was given by the expert as 38.8 m^3/hour.

In a survey by Holmes *et al*. (2017) the average productivity was assessed for a cable yarder as 53 m^3/hour. This increase in productivity would result in a 5% reduction in GWP per m^3.

The productivity of the processor was increased like in figure 32 from 38 m^3/hour (according to the expert) to 62 m^3/hour (Berry, 2019). This increase in productivity would result in a GWP reduced by 10%. The loader's productivity was also increased from 38 m^3/hour to 102 m^3/hour, which results in a decrease of the GWP by 13%.

Increasing the productivity of harvesting machines, or changing the assumptions of their productivity, would decrease the GWP in the stage of harvesting, but in most cases the result of the supply chain would not change a lot Even though it may not be realistic to compare the productivity of different machines under different conditions, it is important to assess the influence on the environmental impact of the supply chain.

4.4.4 Results Sensitivity Analysis for 'Transport'

'Transport' entails transporting the logs to the sawmill, pulpmill, and energy wood plant. The impact of this stage depends highly on the transport distance. In this section all significant sensitivity tests of this stage are shown that were found to change the result by more than 5%.

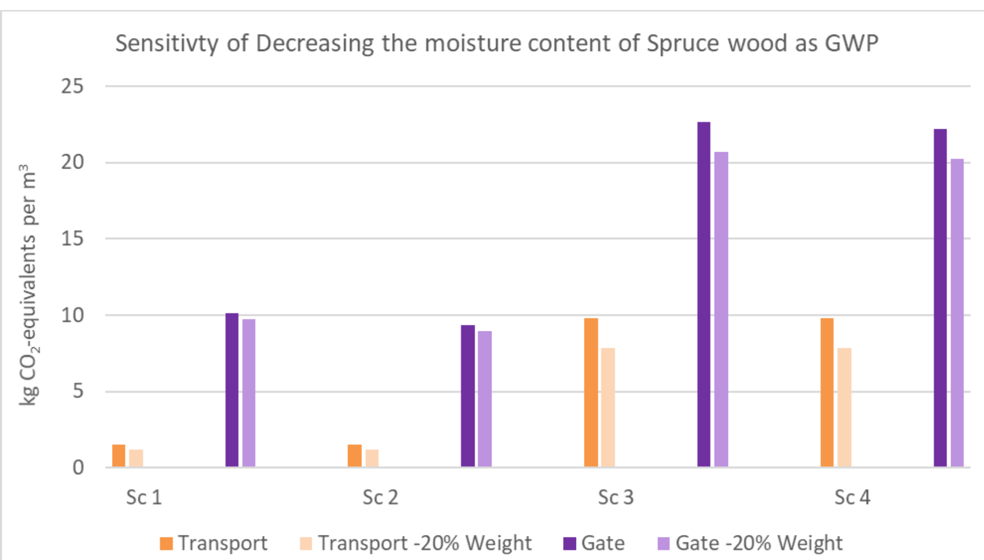


Figure 33: Sensitivity of global warming potential on a decrease of spruce weight per m^3 by 20% in Scenarios 1-4, and the influence on transport and the result for the supply chain at the gate.

Figure 34 shows the influence of the weight of spruce on the global warming potential of transport and the result for the supply chain at the gate. The weight of spruce varies highly, depending mostly on moisture content. Therefore, there is no agreed-upon average weight of green wood. Thus, the weight was assumed to be 950 kg per m^3. If 1 m^3 were 20% lighter, the GWP of transport would decrease by 20%. In Scenarios 1 and 2 the result at the plant gate would decrease by 4.5%. In those two scenarios, the weight not only influences transport, but also harvest by 2% because forwarders are also limited by weight. In Scenarios 3 and 4 the end result would decrease by 8.6%. Even though the cable yarder in Scenarios 3 and 4 is not limited by weight but by diameter, the influence is more significant in those scenarios because the transport distances are longer and therefore the share of transport of the final result is larger.

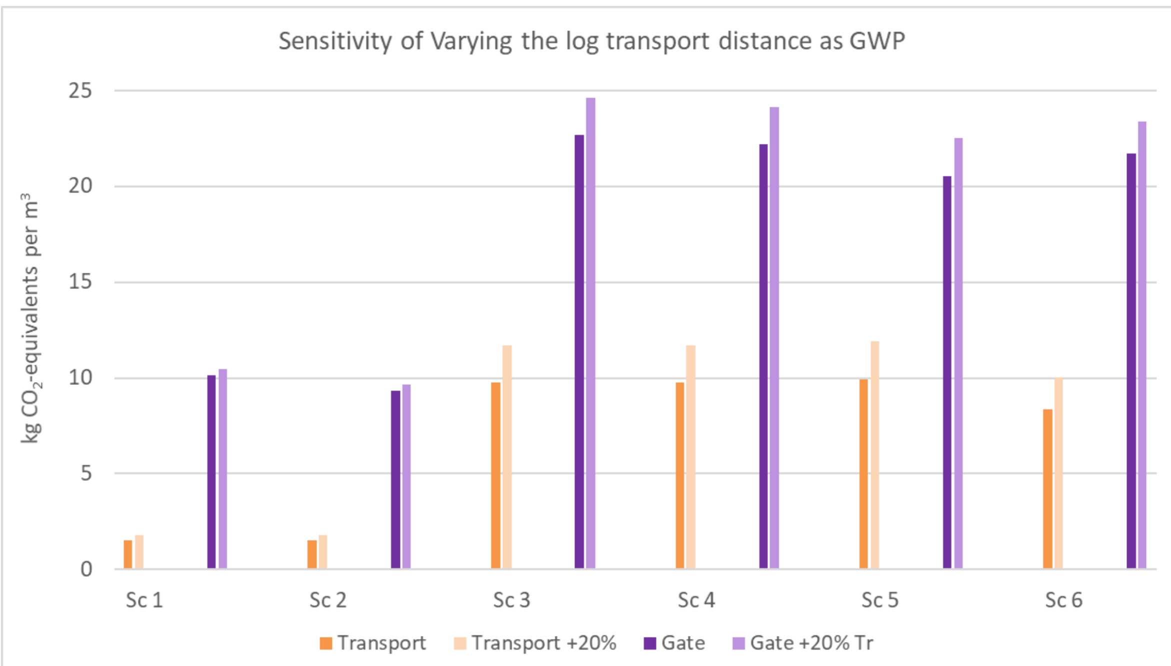


Figure 34: Sensitivity of global warming potential to increase of transport distances by 20% in Scenarios 1-6.

If the transport distance is increased by 20%, the GWP in the stage of transport rises by 20% in all scenarios. In Scenarios 1 and 2 this increase is not significant for the end result, because the transport distances are short. In the other scenarios, on the other hand, the transport distance has a significant influence. In Scenario 3 the GWP increases at the gate by 8.6%, in Scenario 4 by 8.8%, in Scenario 5 by 9.6%, and in Scenario 6 by 7.7%. This means that by planning and an increased efficiency in the transport chain the GWP could be reduced (Figure 35).

Normalization of transport distances of forest operations and log transport

Figure 36 shows what the result would look like if the transport distances of machinery, workers, and log transport were the same in all scenarios. This is a normalization rather than a sensitivity test. It was conducted to demonstrate the importance of transport distance on the logs' transport, as well as on the stages of harvesting and workers' transport.

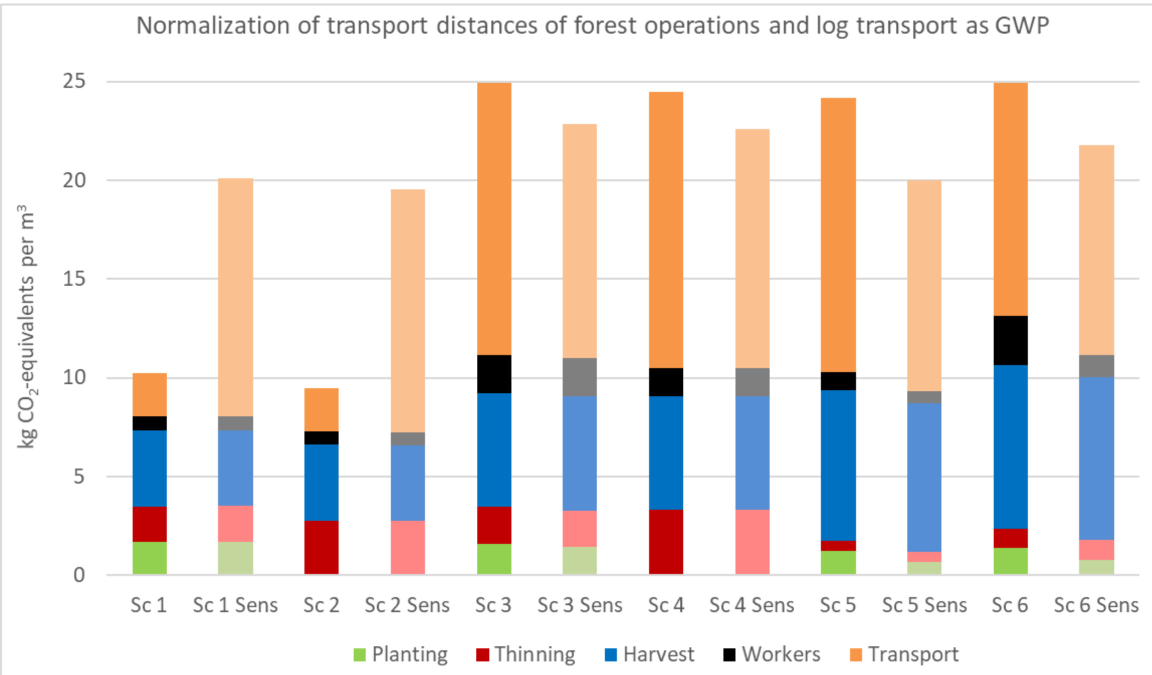


Figure 35: Normalization of transport distances in all stages for all scenarios. In bright colors are the results from before, and in dim colors the changed results.

It is shown that Scenarios 1 and 2 would have a significantly larger impact than before. Scenario 2 still has the smallest impact, but the difference is no longer as substantial. Also, Scenario 5 would have the same environmental impact as Scenario 1. It was also found that changing the transport distances of the machinery from their production site to the forest, had little influence. Transport of the seedlings, on the other hand has a larger influence on the stage of planting. If workers drove the same distance in New Zealand as in Austria, their impact would decrease by 32%.

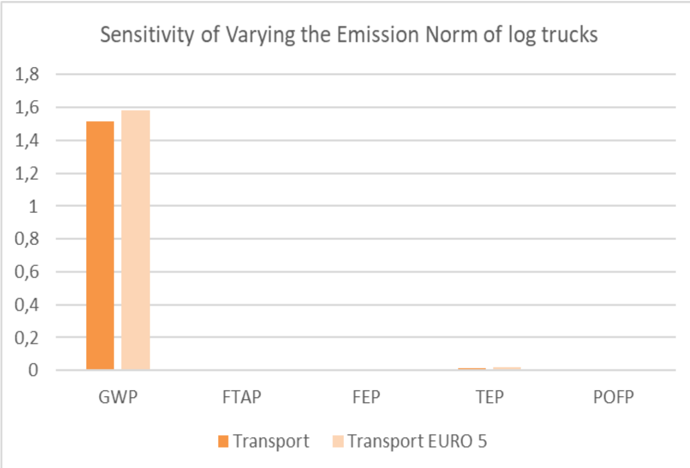


Figure 36: Sensitivity of all impact categories to a change of emission norm of timber trucks from EURO 6 to EURO 5 in total numbers

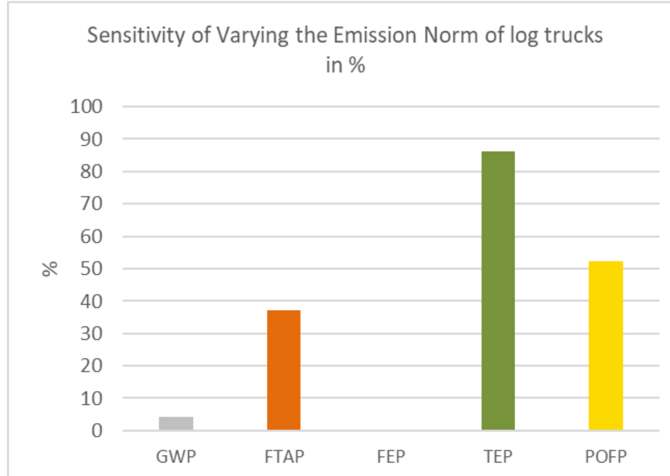


Figure 37: Sensitivity of all impact categories to a change of emission norm of timber trucks from EURO 6 to EURO 5 in %

It was assumed that the log trucks in this study are new and have the highest emission standard, EURO 6. Figure 37 and figure 38 show how the impact of transport would change if EURO 5 trucks were used instead. Figure 37 shows the increase of emissions in absolute numbers as kg equivalents per m^3 with the EURO 6 scenario on the left and the changed EURO 5 scenario on the right for all impact categories. Figure 38 demonstrates the effect of changing the emission standard in % compared to the previous emission standard, for all impact categories. The GWP changes by 4.3% in this impact category. The other categories are small compared to GWP, but they change significantly with the use of older log trucks: FTAP increases by 37%, and TEP by 86.3%. POFP also increases by 52%. This means that the use of new log trucks is recommended.

For all other input factors and parameters, their sensitivity was not found significant. The sensitivity analysis showed that contrary to expectations the use of helicopters and herbicide had little or no influence on the result in the chosen impact categories. Also, it was found that as long as the total harvested volume per hectare stays the same it does not matter at which point in the rotation period it is extracted. The lateral yarding distance was found to have an unexpectedly large influence on the productivity of the cable yarders and therefore also on the result. Changing fueled to electric chainsaws would decrease the environmental impact significantly. The productivity was found to have a considerable impact on the result. Lastly, the transport distance is the most crucial factor, and the emission norm was found to have a large impact on the result especially for TEP, and POFP.

5. Discussion

In this study a life cycle assessment of forest operations in Austria compared to New Zealand was conducted. The environmental impact of 1 m^3 of wood that is produced and transported to a sawmill, pulpmill or energy plant is assessed. In this chapter, firstly, the key results of the study are discussed. Then, the results are compared with the results from other studies and with Ecoinvent, followed by an evaluation of the influence of forest operations on soil, water, and biodiversity, and lastly a discussion of shortcomings of the study.

5.1 Discussion of Key Results

In this study seven key results were found. The first one is that forest operations have an environmental impact, with a global warming potential (GWP) between 10 and 26kg CO_2-equivalents per m^3. Secondly, it was found that not only GWP, but also at other impact categories like acidification, eutrophication, and photochemical oxidant formation are connected to and impacted by forest management. Thirdly, all forest operations should be considered when assessing forestry, opposed to studies that start their assessment with final harvesting because planting and thinning processes contribute up to 40% of the impact at the plant gate. Also, it was found that even though New Zealand's system is more intensive, its environmental impact was not higher than in Austria. Moreover, timber harvesting in steep terrain has a higher impact than ground-based harvesting. It was also found that silvicultural systems with natural regeneration have a significant impact which is as high or higher than clear-cuts where the seedlings are planted. Lastly, the transport distance was found to be the most crucial factor for the impact of the production of sawlogs, pulpwood or energy wood.

5.1.1 Difference Forest Operation on Slopes, Silvicultural Systems and Regeneration

Scenarios 1 and 2 in Austria represent forest operations in flat terrain, Scenarios 3 and 4 Austrian forestry in steep terrain. Scenario 5 in New Zealand represents flat terrain and Scenario 6 in steep terrain.

Firstly, the influence of slope is discussed. For Austria it was found that the GWP of thinnings is twice as high in steep terrain as in flat terrain, final harvesting has a 44% higher GWP in Scenarios 3 and 4, than in 1 and 2. In New Zealand the difference between the terrains is smaller than in Austria. In Scenario 5 the GWP of thinning is 45% smaller than in Scenario 6, and harvesting has a 29% smaller GWP. The difference between the slopes results from a smaller productivity in steep terrain, as well as different machinery that is used.

Cable yarders have a higher fuel use than ground-based machines, which results in an 83% higher GWP than forwarders and chainsaws have a 21% smaller GWP per m^3 than harvesters. The harvesting scheme has an influence on the results of thinnings in Austria. In Scenarios 1 and 3 the trees are harvested by clearcutting whereas in Scenarios 2 and 4 a patch-cut is applied. This results in an 8% higher GWP during thinnings in Scenario 2 compared to Scenario 1 and an 22% higher GWP in Scenario 4 compared to Scenario 3. The GWP is higher in Scenarios 2 and 4 because the tree diameters are smaller, because the tree age is mixed and therefore on average five years younger with an accordingly smaller diameter.

Lastly, the difference between natural regeneration and planting is discussed. With a different harvesting-scheme the forest either regenerates naturally (Scenarios 2 and 4), or it is planted (Scenarios 1 and 3). In Scenario 3 the GWP of planting is 33% higher than pre-thinnings in Scenario 4. In Scenario 1 the impact of planting has double the GWP as the pre-thinnings conducted in Scenario 2. The difference between the forms of regeneration is similar in the other impact categories. This means that planting does have a higher impact than natural regeneration. However, the impact increases with patch-cut compared to clearcutting. Therefore, a clear-cut in flat terrain with natural regeneration would have the smallest impact.

5.1.2 Significance of the Global Warming Potential Impact of Forestry

In this study it was found that forest operations have an environmental impact. Planting, thinning, harvesting, transport, and workers contribute to the GWP between 10 and 26 kg CO_2-equivalents per m^3. Compared to other materials, this number is small, but if that value were extrapolated for all of Austria, the GWP for the 18 million m^3 of wood that are harvested every year, (proHolz Austria, 2013b) would account for 180 million to 468 million kg of CO_2-equivalents. On the other hand, wood still has a small impact compared to any other product or material that could substitute wood. In this study 1 m^3 of wood was assumed to have a weight of 950 kg (spruce wood) or 1 ton (radiata pine wood), but if the wood were dry it would have about 430 kg (Ecoinvent, 2012m) or 490 kg (Ecoinvent, 2012l) respectively. This results in a value of 0.023 to 0.06 kg CO_2/kg wood. For comparison 1 kg of forging steel has a GWP of 1.04 kg CO_2-equivalents (Ecoinvent, 2011b), 1kg of concrete block has a GWP of 0.14 kg CO_2-equivalents (Ecoinvent, 2011a) and 1kg of non-recycled polyethylene has a GWP of 2.5kg CO_{2w}-equivalents (Ecoinvent, 2011f).

This study calculated a total GWP of 9 to 13 kg CO_2-equivalents per m^3 at the forest road, which is similar to some studies. Klein *et al*. (2015) determined an average of 14.3kg CO_2-equivalents per m^3 at the forest road from all 26 studies they reviewed with a standard deviation of +/- 10.7kg CO_2-equivalents per m^3. The differing numbers between their review and the present study result from more energy intensive stand establishment and thinning operations than in the present study.

A study by González-García, Bonnesoeur, *et al.* (2013) assessed a similar GWP to the present study, of 9.5 kg CO_2-equivalents per m^3 at the forest road for an extensive scenario. They studied Douglas-fir production in France and extensive forest management entailed no fertilization and about the same rotation length as in the present study. The intensive scenario had a GWP of 23 kg CO_2-equivalents per m^3 at the forest road, which is higher than the result in the present study where transport is included. Both scenarios in their study are more intensive than the present study because they included soil scarification and at least five thinning operations, both of which are not applied with that intensity in Austria nor in New Zealand.

A different study by González-García *et al*. (2013b) about Douglas-fir production in Germany calculated a GWP of 2.35kg CO_2-equivalents per m^3 in an intensive scenario. Since in their study 2200 m^3 are harvested per hectare, the GWP of their study was normalized to 7.4 kg CO_2-equivalents per m^3, which is still significantly smaller than the 9 to 13 kg CO_2-equivalents per m^3 in the present study. They used different harvesting machines, which results in those smaller numbers.

The impact of forest operations were found to have a GWP of 10 to 26 kg CO_2-equivalents per m^3 at the gate in the present study and forest operations in steep terrain have a GWP of 25 to 26.6 kg CO_2-equivalents per m^3. Valente *et al*. (2011a) calculated in a study about Norwegian biomass supply in mountain areas a GWP of 17.6kg kg CO_2-equivalents per m^3 at the 'terminal'. This number is significantly smaller than that of forest operations in mountainous areas in the present study. They, however, did not consider thinning operations and the machines used in their study are harvester and forwarder, which have smaller emissions than cable yarders in the present study.

Dias and Arroja (2012) examined maritime pine and eucalyptus plantations in Portugal and found a GWP of 12.2 kg CO_2-equivalents per m^3 at the forest road for maritime pine. This value is similar to Scenarios 3-6 at the forest road for which the values are between 10.5 and 13.3 kg CO_2-equivalents per m^3.

This study found that forest operations have an environmental impact, but they are small compared to all succeeding processing steps. For example, a study from Laschi *et al*. (2016) called “Environmental performance of wood pellets' production through life cycle analysis” found that all operations conducted in the forest are only 1.4% of the impact, compared to 2% by transport and 96% by pellet production. Pellets is only one of the applications of wood, but for almost every form of wood processing it is dried which uses a significant amount of energy. Because all further processing steps are more energy and resources intensive than forest operations, they are often not considered in studies about wood use and processing.

This study and studies about forest operations can only assess the small part of anthropogenic interventions, and not the far more diverse and complex natural interactions of a forest ecosystem. Also, forest operations have a smaller impact than providing similar building or fuel materials, and than the rest of the production chain. However, it is still important to assess forest operations, because with the mass of wood harvested in Austria and in New Zealand the impact adds up. Lastly, in order to tackle climate-change the actual effects of forest operations need to be assessed.

5.1.3 Significance of Impact Categories Beside GWP

It was found in this study that even though GWP had the highest values, other impact categories were also found to be significant and had different sensitivities to different input parameters. However, in many life cycle assessment studies about forestry, global warming potential is the only impact category that is assessed because it is in most studies the impact category with the highest numbers (Pyörälä *et al*., 2012; White *et al*., 2005; Saud *et al*., 2013; Sonne, 2006 and Kilpeläinen *et al*., 2011). Additionally, climate change is the most discussed and for many the most pressing global issue at the moment (Klein *et al.*, 2015). However, there are a range of other impact categories that are also important and damaging to the environment which are often not considered. In this study freshwater and terrestrial acidification potential, freshwater eutrophication potential, terrestrial eutrophication potential, and photochemical ozone formation potential were assessed. The impact categories were recommended by Klein *et al*. (2015), and they were also used by Michelsen *et al*. (2008), Dias and Arroja (2012), González-García, Krowas, *et al.* (2013) and González-García, Bonnesoeur, *et al.* (2013). These papers not only were found to use the same impact categories as the present study, but they also had similar results in most of those categories.

Dias and Arroja (2012) calculated an acidification potential of 0.07 kg SO_2-equivalents per m^3, which is higher than the 0.04 to 0.06 kg SO_2-equivalents per m^3 in the present study.

Their value for the eutrophication potential of 0.03 kg PO_4-equivalents per m^3 lies between the freshwater-and the terrestrial eutrophication potential in the present study of 0.002 and 0.16 kg PO_4-equivalents per m^3.

González-García *et al*. (2013a) calculated an acidification potential (AP) per m^3 in their study of 0.058 kg SO_2-equivalents per m^3 in the extensive scenario and 0.133 kg SO_2-equivalents per m^3 in the intensive scenario. In González-García *et al*. (2013b), they found a similar AP to the extensive scenario of 0.047 kg SO_2-equivalents per m^3. The FEP is in González-García *et al*. (2013a) 0.003 kg PO_4-equivalents per m^3 , which is the same as in the present study. In González-García *et al*. (2013b) the FEP is 0.023 kg PO_4-equivalents per m^3, this is mainly due to fertilization. The POFP is in González-García *et al*. (2013a) 0.1 kg NMVOC per m^3 and in González-García *et al*. (2013b) 0.078 kg NMVOC per m^3, both are similar to the values in the present study which are between 0.07 and 0.16 kg NMVOC per m^3.

5.1.4 Importance of Considering all Forest Operations

The aim of a LCA is to assess the full life cycle of a product. This study examines only the production of a raw material, but it considers all aspects until the factory gate. Starting the assessment with final harvesting would mean disregarding between 15% and 40% of the environmental impact. However, there are a range of studies that started their assessment at the “extraction of raw materials”, i. e. at the stage of harvesting. Examples for those studies are: Laschi *et al*. (2016), Gonzales-Garcia *et al*. (2014), White *et al*. (2005) and Engel *et al*. (2012). The reason why stand establishment, tending and thinnings are often not considered is mostly lack of data and because harvest operations usually emit significantly more than all other operations (González-García *et al*., 2013b; England *et al*., 2013; Ferro *et al*., 2018 and González-García *et al*., 2009). It is however important to note that if fertilizers and herbicides are applied there is a significant contribution to eutrophication and acidification potential (Gonzales-Garcia *et al*., 2014; Ferro *et al*., 2018; González-García *et al*., 2009 and Gonzales-Garcia *et al*., 2014). All of these impacts would not be considered if the assessment started with the extraction of raw materials.

According to the ISO-14040 norm it would be best to assess every product from raw materials to its disposal. However, this is not possible in many cases because the assessment becomes complex, and the data availability becomes smaller the more processing steps a product goes through. Even more complex are the phases of consumption and disposal.

5.1.5 New Zealand's Forest Operations have the Same Impact as Austria's

At the beginning of the assessment, it was assumed that the system in New Zealand has a higher environmental impact because of large-scale clearcuttings, herbicide sprayings by helicopter, heavy machinery, and rather short rotations. However, within the scope of this study, New Zealand's forestry was found to have the same and even slightly smaller impact values than forest operations in steep terrain in Austria.

It was found that the transport distances are similar, as was the amount harvested in one rotation, as well as the fuel use of machinery. In the categories that were chosen for the assessment the scale of a clearcutting has no effect on the results. Also, while helicopters have a high environmental impact, their overall impact is low, since spraying one hectare takes only around 1 minute. Moreover, the heavy machinery plays a major role for the environmental impact, but that is the case for Austria as well. Since plantations in New Zealand have not been established for a long time, there are no long-term effects yet. The impact of plantations over the next 100 years is not known and difficult to estimate. Additionally, it is important to mention that impacts such as biodiversity depletion or erosion were not considered in the assessment. There are no studies that assess the environmental impact of forestry in New Zealand yet (Engelbrecht *et al.*, 2018).

There is a study conducted by England *et al*. (2013) about the carbon sequestration and emissions from Australian softwood plantations. They calculated a total GWP of 25.86kg CO_2-e per m^3. This number is similar to Scenarios 3-6. However,20% of the impact derives from fire management and slash burning and if those 20% are subtracted the impact would be 20.68kg CO_2-e/m^3, which is the same as the average of all scenarios in the present study.

5.1.6 Steep-Terrain Harvesting has a Higher Impact than Flat-Terrain Operations

Timber harvesting in mountain forests was found to have a higher impact than ground-based harvesting in flat terrain. This comparison has not been done in other studies. However, Proto *et al*. (2017) and Sonne (2006) found that a cable yarder has higher emissions and a larger environmental impact than a tractor with a winch or a skidder. Mountain harvesting has a higher impact because it is less efficient, because tree diameters are smaller, working conditions are more difficult and therefore and every step takes longer. Also, cable yarders are heavier and have a higher fuel use than ground-based machines.

5.1.7 Influence of Harvesting Scheme and Volume Harvested

The influence of the harvesting scheme on the final result mainly derives from leaving out the stage of planting when the forest regenerates naturally in the harvesting scheme of patch-cut.

However, it was found that the additional steps of two pre-thinnings that have to be taken after natural regeneration, in order to produce high-quality logs, have higher or as high emissions as the emissions avoided by not using seedlings. There was no study found that compared the natural regeneration with planting.

The harvested volume was found to be a significant input parameter. It was assumed that the volume harvested on one hectare is fixed, as 700 m^3 in Scenarios 3-6 and 800 m^3 in Scenarios 1 and 2. However, there are stands with ideal conditions that have a higher yield. For example in a study by González-García *et al*. (2013b) a biomass volume of 2200 m^3 per ha was harvested. Other stands with worse conditions can have lower yields. The harvested volume in this study is based on expert knowledge in the case studies.

5.1.8 Transport Distance is a Crucial Factor

In this study it was found that the impact of transport is between 22% and 56% of the entire environmental impact. This means that transport is a significant factor in the assessed part of the production chain of wood. Similar results were found in a study by Valente, Hillring and Solberg (2011), which found that transport contributed 31% of all emissions. In their study they assessed a transport distance of 65 km, which is shorter than the 70 km to 400 km in Scenarios 3-6. Pieratti *et al*. (2020) also found that transport was one of the most impactful phases of roundwood production. In their study transport corresponds to 30% of the total GWP. Michelsen *et al*. (2008) and González-García *et al*. (2009) also found that the most important processes are logging and transport operations. They emphasized the influence of the type of machines used and the amount of wood that is produced.

The influence of slope on fuel use and on road construction was not considered in this study, because the values were taken from Ecoinvent, and road building was not the focus of this study. However, in the study from Heinimann (2012) they found that on a slope of 40%, the construction of a road consumes 350MJ and emits 20kg CO_2-equivalents per running meter. In the present assessment the impact of road construction and maintenance is half that number. On the other hand, the logs are not transported on a steep slope for very long, and the larger portion of the transport happens on a highway or at least on a paved, rather flat road. The possibility of choosing a different size of log truck or the maximum load capacity was not considered in this study because the maximum load is defined by law in Austria and in New Zealand and it would not make sense to use smaller log trucks.

The assessment and consideration of transport distances is important because they contribute significantly to the environmental impact. However, the point in the production chain at which transport should be considered is difficult to determine. It might be more efficient to transport the logs further to shorten the transport distance for the finished wood product. The transport distance should be considered but reducing it before the factory gate might be not beneficial for the overall system.

5.1.9 Comparison of Results with Ecoinvent

The values for the impact factors used in this study are taken from Ecoinvent (Table 3, Appendix). In Ecoinvent they offer values for sawlogs, pulpwood, and energy wood. There are various datasets calculated. For softwood alone there are 326 entries. For the comparison three were found that are assumed to reflect the situation in the present study most closely.

The first dataset by Ecoinvent that fits closest to this study is “softwood forestry, mixed species, sustainable forest management” from Switzerland. In those calculations they considered different log sorts that were produced in that forest. Per m^3 produced wood 0,78m^3 sawlogs, 0,09m^3 pulpwood, but also energy wood and cleft timber were produced. They calculated a GWP of 13kg CO_2-equivalents/m^3 at the forest road. In the present study the GWP at the forest road is between 7.8 and 12.89 kg CO_2-equivalents/m^3. The value from Ecoinvent is a weighted average of different harvesting methods: harvester and forwarder, chainsaw, and cable-yarder, but also chainsaw and helicopter. This could be the reason why the value for GWP is rather high compared to this study. The values for FTAP are similar to this study, as is the TEP. FEP and POFP are significantly higher in Ecoinvent than in this study. That could be because the input of chainsaws is higher, which are most responsible for these impact categories. Also, land occupation and land transformation are considered in Ecoinvent, which was not done in this study.

The second dataset is “softwood forestry, pine, sustainable forest management, global”. They also considered different logs sorts; per m^3 wood 0.43m^3 of pulpwood and 0.498m^3 of sawlogs are produced, as well as cleft timber and energy wood. They calculated a GWP of 14.16kg CO_2-equivalents/m^3 at the forest road. This is a higher value than in the scenario with the highest impact in this study. This is because in that dataset the area is mechanically prepared before planting, the seedlings are planted mechanically, and tending and thinning operations are also conducted more intensely than in this study. This is also the reason why the other impact categories are significantly lower in this study than in the one from Ecoinvent. As before, Ecoinvent considered land transformation and land occupation in this dataset.

The third and last dataset is “softwood forestry, spruce, sustainable forest management”. The dataset is from Germany, where they produced 0.71m^3 of sawlogs, 0.17m^3 of pulpwood, and 12 kg energy wood per m^3 wood. They calculated a GWP of 12.42kg CO_2-equivalents/m^3 at the forest road. This value is similar to Scenarios 3-6 in the present study.

The trees are harvested by harvester and forwarder, which cause less emissions than chainsaws and cable yarder in Scenarios 3-6. However, in the dataset from Ecoinvent site establishment and tending is more intensive than in this study. Additionally, land transformation and occupation, as well as occupation of traffic area are considered, contrary to the present study.

5.2 Discussion of Impact on Soil and Water and Biodiversity

The impact of forest operations was assessed with five different impact categories. However, other measures like the influence on soil, water, and biodiversity cannot or can only to some extent be evaluated with an LCA. Since, the conservation of a high quality of soil, water, and biodiversity is considered important, the impact of forest operations is discussed below.

Impact on Soil and Water

After a clearcutting, the soil is bare and without canopy above for protection. This results in a disruption of the forest microclimate, since the buffering functions of the canopy are removed (Pawson *et al.*, 2006). Sunlight reaches the soil, and the radiation intensity is 10 to 20 times higher on the top organic layer than before harvesting. Also, water is not transpired in the canopy as well as in the litter layer and therefore precipitation water reaches the forest floor and directly wets the topsoil and is then leached into deeper layers, which increases soil moisture. This increase of temperature and moisture in the soil increases mineralization processes. Which, in turn, increases the release of N_2O, with a GWP of 265 kg CO_2-equivalents per kg. Additionally, the clearcut area’s capacity to capture carbon and gases is reduced, until it is vegetated to a certain extent (Göttlein *et al.*, 2013). If the area is cut using a patch-cut technique, on the other hand, the soil is never bare and always vegetated, because the harvested area is already undergrown by natural regeneration. This means that the top soil does not heat up and more water is retained by the canopy (Göttlein *et al.*, 2013). With regards to the present study, it can be concluded that concerning soil-heating and therefore faster metabolism of the organic layer, Scenarios 2 and 4 are favorable.

Certain harvesting processes with heavy wheeled machinery lead to soil compaction, in this study Scenarios 1, 2 and 5 use wheeled machinery, contrary to Scenarios 3, 4 and 6. A study by Gebauer *et al.* (2012) found that the bulk density in the top 10 cm of the soil increased by 15-60% after use of heavy machinery. Increasing bulk density decreases soil porosity, which leads to a change in soil aeration and therefore a possible increase of anaerobic conditions in the soil, also resulting in decreased plant growth (Gebauer *et al.*, 2012).

Skidders have the highest impact on the soil because they are not only wheeled and heavy, but they also drag the logs on the forest floor (Elliot, Dumroese and Robichaud, 1998). In Scenarios 3, 4 and 6, conversely, tree felling is done on-foot with chainsaws, and logging by a cable yarder. If the cable yarder is set up correctly and the logs are not dragged on the forest floor, then the impact is low, especially compared to ground-based harvesting.

Apart from soil compaction, soil erosion is also a considerable issue of harvesting practices. Deforested areas are significantly more prone to erosion than vegetated areas. Also, the soil erosion risk increases with slope (Borrelli *et al.*, 2017), which means that Scenario 3 has a higher risk of soil erosion than Scenario 1. In New Zealand the risk of erosion is higher and more severe than in Austria since larger areas are harvested at the same time. There are various measures taken to avoid erosion in New Zealand; for example, erecting barriers to keep slash from getting into water ways, adapting time of harvests not to coincide with heavy rain events, leaving tree buffers to retain land-slide material, or planting buffer zones close to water channels (NZ Farm Forestry, 2018).

Harvesting influences soil water by compaction and it leads to a decrease of water infiltration and an increase of run-off and therefore of erosion. Harvester and forwarders, as well as similar machinery, can accelerate the rate of surface-runoff 2-15 times (Gebauer *et al.*, 2012). An increase of run-off and soil erosion has a negative effect on water-ways (NZ Farm Forestry, 2018). Scenarios 1,2 and 5 disrupt the soil with heavy machinery, while in Scenarios 3 and 6, in steep terrain erosion is the more serious problem. This means that in terms of soil disruption and erosion, Scenario 4 would be the best option.

Impact on Biodiversity

Biodiversity was not included as an impact factor for the LCA, because it is hard to measure and there is no agreed upon scale or measurement method (Rossi *et al.*, 2018). Rossi *et al*. (2018) propose a simplified method to measure biodiversity in a forest stand.

According to them, biodiversity depends on four factors: native tree species composition and diversity of tree species, volume and quality of deadwood, protection of valuable habitats and biological corridors, and forest structure and continuity of forested area (Rossi *et al.*, 2018).

The native tree species composition and diversity of tree species is higher in Austria than in New Zealand because spruce is native to Austria while radiata pine is not to New Zealand. Still, the overall diversity of tree species is low in both cases because both are monocultures. However, spruce monocultures are the natural vegetation in some areas of Austria.

Since it is a native tree species it might follow that the vegetation growing under the canopy is likewise more adapted to spruce trees. Additionally, no herbicides are applied in this case study in Austria, which also increases the diversity of plants growing beside or under the trees.

The amount of deadwood left in the forest is larger in New Zealand since the material cut in the thinnings is left in the forest. Branches and treetops are left in the forest in both countries. However, in Scenarios 1 and 2, the trees are processed within the stand, so the material is more spread out than in the other scenarios. In all scenarios there is no standing deadwood because damaged trees are taken out, or because the trees are harvested before they die. The quality of the deadwood is supposedly higher in New Zealand, because in Austria only branches and small diameters are left to decompose, compared to small trees from thinnings in New Zealand.

Protection of valuable habitats is presumably considered in both countries. For New Zealand, more explicit plans and official requirements about the protection of water bodies were found. There is no area set aside for old trees in any scenario, but in Austria the stand age is significantly more mixed, because of the small-scale harvests. Therefore, biological corridors can form automatically, since a large area is not harvested at once.

Biodiversity is linked to the number of diverse habitats; the more habitats there are the more species can live in them. Therefore, small-scale clearcuttings offer more different habitats than continuous forest. After the area is cut, generalist plant and animal species repopulate the area within a few months (Göttlein *et al.*, 2013). Flowers and plants grow which are usually suppressed or cannot grow in the shade of the trees. However, the number of animal species that are adapted to forest, or cannot fly, decrease on clear-cut areas. In terms of biodiversity, a small-scale clear-cut could increase biodiversity, but it depends on which group of species or parameters are examined.

Pawson *et al.* (2006) studied the influence of clearcutting on biodiversity and found that there is no clear answer whether it is beneficial for biodiversity or not. They did state that clearcuttings and especially large-scale clearcuttings have a low social acceptance, which is more likely to be the reason for clearance size restrictions than other factors. They also found that harvesting releases resources that are otherwise monopolized by mature canopy species. This increases the plant species richness after the clear-felling, with open-habitat specialists. The species richness, however, decreases after the first few years, when the planted trees are starting to mature. After a clearcutting some insect species are lost, others benefit from open space. Also, insect species richness decreases with clear-cut size. Birds, on the other hand, are not heavily influenced by the clear-cut size, but rather by the even-aged forest structure of clear-cut stands.

Additionally, birds that are adapted to old stands are endangered by short-rotation clear-felling practices. Plants that colonize clearcutting sites increase the local biodiversity, but on large scale plantations, the ability to colonize depends on dispersal abilities and the proximity and size of the source population (Pawson *et al.*, 2006). Thus, while clearcutting does increase biodiversity of some species, or species groups, the peak is only ever in the first few years. So, patch-cut in Scenarios 2 and 4 could be considered favorable in terms of biodiversity.

Another measure that has to be considered is climate change. Climate change is likely to decrease global biodiversity, and plantations are one measure to mitigate climate change. In that case any forest that is planted and sequestrates carbon has a positive effect on global biodiversity (Pawson *et al.*, 2013).

5.3 Limits and Shortcomings of the study

This section outlines and discusses limits and shortcomings of the study. These are mainly: a lack of data, the choice of system boundary and functional unit, as well as the choice and location of scenarios, choice of impact categories and the choice of tree species.

5.3.1 Lack of Data

There is a lack of data on three different levels. Firstly, there is a general lack of LCA studies about forestry (Klein *et al.*, 2015). The even bigger issue is the comparability of studies. The functional unit, the system boundary, the impact assessment method, and the impact factors are chosen by every author to fit their study, and they are not necessarily all mentioned in the studies.

Additionally, the studies are conducted in different countries, they study different tree species, consider different machinery, assess highly varying rotation periods with differing intensities, and are therefore not easy to compare. In order to increase comparability, LCA should be more standardized.

Secondly, there is still no agreed upon method to assess carbon sequestration and climate change mitigation effects of wood (Klein *et al.*, 2015). The carbon content in the wood tissue is on average 50%, but it varies by about 10% and it depends on species and on surrounding conditions (Martin, Doraisami and Thomas, 2018). A forest ecosystem is more complex than the carbon stored in the wood itself. Carbon is built up in the soil and released from it again. Organisms influence carbon as well. Also, if material is left in the forest, it decays and releases carbon. In the long run, all carbon that was built up in the wood tissue is released again, which means that the only way that wood contributes to climate change mitigation is by substitution effects.

The impact of the substitution depends on assumptions that were taken for the material that is substituted (Klein *et al.*, 2013). Once again, the best solution would be to standardize LCA and the method for assessing carbon sequestration.

Thirdly, there is a lack of data for forest management. There are significantly more data available in New Zealand because the government provides data as well as recommendations for forest management. In Austria, such offers of general information are less prevalent. However, for both countries data about machine productivity and transport distances are scarce. In addition to that, in Austria, there is no information about thinning or harvesting schemes, tree diameters, or harvested volumes per hectare. These data were obtained by experts, but it might be more reliable and more applicable to other regions in the respective countries if these numbers were given by official or state institutions.

5.3.2 Choice of System Boundary

The system boundary of production of seedlings until factory gate was chosen because that way all operations that are connected to wood production are examined in that system. Moreover, there are other studies that chose the same system boundaries (Michelsen *et al*., 2008; Pyörälä *et al*., 2012; Karjalainen and Asikainen 1996), which is important for comparability.

On the other hand, setting the system boundary at the factory gate may be misleading. Considering the supply chain until the factory gate means that log transport is included. It was found in this study, as well as in many others, that log transport is a main contributor to the environmental impact.

Therefore, if the impact were to be reduced, the factory should be placed as close to the forest as possible. However, for the whole production chain, if for example the wood is used for paper, it might make more sense to build the papermill in or close to a city. This might increase the transport distance of the logs but shorten the transport later on. Therefore, it might make more sense to set the system boundary at the forest road and consider transport at the point of consumption or disposal. On the other hand, if the transport distances are not recorded in some parts of the value chain, then the impact may be erroneously ignored.

5.3.3 Choice of Functional Unit

The functional unit is 1 m^3 of green wood with bark which is harvested and transported to a sawmill, pulpmill, and energy wood factory. 1 m^3 is a typical form of measurement in forestry and also used in most studies. The weight of 1 m^3 of spruce was assumed and not based on a scientific source, but on estimates and grey literature. The weight for 1 m^3 of radiata pine was confirmed by experts and is on average 1 ton.

For both tree species the weight differs highly because of fluctuating water contents and different wood densities depending on growth velocity.

One m^3 is a typical measurement in the field of forestry and also in the timber industry. However, one m^3 changes its weight, properties and value over time and processing steps in the supply chain. Especially by drying the weight changes, which is why it is crucial to mention the assumed weight of the wood.

5.3.4 Influence of Rotation Period

The impact of forestry was calculated for both countries per m^3 whereby the length of the rotation period was not considered, because it has no effect on the results. With a prolonged observation period of, for example, 100 years the impact in Austria would not change at all, while in New Zealand the volume harvested would be 3.6 times higher, but so, correspondingly, would be the impact, resulting in the same impact per m^3. If other measures like water use, or carbon sequestration had been considered, the duration of the rotation period would make a substantial difference. Over a period of 100 years, for example, the trees grown in New Zealand need at least 3.6 times the amount of water that spruce trees need, assuming that the water use of the tree species is similar. If the aspect of land occupation would be considered then the value would be favorable for New Zealand, because per m^3 less land is occupied.

Also, the carbon sequestration in wood tissue falls under the same assumptions, 3.6 times higher in New Zealand than in Austria, in a period of 100 years. From a climate change point of view, it would be most desirable to plant fast and tall growing plants. However, the growth of plants per m^2 is limited by photosynthesis and can therefore not be increased arbitrarily (Meyer, Nagel and Feldmann, 2021).

5.3.5 Choice and Location of Scenarios

It was assumed that the scenarios chosen are representative for Austria and New Zealand. However, especially in Austria the representativeness could be challenged. Two experts helped with obtaining the primary data for the case studies, both in Lower Austria, and both responsible for forests that are managed sustainably and as close to nature as possible. This is not necessarily typical. In order to actually represent Austria, case studies of small forest owners, as well as from large companies like Mayr-Melnhof would have to be conducted, and different regions of Austria would have to be compared.

In New Zealand the choice of the scenarios might be more representative because assessed the areas are located in the most productive region for forest plantations. Still, there was no assessment of forests in other parts of the North Island nor on the South Island, where the conditions might be different.

5.3.6 Choice of Impact categories and Impact assessment method

Five impact categories were chosen for the assessment which were mentioned by Klein *et al*. (2015) as the most commonly used impact categories. They were also used by Dias and Arroja (2012); Michelsen *et al*. (2008); González-García *et al*. (2013a); Ferro *et al*. (2018); González-García *et al*. (2013b); Proto *et al*., (2017); González-García *et al*. (2009) and Gonzales-Garcia *et al*. (2014). Other impact categories could have been included such as ecotoxicity, water use, or fossil resource depletion. Fossil resource depletion was not chosen because it is based on human consumption rather than on the environment. Water use was not chosen because it is difficult to assess, the trees in the assessment are not watered, and there is enough precipitation over the year to meet the forests' requirements. Ecotoxicity is mentioned in the results concerning the use of herbicides, but it was not used for every machine and operation in this study. For biodiversity and the influence on soils there are still no impact categories, which is why those parameters are discussed separately but are not part of the assessment.

In this study the impact assessment method chosen is the environmental footprint 2.0. In other studies, if the method is described at all, they chose other impact assessment methods like ReCiPe (Pieratti *et al*., 2020; González-García *et al*., 2013b; González-García *et al*., 2013a; Ferro *et al*., 2018), IPCC (Valente *et al*., 2011a; Saud *et al*., 2013; Sonne, 2006; González-García *et al*., 2009), ILCD (Proto *et al.*, 2017), CML (Gonzales-Garcia *et al*., 2014). The reason why EF 2.0 was chosen in this study is that the product environmental footprint (PEF) is expected to become the future standard for LCA in the EU (Lehmann, Bach and Finkbeiner, 2015).

5.3.7 Choice of tree species

The tree species chosen for the assessment are the most common tree species in the respective countries. However, especially in Austria spruce is often grown in mixed stands, which was not considered. The reason is that the effects of mixed stands have been examined but would have complicated the calculations in this study. It would be interesting for future research to assess the differences between mixed stands in Austria, and monoculture in New Zealand.

The three most important discussion points are firstly that the contribution of forestry compared to other materials and compared to the rest of the value chain of wood products is small. That means that the relevance of assessing forest operations in general could be discussed. On the other hand, a lot of hope relies on forests to mitigate climate change, which is why it is crucial to assess the impacts of forest management.

Secondly, the number of LCA studies about forestry has been increasing, but the comparability is generally low. There is still a lack of standardization or rules to continue, widen, or compare with previous research.

Lastly, the influence of transport distances was found to be a significant contributor to the impact of forest operations. However, the correct point in the value chain in which transport should be considered is difficult to determine.

6. Conclusion

Austria, a country with a long history of forest management and a strong connection to tradition, was compared to New Zealand with a relatively new system of efficient plantations with short rotations. The aim of this study was to assess the environmental impacts of forest operations in Austria and in New Zealand. The goal was also to compare their systems and to find possibilities for reducing their environmental impact. A life cycle assessment of six case studies was conducted to determine and calculate the impact of forest operations. These six case studies entailed ground-based and cable-based timber harvesting in Austria and in New Zealand. Also, a comparison between different harvesting schemes (patch-cut with natural regeneration vs. clearcutting with planting of seedlings) was conducted in Austria.

In this study five key results were found. The first one is that forest operations have an environmental impact, which is still small compared to other materials, but important to assess in terms of climate change mitigation. Stand establishment, thinning, final harvesting, and transport not only contributes to global warming, but also to acidification, terrestrial eutrophication, and photochemical oxidant formation. In Austria 1 m^3 of spruce wood produced in flat terrain (<20%) was found to have a GWP of 10 kg CO_2-equivalents, a FTAP of 0.05 kg SO_2-equivalents/m^3, a TEP of 0.17 kg PO_4-equivalents/m^3, and a POFP of 0.08 kg NMVOC-equivalents/m^3. While 1 m^3 of spruce grown in steep terrain (<70%) has a GWP of 26 kg CO_2-equivalents, a FTAP of 0.1 kg SO_2-equivalents/m^3, a TEP of 0.3 kg PO_4-equivalents/m^3, and a POFP of 0.23kg NMVOC-equivalents/m^3. 1 m^3 of radiata pine wood grown in New Zealand has a GWP of 24 kg CO_2-equivalents, a FTAP of 0.09 kg SO_2-equivalents/m^3, a TEP of 0.26 kg PO_4-equivalents/m^3, and a POFP of 0.15 kg NMVOC-equivalents/m^3. The impact heavily depends on terrain and the suitable harvesting equipment and on transport distances of the logs to their destination at a sawmill, pulpmill or energy plant. The environmental impact of forest operations was expected to be considerable, and even though the impact is small compared to other materials and also compared to the full value chain of wood products, it should not be ignored. It is important to assess, because a lot of hope relies on forests to mitigate climate change, and the potentials as well as the effects of forest management need therefore to be measured.

Secondly, forest operations in New Zealand were not found to have a higher environmental impact than in Austria; their impacts were even smaller than forest operations in steep terrain in Austria. This is contrary to previous expectations, because in New Zealand heavy machinery are used, the plantations and clearcuttings are on a large scale, and because the site preparations are more intensive than in Austria.

The third key result is that harvesting in steep terrain has a higher impact than in flat terrain. This was expected, but it was not expected that the main reason was the fuel use of the cable yarder rather than the lower efficiency, smaller tree diameters and more difficult working conditions.

The fourth main finding is that the harvesting-scheme patch-cut, with the resulting natural regeneration of the forest had a higher or as high impact as the production, transport, and planting of seedlings, which was not anticipated.

Lastly, log transport was found to be one of the most contributing factors to the environmental impact of forest operations. However, it was not predicted that the transport distances would be so similar between Scenarios 3, 4 in Austria and 5 and 6 in New Zealand.

In accordance with the key results, the following suggestions for improvements are made. The most important factor to decrease the environmental impact is to reduce transport distances, or by electrifying wood transport. The second largest contributor are emissions from large machines used for harvesting, these could be fueled by biodiesel or be electrified as well. In terms of climate change and soil erosion it would be beneficial to ensure that the soil is always vegetated (Göttlein *et al.*, 2013).

Forests are seen as a measure to mitigate climate change, which is why it is crucial to assess the environmental impact of managing and using forests and wood. However, it is important to not only determine the effects on climate but also on acidification, eutrophication, and ozone emissions.

Forest management is not assessed well enough by LCA neither in Austria nor in New Zealand. There are studies about wood and wood products in Austria, but forestry plays a secondary role in those studies, if it is mentioned at all. In New Zealand there are no studies about wood products, and none about forestry. This study is the first one that assesses forestry in both countries, and the first one that compares them. Still, the case studies chosen for the assessment do not fully represent the countries, because not all regions and management sizes were considered. Therefore, further LCA should be done for small-scale forestry, as well as for large-scale companies or forest management areas like Kaingaroa forest, or Mayr-Melnhof. Additionally, LCA about different regions in Austria and in New Zealand should be conducted, to completely represent forestry in the respective countries. There were no studies found that assessed the difference between natural regeneration and planting. This should be further examined, and the impacts of tree nurseries could be compared in more detail to natural regeneration and the additional steps that have to be taken in both cases.

This is also the first study that compares forest operations in flat and steep terrain. More studies should be conducted to confirm the higher impact that comes with difficult terrain. There are also more studies needed that go further than the system boundary in this study, so beyond the gate of a sawmill, pulpmill or energy plant. Future research could continue the assessment from there, preferably up to the disposal of the wood product.

For all future studies it is important to assess more than one impact category, because even though GWP has the highest values it does not mean that the others should be ignored. In order to be able to compare studies it is crucial to mention the method of the impact assessment. Transport distance, harvested volume, and machines used need to be mentioned and discussed so that the results can be used for further research. Lastly, it is important to consider all processes that are conducted in the forest, not only harvesting.

7. References

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8. List of Tables and Figures

9. Appendix

Scenario 1: Impact assessment per ha

Scenario 1: spruce monculture, flat terrain, clear felling, Stift Zwettl, rotation period=100 years

Stage	Process	Action	Machine	Weight in t	fm/h	Working hours (h)	Transport product tkm	Transport mach. Austria Ferry (k	Transport mach. Austria Lorry	Fuel kg/tkm	Amount		EF 2.0 Global Warming Potential kg CO2 eq	EF 2.0 Freshwater and terrestrial acidification kg SO2 eq	EF 2.0 Freshwater eutrophication kg PO4 eq	EF 2.0 Terrestrial eutrophication kg PO4 eq	EF 2.0 Photochemical ozone formation kg NMVOC eq
Planting	Seedlings	Bare-rooted Seedlings	Transport Klein LKW	0,4	_		6,92				2000		94,09	0,49	0,06	1,09	0,29
	Site Preparation	Mähen	Freischneider			70	_	_			17,5		660,85	2,00	0,87	6,07	31,91
	Planting	Planting	Forw John Deere 1110D	12,8		11,42857143		0,664935065	18,28571429				597,79	3,20	0,04	13,05	3,77
												Σ Planting	1352,73	5,68	0,97	20,21	35,98

Stage	Process	Action	Machine	Machine weight t	Productivity m3/h	Working hours h	Transport product tkm	Transport mach. Austria Ferry tk	Transport mach. Austria Lorry	Fuel machine kg/h	m3 Harvested		kg CO2 eq	kg SO2 eq	kg PO4 eq	kg PO4 eq	kg NMVOC eq
Thinning	Thinning	Thinning 1	Harv: John Deere 1070G	17,8	9,019232749	5,543902834		0,448552138	12,33518381	10,5	50,00175		318,99	1,82	0,07	7,43	2,10
		Thinning 2	Harv: John Deere 1270G	20,65	12,94702886	3,862025067		0,362503716	9,968852203	14,7	50,00175		310,76	1,77	0,07	7,24	2,04
		Thinning 3	Harv: John Deere 1270G	20,65	17,83114794	2,804180088		0,26321054	7,238289852	14,7	50,00175		225,64	1,28	0,05	5,26	1,48
		Thinning 4	Harv: John Deere 1270G	20,65	21,32250133	2,345022717		0,22011236	6,053089889	14,7	50,00175		188,69	1,07	0,04	4,40	1,24
	Logging	Logging 1	Forw John Deer1110D	12,8	26,77866717	1,867223252		0,108638444	2,987557203	10,5	50,00175		97,67	0,52	0,01	2,13	0,62
		Logging 2	Forw John Deer1110D	12,8	26,24175453	1,905427091		0,110861213	3,048683346	10,5	50,00175		99,67	0,53	0,01	2,18	0,63
		Logging 3	Forw John Deer1110D	12,8	25,87035291	1,932781906		0,112452765	3,092451049	10,5	50,00175		101,10	0,54	0,01	2,21	0,64
		Logging 4	Forw John Deer1110D	12,8	25,36772129	1,971077711		0,114680885	3,153724337	10,5	50,00175		103,10	0,55	0,01	2,25	0,65
												Σ Thinning	1445,61	8,09	0,25	33,09	9,40

Stage	Process	Action	Machine	Machine weight t	Productivity m3/h	Working hours h	Transport product tkm	Transport mach. Austria Ferry (tk	Transport mach. Austria Lorry	Fuel kg/h	m3 Harvested						
Harvest	Harvest	Felling, limbing	Harv John Deer 1270G	20,65	28,14305348	21,31966641		2,001141416	55,03138893	14,7	600,000512		1715,49	9,77	0,37	39,97	11,29
	Logging	Logging	Forw John Deer 1510G	16,33	25,60121529	23,43640742		1,739620605	47,83956665	11,76	600,000512		1373,95	7,35	0,08	29,99	8,67
												Σ Harvest	3089,44	17,12	0,45	69,95	19,96
												ΣΣ	5887,78	30,89	1,67	123,25	65,34

Stage	Process	Action	Machine	Machine weight t	Working hours	Number of workers for operation	km to forest site	Person*km									
Worker	Planting, site preparation	Work	Car	1,5	81,42857143	13	65	845					269,78	1,08	0,04	2,78	0,95
	Thinning and Logging	Thinning and Logging	Car	1,5	22,23164067	8	65	520					166,02	0,66	0,02	1,71	0,59
	Harvesting	Harvesting	Car	1,5	44,75607383	6	65	390					124,52	0,50	0,02	1,28	0,44
												Σ Workers	560,32	2,24	0,08	5,78	1,98

Stage	Process	Action	Machine	m road built/ha	tkm machine	Person km workers	Amount/m	Fuel/m									
Road	Road construction & maintenance	Road construction and maintenance	Gravel	45			11,25						87,49	0,63	0,02	2,49	0,62
			Passenger car	45		21,375		189					6,82	0,03	0,00	0,07	0,02
			Lorry 16-32t	45	2205								358,81	1,00	0,02	2,26	0,86
												ΣΣ Road constr	453,13	1,65	0,04	4,82	1,51
												ΣΣ Forest road	6901,23	34,79	1,80	133,85	68,83
												Σ/m3	8,63	0,04	0,00	0,17	0,09

Stage	Process	Action	Machine	Truck net weight	Share of wood type	m3 harvested per ha	Kilometers to plant	tons transported	Number of tours driven	Ton*km wood transport	km truck driving back						
	Transport wood from thinnings to sawmill/industrial plant/energy wood plant	Transport Th 1	Truck (lorry <32t	14	0,1	50,00175	19	4,75016625	1	90,25315875	19		24,93	0,08	0,00	0,19	0,07
		Transport Th 1	Truck (lorry <32t	14	0,8	50,00175	20	38,00133	2	760,0266	40		101,97	0,32	0,01	0,79	0,31
		Transport Th 1 energy	Truck (lorry <32t	14	0,1	50,00175	3,4	4,75016625	1	16,15056525	3,4		4,46	0,01	0,00	0,03	0,01
		Transport Th 2	Truck (lorry <32t	14	0,2	50,00175	19	9,5003325	1	180,5063175	19		32,77	0,10	0,00	0,25	0,10
		Transport Th 2	Truck (lorry <32t	14	0,7	50,00175	20	33,25116375	2	665,023275	40		93,72	0,29	0,01	0,72	0,28
		Transport Th 2 energy	Truck (lorry <32t	14	0,1	50,00175	3,4	4,75016625	1	16,15056525	3,4		4,46	0,01	0,00	0,03	0,01
		Transport Th 3	Truck (lorry <32t	14	0,3	50,00175	19	14,25049875	1	270,7594763	19		40,60	0,13	0,00	0,31	0,12
		Transport Th 3	Truck (lorry <32t	14	0,6	50,00175	20	28,5009975	1	570,01995	20		67,48	0,21	0,00	0,52	0,21
		Transport Th 3 energy	Truck (lorry <32t	14	0,1	50,00175	3,4	4,75016625	1	16,15056525	3,4		4,46	0,01	0,00	0,03	0,01
		Transport Th 4	Truck (lorry <32t	14	0,4	50,00175	19	19,000665	1	361,012635	19		48,43	0,15	0,00	0,37	0,15
		Transport Th 4	Truck (lorry <32t	14	0,5	50,00175	20	23,75083125	1	475,016625	20		59,23	0,18	0,00	0,46	0,18
		Transport Th 4 energy	Truck (lorry <32t	14	0,1	50,00175	3,4	4,75016625	1	16,15056525	3,4		4,46	0,01	0,00	0,03	0,01
	Transport logs from harvest	Logs to sawmill	Truck (lorry <32t	14	0,8	600,000512	19	456,0003891	16	8664,007393	304		1025,59	3,20	0,07	7,94	3,12
		Logs to industrial plant	Truck (lorry <32t	14	0,15	600,000512	20	85,50007296	3	1710,001459	60		202,42	0,63	0,01	1,57	0,62
		Logs to energy wood	Truck (lorry <32t	14	0,05	600,000512	3,4	28,50002432	1	96,90008269	3,4		11,47	0,04	0,00	0,09	0,03
												Σ transport	1726,46	5,38	0,12	13,34	5,24
												Σ/m3	2,16	0,01	0,00	0,02	0,01

Age	Treediameter in cm	Treevolume	Logvolume	HK 1 (techfak)	HK 2 (techfak)	Forwarding Distance	Forwarded Volume	Productivity Harvester	Productivity Forwarder
25	15	0,225	0,07794	2,99	-0,57	267	10,52631579	9,019232749	26,77866717
35	22	0,484	0,127561022	2,99	-0,57	267	10,52631579	12,94702886	26,24175453
40	24	0,576	0,143049694	5,23	-0,18	267	10,52631579	16,19671725	26,09195077
45	27	0,729	0,167260156	5,23	-0,18	267	10,52631579	17,83114794	25,87035291
55	34	1,156	0,227921835	5,23	-0,18	267	10,52631579	21,32250133	25,36772129
100	50	2,5	0,385360009	5,23	-0,18	267	12,63157895	28,14305348	25,60121529

	GWP	FTAP	FEP	TEP	POFP
ΣΣ At gate/ha	8627,69	40,16	1,91	147,20	74,07
Σ/m3	10,78	0,05	0,002	0,18	0,09

Scenario 2: Impact assessment

Scenario 2: spruce monculture, flat terrain, patch-cut, Stift Zwettl, rotation period=100 years, per ha

Stage	Process	Action	Machine	Machine weight in t	Productivity m3/h	Working hours h/m3	Trans product tkm/	Trans mach. Austria F	Trans mach. Austria Lorry (tkn	Fuel machine kg/h	m3 Harvested		EF 2.0 Global Warming Potential	EF 2.0 Freshwater and terrestrial acidification	EF 2.0 Freshwater eutrophication	EF 2.0 Terrestrial eutrophication	EF 2.0 Photochemical ozone formation
													kg CO2 eq	kg SO2 eq	kg PO4 eq	kg PO4 eq	
Planting	Seedlings	Nackwurzler	Transport Klein LKW														
		Mähen	Freischneider	Assumption: only natural regeneration -> no planting needed!													

Stage	Process	Action	Machine	Machine weight in t	Productivity m3/h	Working hours h	Transport product	Trans mach. Austria F	Trans mach. Austria Lorry (tkn	Fuel machine kg/h	m3 Harvested		kg CO2 eq	kg SO2 eq	kg PO4 eq	kg PO4 eq	kg NMVOC eq
Thinning	Thinning	Jungwuchspflege /ha	Freischneider/Motorsäge	0,0075		21			0,063	1,6	800		198,25	0,60	0,26	1,82	9,57
		Tending thicket	Chainsaw	0,0075		45			0,135	1,6	800		424,83	1,28	0,56	3,90	20,52
		Thinning 1	Harv John Deere 1070G	17,8	7,73	6,46		0,52	14,38	10,5	50,00034		371,98	2,12	0,08	8,66	2,45
		Thinning 2	Harv: John Deere 1270G	20,65	11,35	4,40		0,41	11,37	14,7	50,00034		354,35	2,02	0,08	8,26	2,33
		Thinning 3	Harv: John Deere 1270G	20,65	16,20	3,09		0,29	7,97	14,7	50,00034		248,40	1,41	0,05	5,79	1,63
		Thinning 4	Harv: John Deere 1270G	20,65	19,38	2,58		0,24	6,66	14,7	50,00034		207,63	1,18	0,04	4,84	1,37
	Logging	Logging 1	Forw: John Deer1110D	12,8	26,94	1,86		0,11	2,97	10,5	50,00034		97,10	0,52	0,01	2,12	0,61
		Logging 2	Forw: John Deer1110D	12,8	26,47	1,89		0,11	3,02	10,5	50,00034		98,81	0,53	0,01	2,16	0,62
		Logging 3	Forw: John Deer1110D	12,8	26,09	1,92		0,11	3,07	10,5	50,00034		100,24	0,54	0,01	2,19	0,63
		Logging 4	Forw: John Deer1110D	12,8	25,65	1,95		0,11	3,12	10,5	50,00034		101,95	0,55	0,01	2,23	0,64
												Σ Thinning	2203,53	10,74	1,10	41,95	40,38
												Σ/m3	11,02	0,05	0,01	0,21	0,20

Stage	Group	Action	Machine	Machine weight in t	Productivity m3/h	Working hours h	Transport product	Trans mach. Austria F	Trans mach. Austria Lorry (tkn	Fuel machine kg/h	m3 Harvested						
Harvest	Harvest 1	Felling, limbing	Harv John Deer 1270G	20,65	28,14	10,66		1,00	27,52	14,7	300,00256		857,75	4,88	0,19	19,98	5,64
	Harvest 2	Felling, limbing	Harv John Deer 1270G	20,65	28,14	10,66		1,00	27,52	14,7	300,00256		857,75	4,88	0,19	19,98	5,64
	Logging 1	Logging	Forw John Deer 1510G	16,33	25,60	11,72		0,87	23,92	14,7	300,00256		686,98	3,67	0,04	14,99	4,33
	Logging 2	Logging	Forw John Deer 1510G	16,33	25,60	11,72		0,87	23,92	14,7	300,00256		686,98	3,67	0,04	14,99	4,33
												Σ Harvest	3089,47	17,12	0,45	69,96	19,96
												ΣΣ after harvest	5293,00	27,86	1,55	111,91	60,34

Stage	Process	Action	Machine	Machine weight	Working hours	Number of workers for operation	km to forest site	Person*km								
												Σ/m3	6,62	0,03	0,00	0,14	0,08
Worker	Planting and site preparati	Work	Car	1,5	0	0	0	0									
	Thinning and Logging	Thinning and Logging	Car	1,5	90,14676556	17	65	1105					352,79	1,41	0,05	3,64	1,24
	Harvesting	Harvesting	Car	1,5	22,37820878	8	65	520					166,02	0,66	0,02	1,71	0,59
												Σ Workers	518,82	2,08	0,08	5,35	1,83

Stage	Process	Action	Machine	m of road built/ha	tkm machine	Person km workers	Amount/m	Fuel/m									
													87,49	0,63	0,02	2,49	0,62
Road	Road construction & maintenance		Gravel	45			11,25						6,82	0,03	0,00	0,07	0,02
			Passenger car	45		21,375		189					358,81	1,00	0,02	2,26	0,86
			Lorry 16-32t	45	2205							Σ Road	453,13	1,65	0,04	4,82	1,51
												ΣΣ forest road	6264,95	31,59	1,67	122,08	63,68
												Σ/m3 FR	7,83	0,039	0,00	0,15	0,08

Stage	Process	Action	Machine	Truck net weight	Share of wood type	m3 harvested/ha	km to plant	tons transported	Number of tours driven	Tonkilometers wood	km of truck driving back						
Transport	Transport wood from thinnings to sawmill/industrial plant/energy wood plant	Transport Th 1 sawmill	Truck (lorry 40t)	14	0,1	50,00034	19	4,75	1	90,25	19		24,93	0,08	0,00	0,19	0,07
		Transport Th 1 industry	Truck (lorry 40t)	14	0,8	50,00034	20	38,00	2	760,01	40		101,96	0,32	0,01	0,79	0,31
		Transport Th 1 energy	Truck (lorry 40t)	14	0,1	50,00034	3,4	4,75	1	16,15	3,4		4,46	0,01	0,00	0,03	0,01
		Transport Th 2 sawmill	Truck (lorry 40t)	14	0,2	50,00034	19	9,50	1	180,50	19		32,77	0,10	0,00	0,25	0,10
		Transport Th 2 industry	Truck (lorry 40t)	14	0,7	50,00034	20	33,25	2	665,00	40		93,72	0,29	0,01	0,72	0,28
		Transport Th 2 energy	Truck (lorry 40t)	14	0,1	50,00034	3,4	4,75	1	16,15	3,4		4,46	0,01	0,00	0,03	0,01
		Transport Th 3 sawmill	Truck (lorry 40t)	14	0,3	50,00034	19	14,25	1	270,75	19		40,60	0,13	0,00	0,31	0,12
		Transport Th 3 industry	Truck (lorry 40t)	14	0,6	50,00034	20	28,50	1	570,00	20		67,47	0,21	0,00	0,52	0,21
		Transport Th 3 energy	Truck (lorry 40t)	14	0,1	50,00034	3,4	4,75	1	16,15	3,4		4,46	0,01	0,00	0,03	0,01
		Transport Th 4 sawmill	Truck (lorry 40t)	14	0,4	50,00034	19	19,00	1	361,00	19		48,43	0,15	0,00	0,37	0,15
		Transport Th 4 industry	Truck (lorry 40t)	14	0,5	50,00034	20	23,75	1	475,00	20		59,23	0,18	0,00	0,46	0,18
		Transport Th 4 energy	Truck (lorry 40t)	14	0,1	50,00034	3,4	4,75	1	16,15	3,4		4,46	0,01	0,00	0,03	0,01
	Transport from harvest	Logs to sawmill 1	Truck (lorry 40t)	14	0,8	300,00256	19	228,00	8	4332,04	152		512,80	1,60	0,03	3,97	1,56
		Logs to industrial plant 1	Truck (lorry 40t)	14	0,15	300,00256	20	42,75	2	855,01	40		110,21	0,34	0,01	0,85	0,33
		Logs to energy wood 1	Truck (lorry 40t)	14	0,05	300,00256	3,4	14,25	1	48,45	3,4		7,27	0,02	0,00	0,06	0,02
		Logs to sawmill 2	Truck (lorry 40t)	14	0,8	300,00256	19	228,00	8	4332,04	152		512,80	1,60	0,03	3,97	1,56
		Logs to industrial plant 2	Truck (lorry 40t)	14	0,15	300,00256	20	42,75	2	855,01	40		110,21	0,34	0,01	0,85	0,33
		Logs to energy wood 2	Truck (lorry 40t)	14	0,05	300,00256	3,4	14,25	1	48,45	3,4		7,27	0,02	0,00	0,06	0,02
												Σ Transport	1747,52	5,44	0,12	13,50	5,30

Age	Age	Treediameter in cm	Treevolume	Logvolume	HK 1 (techfak)	HK 2 (techfak)	Forwarding distanc	Forwarded Volume	Productivity Harvester	Productivity Forwarder							
												Σ/m3	2,18	0,01	0,00	0,02	0,01
20	Average 15-25	13	0,169	0,07	2,99	-0,57	267	10,53	7,73	26,94							
30	Average 25-30	19	0,361	0,11	2,99	-0,57	267	10,53	11,35	26,47			GWP	FTAP	FEP	TEP	POFP
40	Average 35-45	24	0,576	0,14	5,23	-0,18	267	10,53	16,20	26,09		Sc 2 ΣΣ Gate	8012,46	37,03	1,79	135,59	68,98
45	Average 40-50	24	0,576	0,14	5,23	-0,18	267	10,53	16,20	26,09		Σ/m3	10,02	0,0463	0,0022	0,17	0,086
50	Average 45-55	30	0,9	0,19	5,23	-0,18	267	10,53	19,38	25,65							
100		50	2,5	0,39	5,23	-0,18	267	12,63	28,14	25,60							

Scenario 3: Impact assessment

		Scenario 3: spruce monculture, steep terrain, clear-cut, Stift Rosalia, rotation period=100 years, per ha											EF 2.0 Global Warming Potential	EF 2.0 Freshwater and terrestrial acidification	EF 2.0 Freshwater eutrophication	EF 2.0 Terrestrial eutrophication	EF 2.0 Photochemical ozone formation
Stage	Process	Action	Machine	Machine weight	Working hours h/ha	Transport product tkm/ha	Trans machine (tkm/h	Fuel machine kg/h	Oil lubricant kg/h	Amount			kg CO2 eq	kg SO2 eq	kg PO4 eq	kg PO4 eq	kg NMVOC eq
Planting	Seedlings	Bare-rooted Seedlings	Transport Klein LKW	2,8		495,60				1500			320,923	1,062	0,070	2,263	0,777
	te preparatio	Herbizid-Verteilung	_														
		Mähen	Motorsense=Freischn	0,0075	84		0,252	1,6	0,54				793,016	2,395	1,041	7,282	38,296
	Planting	Planting	by hand														
												Σ Planting	1113,939	3,457	1,111	9,545	39,073
Stage	Process	Action	Machine	Machine weight	Productivity m3/h	Working hours h	Transport product tkm	Trans mach. ->Austria	Fuel machine kg/h	Fuel kg/m3	m3 Harvested						
Thinning	Thinning	Thinning 1 and processin	Chainsaw	0,0075	2,34	21,35624154		0,064068725	1,6		50,000384		201,628	0,609	0,265	1,851	9,736
		Thinning 2 and processin	Chainsaw	0,0075	3,18	15,71037291		0,047131119	1,6		50,000384		148,324	0,448	0,195	1,362	7,162
	Logging	Logging 1	K300T on tractor	6,595	3,68174	13,58062697		0,407110158	12,6	171,1158998	50,000384		675,744	2,962	0,020	12,037	3,443
		Logging 2	K300T on tractor	6,595	5,37127	9,308860224		0,279054242	12,6	117,2916388	50,000384		463,190	2,030	0,014	8,251	2,360
												Σ Thinning	1488,886	6,049	0,493	23,502	22,701
												Σ Thinning/m3	14,889	0,060	0,005	0,235	0,227
Stage	Process	Action	Machine	Machine weight	Productivity m3/h	Working hours h/ha	Transport product tkm	Trans mach. ->Austria	Fuel machine kg/h	Fuel kg/m3	m3 Harvested						
Harvest	Harvest	Felling, limbing	Chainsaw	0,0075	7,37155	81,39399174		0,244181975			600,00024		768,454	2,321	1,009	7,056	37,108
	Logging	Logging	Gebirgsharv Mounty	31,00	19,11981669	31,38106655		11,44485957	29,7	932,0176766	600,00024		3849,403	19,210	0,182	77,483	22,217
												Σ Harvest	4617,856	21,531	1,191	84,539	59,325
												Σ Harvest/m3	7,696	0,036	0,002	0,141	0,099
												ΣΣ After Harvest	7220,681	31,037	2,796	117,586	121,100
Stage	Process	Action	Machine	Machine weight	Working hours	Number of workers for operation	km to forest site	Person*km									
Workers	Planting and	Work	Car	1,5	208,3333333	26	65	1690					539,568	2,160	0,080	5,566	1,903
	Thinning and	Thinning and Logging	Car	1,5	59,95610165	15	65	975					311,289	1,246	0,046	3,211	1,098
	Harvesting	Harvesting	Car	1,5	112,7750583	24	65	1560					498,063	1,994	0,074	5,138	1,756
												Σ Workers	1348,920	5,400	0,200	13,915	4,757
Stage	Process	Action	Machine	Meters of road b	tkm machine	Person km workers	Amount/m	Fuel/m									
Road	Road construction &	Road construction and maintenance	Gravel	45			11,25						87,49	0,63	0,02	2,49	0,62
			Passenger car	45		21,375		189					6,82	0,03	0,00	0,07	0,02
			Lorry 16-32t	45	2205								358,81	1,00	0,02	2,26	0,86
												Σ Road	453,13	1,65	0,04	4,82	1,51
												ΣΣ Forest Road	9022,730	38,091	3,038	136,324	127,367
												Σ/m3 FR	12,890	0,054	0,004	0,195	0,182
Stage	Process	Action	Machine	Truck net weight	Share of wood type	m3 harvested/ha	Kilometers to plant	tons transported	Number of tours driven	Tonkilometers wood trans	km of truck driving back						
Transport	Transport from thinnings	Transport Th 1 sawmill	Truck (lorry 40t)	14	0,1	50,000384	123	4,75003648	1	584,254487	123		161,411	0,496	0,011	1,230	0,483
		Transport Th 1 industry	Truck (lorry 40t)	14	0,8	50,000384	127	38,00029184	2	4826,037064	254		647,477	2,012	0,043	4,994	1,961
		Transport Th 1 energy	Truck (lorry 40t)	14	0,1	50,000384	18,5	4,75003648	1	87,87567488	18,5		24,277	0,075	0,002	0,185	0,073
		Transport Th 2 sawmill	Truck (lorry 40t)	14	0,2	50,000384	123	9,50007296	1	1168,508974	123		212,121	0,655	0,014	1,626	0,639
		Transport Th 2 industry	Truck (lorry 40t)	14	0,7	50,000384	127	33,25025536	2	4222,782431	254		595,118	1,848	0,040	4,585	1,801
		Transport Th 2 energy	Truck (lorry 40t)	14	0,1	50,000384	18,5	4,75003648	1	87,87567488	18,5		24,277	0,075	0,002	0,185	0,073
	Transport from harvest	Logs to sawmill	Truck (lorry 40t)	14	0,8	600,00024	123	456,0001824	16	56088,02244	1968		6639,376	20,699	0,447	51,373	20,173
		Logs to industrial plant	Truck (lorry 40t)	14	0,15	600,00024	127	85,5000342	3	10858,50434	381		1285,367	4,007	0,086	9,946	3,905
		Logs to energy wood	Truck (lorry 40t)	14	0,05	600,00024	18,5	28,5000114	1	527,2502109	18,5		62,413	0,195	0,004	0,483	0,190
												Σ Transport	9651,837	30,061	0,648	74,607	29,296
Age	Age	Treediameter in cm	Treevolume	Logvolume	Yarding distance	Lateral yarding distance	Branch %	Slope	Productivity Yarder K300	Productivity Mounty 4000	Producitvity Chainsaw	Σ/m3	13,788	0,043	0,001	0,107	0,042
30	25-40	16,00	0,26	0,08	100,00	16,60	0,50	0,60	3,68174	8,693091972	2,34125	Σ Säge	7012,907	21,850	0,471	54,229	21,294
45	35-55	19,60	0,38	0,11	100,00	16,60	0,50	0,60	5,37127	10,4081459	3,18264	Σ ind	2527,962	7,867	0,170	19,525	7,667
50		22,00	0,48	0,13	100,00	16,60	0,50	0,60	6,25338	11,43200177	3,75868	Σ Energy	110,967	0,344	0,007	0,853	0,335
100		47,00	2,21	0,35	100,00	16,60	0,50	0,60	13,19021	19,11981669	7,37155						
													GWP	FTAP	FEP	TEP	POFP
												ΣΣ Gate	18674,566	68,152	3,687	210,931	156,663
												Σ/m3 Gate	26,678	0,097	0,0053	0,301	0,224

Scenario 4: Impact assessment

Stage	Process	Action	Machine	Machine weight i	Productivity m3/h	Working hours h/m3	Trans product tkm/r	Trans mach. Austria Lorry	Fuel machine kg/h		m3 Harvested		EF 2.0 Global warming potential	EF 2.0 Freshwater and terrestrial acidification	EF 2.0 Freshwater eutrophication	EF 2.0 Terrestrial eutrophication	EF 2.0 Photochemical ozone formation
		Scenario 4: spruce monculture, steep terrain, patch-cut, Stift Rosalia, rotation period=100 years, per ha											kg CO2 eq	kg SO2 eq	kg PO4 eq	kg PO4 eq	kg NMVOC eq
Planting	Seedlings	Bare-rooted seedlings	Transport Klein LKW	Assumption: only natural regeneration -> no planting needed!													
	Sum Workers	Work	Car														

Stage	Process	Action	Machine	Machine weight i	Productivity m3/h	Working hours h	Transport product tl	Trans mach. Austria Lorry	Fuel machine kg/h		m3 Harvested		kg CO2 eq	kg SO2 eq	kg PO4 eq	kg PO4 eq	kg NMVOC eq
Thinning	Thinning	Jungwuchspflege /ha	Freischneider/Motoı	0,0075		25,2		0,0756	1,6		700		237,92	0,72	0,31	2,18	11,49
		Dickungspflege/ha	Chainsaw	0,0075		54		0,162	1,6		700		509,82	1,54	0,67	4,68	24,62
		Thinning 1 and processin	Chainsaw	0,0075	1,89	26,38980797		0,079169424	1,6		50,000384		249,15	0,75	0,33	2,29	12,03
		Thinning 2 and processin	Chainsaw	0,0075	2,52	19,80378283		0,059411349	1,6		50,000384		186,97	0,56	0,25	1,72	9,03
	Logging	Logging 1	K300T on tractor	6,595	2,75968	18,1181927		0,543134004	12,6		50,000384		901,52	3,95	0,03	16,06	4,59
		Logging 2	K300T on tractor	6,595	4,39250	11,38312568		0,341235063	12,6		50,000384		566,40	2,48	0,02	10,09	2,89
												Σ Thinning	2651,79	10,01	1,60	37,02	64,65

Stage	Process	Action	Machine	Machine weight i	Productivity m3/h	Working hours h	Transport product tl	Trans mach. Austria Lorry	Fuel machine kg/h		m3 Harvested						
Harvest	Harvest 1	Felling, limbing	Chainsaw	0,0075	7,37	40,69706153		0,122091185	1,6		300,000604		384,23	1,16	0,50	3,53	18,55
	Harvest 2	Felling, limbing	Chainsaw	0,0075	7,37	40,69706153		0,122091185	1,6		300,000604		384,23	1,16	0,50	3,53	18,55
	Logging 1	Logging	Mounty 4000	31,00	19,11981669	15,69055859		5,722439015	29,7		300,000604		1924,70	9,61	0,09	38,74	11,11
	Logging 2	Logging	Mounty 4000	31,00	19,11981669	15,69055859		5,722439015	29,7		300,000604		1924,70	9,61	0,09	38,74	11,11
												Σ Harvest	4617,86	21,53	1,19	84,54	59,33
												ΣΣ After Harvest	7269,65	31,54	2,79	121,56	123,97
												Σ/m3	10,39	0,05	0,00	0,17	0,18

Stage	Process	Action	Machine	Machine weight	Working hours	Number of workers for operation	km to forest site	Person*km									
Workers	Planting and site p	Work	Car	1,5	0	0	0	0					0	0	0	0	0
	Thinning and Logg	Thinning and Logging	Car	1,5	154,8949092	23	65	1495					477,31	1,91	0,07	4,92	1,68
	Harvesting	Harvesting	Car	1,5	40,69706153	24	65	1560					498,06	1,99	0,07	5,14	1,76
												Σ Workers	975,37	3,90	0,14	10,06	3,44
Stage	Process	Action	Machine	Meters of road bı	tkm machine	Person km workers	Amount/m	Fuel/m									
Road	Road construction & maintenance	Road construction and maintenance	Gravel	45			11,25						87,49	0,63	0,02	2,49	0,62
			Passenger car	45		21,375		189					6,82	0,03	0,00	0,07	0,02
			Lorry 16-32t	45	2205								358,81	1,00	0,02	2,26	0,86
												Σ Road	453,13	1,65	0,04	4,82	1,51
												ΣΣ Forest Road	8698,15	37,10	2,98	136,44	128,92
												Σ/m3 FR	12,43	0,05	0,00	0,19	0,18

Stage	Process	Action	Machine	Truck net weight	Share of wood type	m3 harvested/ha	Kilometers to plant	tons transported	Number of tours driven	Tonkilometers wood tran	km of truck driving back						
Transport	Transport thinning	Transport Th 1 sawmill	Truck (lorry 40t)	14	0,1	50,000384	123	4,75	1,00	584,25	123						
		Transport Th 1 industry	Truck (lorry 40t)	14	0,8	50,000384	127	38,00	2,00	4826,04	254		161,41	0,50	0,01	1,23	0,48
		Transport Th 1 energy	Truck (lorry 40t)	14	0,1	50,000384	18,5	4,75	1,00	87,88	18,5		647,48	2,01	0,04	4,99	1,96
		Transport Th 2 sawmill	Truck (lorry 40t)	14	0,2	50,000384	123	9,50	1,00	1168,51	123		24,28	0,07	0,00	0,19	0,07
		Transport Th 2 industry	Truck (lorry 40t)	14	0,7	50,000384	127	33,25	2,00	4222,78	254		212,12	0,66	0,01	1,63	0,64
		Transport Th 2 energy	Truck (lorry 40t)	14	0,1	50,000384	18,5	4,75	1,00	87,88	18,5		595,12	1,85	0,04	4,59	1,80
	Transport harvest	Logs to sawmill 1	Lorry <40t	14,00	0,8	300,000604	123	228,00	8,00	28044,06	984		24,28	0,07	0,00	0,19	0,07
		Logs to industrial plant 1	Lorry <40t	14,00	0,15	300,000604	127	42,75	2,00	5429,26	254		3319,69	10,35	0,22	25,69	10,09
		Logs to energy wood 1	Lorry <40t	14,00	0,05	300,000604	18,5	14,25	1,00	263,63	18,5		699,83	2,18	0,05	5,40	2,12
		Logs to sawmill 2	Lorry <40t	14,00	0,8	300,000604	123	228,00	8,00	28044,06	984		39,53	0,12	0,00	0,30	0,12
		Logs to industrial plant 2	Lorry <40t	14,00	0,15	300,000604	127	42,75	2,00	5429,26	254		3319,69	10,35	0,22	25,69	10,09
		Logs to energy wood 2	Lorry <40t	14,00	0,05	300,000604	18,5	14,25	1,00	263,63	18,5		699,83	2,18	0,05	5,40	2,12
													39,53	0,12	0,00	0,30	0,12

Age	Treediameter in c	Treevolume	Logvolume	Yarding distance	Lateral yarding dist	Branch %	Slope	Productivity Yarder K300	Productivity Mounty 4000	Productivity Chainssaw							
25,00	14,00	0,20	0,07	100,00	12,50	0,50	0,60	2,76	7,62	1,89		Σ Transport	9782,80	30,46	0,66	75,59	29,68
40,00	16,80	0,28	0,09	100,00	12,50	0,50	0,60	4,39	9,10	2,52		Σ/m3	13,98	0,04	0,00	0,11	0,04
50,00	22,00	0,48	0,13	100,00	12,50	0,50	0,60	6,54	11,43	3,76							
55,00	23,80	0,57	0,14	100,00	12,50	0,50	0,60	7,11	12,15	4,19							
100	47,00	2,21	0,35	100,00	12,50	0,50	0,60	13,48	19,12	7,37							
												ΣΣ Plant gate	18480,95	67,56	3,63	212,04	158,60
												Σ/m3 plant	26,40	0,0965	0,0052	0,3029	0,23

Scenario 5 Impact Assessment

Rotation period: 28 years

Lowland, clear-cut, pine monoculture, near Hapua Accomodation, NZ

1m^3 of round wood ready to bring to sawmill, per ha

Stage	Process	Action	Machine	Machine weight i	Productivity Plants/h	Working hours h/ha	Transport product	Transport mach.NZ Ship	Transport mach.NZ Lorry	kg pesticide	kg pesticide	Amount of seedlings		EF 2.0 Global warming potential kg CO2 eq	EF 2.0 Freshwater and terrestrial acidification kg SO2 eq	EF 2.0 Freshwater eutrophication kg PO4 eq	EF 2.0 Terrestrial eutrophication kg PO4 eq	EF 2.0 Photochemical ozone formation
Planting	Seedlings	Bare-rooted seedlings	Lorry 16-32 tons	0,1666			20,9916					833		41,135	0,209	0,026	0,466	0,127
	Site preparation	Removal veg and slash	Komatsu small PC55MR-5	5,26		5			2161,86			700		506,577	1,656	0,029	4,972	1,637
		Glyphosate and Metsulfuron	Helicopter AS 350 B3	1,018		0,02		2331,22	407,2	3,5	0,115	700		136,696	0,376	0,059	0,789	5,702
	Planting	Planting	By hand		115	7,243478261												
	Post-planting treatment	Hexazinone, Terbuthylazine	Helicopter AS 350 B3	1,018		0,02		2331,22	407,2	1,75	7			182,427	1,115	0,017	2,750	0,768
													Σ Planting	866,836	3,355	0,130	8,976	8,235
													Σ Planting/m3	1,238	0,005	0,000	0,013	0,012

Stage	Process	Action	Machine	Machine weight i	Productivity m3/h	Working hours h/ha	Transport product	Transport mach.NZ Ship	Transport mach.NZ Lorry	Transport mach forest site	Fuel kg/h	m3 Harvested						
Thinning	Thinning and Pruning	Thinning 1	Chainsaw SHINDAIWA 362Ts	0,0036		11,25		0,36	0,02			700,00002		106,214	0,321	0,139	0,976	5,129
		Pruning 1	Loppers, by hand	0,0015		1,5			0,62			700,00002		0,100	0,000	0,000	0,001	0,000
		Thinning 2	Chainsaw SHINDAIWA 362Ts	0,0036		11,25		0,36	0,02			700,00002		106,214	0,321	0,139	0,976	5,129
		Pruning 2	Chainsaw ECHO CS2511TES	0,0025		2,25		0,05	0,00			700,00002		21,242	0,064	0,028	0,195	1,026
		Thinning 3	Chainsaw SHINDAIWA 362Ts	0,0036		11,25		0,36	0,02			700,00002		106,214	0,321	0,139	0,976	5,129
		Pruning 3	Chainsaw ECHO CS2511TES	0,0025		2,25		0,05	0,00			700,00002		21,242	0,064	0,028	0,195	1,026
													Σ Gr&Main	361,226	1,091	0,474	3,317	17,439

Stage	Process	Action	Machine	Machine weight i	Productivity m3/h	Working hours h	Transport product	Transport mach.NZ Ship	Transport mach.NZ Lorry	Transport mach forest site	Fuel kg/h	m3 Harvested						
Harvest	Site preparation	Landing preparation	Bulldozer CAT D7	29,776		2,55		126,15	3,12	237,19		700,00002		251,915	1,046	0,009	3,952	1,142
			Excavator CAT 326	25,9		2,55		109,72	2,71	206,31		700,00002		187,415	0,775	0,007	2,898	0,841
			Roller CAT 825K	35,528		2,55		150,51	3,72	283,00		700,00002		410,799	1,716	0,014	6,591	1,895
	Harvest	Felling	JD 843	17	119,12	5,88		166,04	166,04		27,8208	700,00002		674,932	2,870	0,021	11,306	3,219
	Logging and processing	Logging	Skidder CAT 648L	14	55,56	12,60		293,18	7,25			700,00002		1069,320	4,719	0,073	17,207	5,178
		Processing	Processor CAT 548	35,354	38,89	18,00		1057,65	26,15			700,00002		1517,700	7,169	0,067	27,551	8,169
			Loader CAT 538	35,563	33,33	21,00		1241,22	30,69	2333,82		700,00002		1233,280	5,003	0,052	17,698	5,233
													Σ Harvest	5345,360	23,298	0,242	87,204	25,678
													Σ Harvest/m3	7,636	0,033	0,000	0,125	0,037
													ΣΣ After Harvest	6573,421	27,745	0,847	99,497	51,352
													Σ/m3	9,391	0,040	0,001	0,142	0,073

Stage	Process	Action	Machine	Machine weight	Working hours	Number of workers for operation	km to forest site	Person*km						
Workers	Workers	Planting, site preparation	Pick-up truck	2	12,24	2	95,8	191,6		61,172	0,245	0,009	0,631	0,216
	Workers	Thinning and Pruning	Pick-up truck	2	39,75	9	95,8	862,2		275,275	1,102	0,041	2,840	0,971
	Workers	Harvest	Pickup truck	2	65,12	10	95,8	958		305,862	1,224	0,045	3,155	1,079
									Σ Workers	642,309	2,571	0,095	6,626	2,265

Stage	Process	Action	Machine	Meters of road b	tkm machine	Person km workers	Amount/m	Fuel/m						
Road	Road construction & maintenance	Road construction and maintenance	Gravel	14,7			3,675			28,58	0,21	0,01	0,81	0,20
			Passenger car	14,7		6,9825		61,74		2,23	0,01	0,00	0,02	0,01
			Lorry 16-32t	14,7	720,3					117,21	0,33	0,01	0,74	0,28
									Σ Road	148,02	0,54	0,01	1,58	0,49
									ΣΣ Forest Road	7363,753	30,857	0,956	107,699	54,110
									Σ/m3 Forest road	10,520	0,044	0,001	0,154	0,077

Stage	Process	Action	Machine	Truck net weight	Share of wood type	m3 harvested/ha	Kilometers to plant	tons transported	Number of tours driven	Ton*km wood transport	km of truck driving back						
Transport	Transport	Logs to sawmill	Truck <40t	14	0,77	700	71,1	539	18	38322,9	1279,8		4478,067	13,966	0,301	34,661	13,611
		Logs to industrial plant	Truck <40t	14	0,13	700	455	91	4	41405	1820		5231,759	16,284	0,351	40,414	15,869
												Σ Transport	9709,826	30,250	0,653	75,075	29,480
												Σ/m3 Transport	13,871	0,043	0,001	0,107	0,042

Age	Treediameter in cm	Treevolume	Piecevolume	Bunch	Distance	Productivity Feller-Buncher	Producitvity FB min	Productivity FB max	Productivity Skidder	Productivity Processor	Productivity Loader	Productivity chainsaw
	25	0,75	0,66		200							
28	60	1,8	1,566	5	200	119,12	76,24	162	31,27	62	102,32	
28	60	1,8	1,566									7,16

ΣΣ Gate	17073,578	61,106	1,608	182,774	83,590
Σ/m3 Gate	24,391	0,087	0,0023	0,261	0,119

Scenario 6 Impact Assessment

1m^3 of round wood ready to bring to sawmill, per ha

Sc 6: Kotemaori NZ, pine monoculture, mountains, rotation period 28 years.

Stage	Process	Action	Machine	Machine weight	roductivity Plants/	Working hours h/ha	Transport product tkm	Transport mach.NZ Ship	Transport mach.NZ Lorry	Fuel kg/h	kg pesticide	kg pesticide	m3 Harvested		EF 2.0 Global warming potential kg CO2 eq	EF 2.0 Freshwater and terrestrial acidification kg SO2 eq	EF 2.0 Freshwater eutrophication kg PO4 eq	EF 2.0 Terrestrial eutrophication kg PO4 eq	EF 2.0 Photochemical ozone formation
Planting	Seedling production	Bare-rooted seedlings	Lorry 16-32 tons	0,1666			36,1522						833		137,187	0,385	0,010	0,873	0,332
	Site preparation	Removal veg and slash	Komatsu small PC55MF	5,26		5			2161,86	7,84			700		506,577	1,656	0,029	4,972	1,637
		Glyphosate and Metsul	Helicopter AS 350 B3	1,018		0,02		2331,22	407,2	146,34	3,5	0,115	700		136,696	1,134	0,061	2,767	0,797
	Planting	Planting	By hand		92	9,054347826							700						
	Post planting treatment	Hexazinone,Terbuthyl azine	Helicopter AS 350 B3	1,018		0,02		2331,22	407,2		1,75	7	700		182,427	1,355	0,032	3,257	0,899
														Σ Planting	962,888	4,531	0,132	11,869	3,665

Stage	Process	Action	Machine	Machine weight	Productivity m3/h	Working hours h/ha	Transport product tkm	Transport mach.NZ Ship	Transport mach.NZ Lorry	Transport mach forest site	Fuel kg/h	Oil kg/h	m3 Harvested						
Thinning	Thinning and Pruning	Thinning 1	Chainsaw SHINDAIWA 3	0,0036		22,5		0,715716	0,033291				700		212,427	0,642	0,279	1,951	10,258
		Pruning 1	Loppers, by hand	0,0015		1,8			0,6165				700		0,100	0,000	0,000	0,001	0,000
		Thinning 2	Chainsaw SHINDAIWA 3	0,0036		22,5		0,715716	0,033291				700		212,427	0,642	0,279	1,951	10,258
		Pruning 2	Chainsaw ECHO CS251	0,0025		2,7		0,059643	0,00277425				700		25,491	0,077	0,033	0,234	1,231
		Thinning 3	Chainsaw SHINDAIWA 3	0,0036		22,5		0,715716	0,033291				700		212,427	0,642	0,279	1,951	10,258
		Pruning 3	Chainsaw ECHO CS251	0,0025		2,7		0,059643	0,00277425				700		25,491	0,077	0,033	0,234	1,231
														Σ Thinning	688,364	2,080	0,903	6,322	33,236

Stage	Process	Action	Machine	Machine weight	Productivity m3/h	Working hours h	Transport product tkm	Transport mach.NZ Ship	Transport mach.NZ Lorry	Transport machforest site	Fuel kg/h	Oil kg/h	m3 Harvested						
Harvest	Site preparation	Landing preparation	Bulldozer CAT D7	29,776		2,549019608		126,1451482	3,119473882	237,1862745			700,00002		251,915	1,046	0,009	3,952	1,142
			Excavator CAT 326	25,9		2,549019608		109,7245882	2,713405882	206,3112745			700,00002		187,415	0,775	0,007	2,898	0,841
			Roller CAT 825K	35,528		2,549019608		150,5133271	3,722080471	283,004902			700,00002		410,799	1,716	0,014	6,591	1,895
	Harvest	Felling	Chainsaw husqarna 572	0,0068	7,156072462	97,81902346		6,236627915	0,027338461				700,00002		923,540	2,791	1,212	8,485	44,597
	Logging and processing	Logging	Yarder Madill 124	56,7	38,88888889	18,00000051		1671,334608	41,9466612				700,00002		1133,193	7,320	0,063	30,676	8,632
		Processing	Processor CAT 548 or 5	35,354	38,88888889	18,00000051		1057,650294	26,15488995				700,00002		1517,700	7,169	0,067	27,551	8,169
			Loader CAT 538 or 558	31,46	33,33333333	21,0000006		1098,016951	27,15312678	2064,562559			700,00002		1187,545	4,835	0,049	17,299	5,095
		Anchoring Yarder	Bulldozer+Backline Exca	55,676		7		235,8697365	6,435486353	1217,9125			700,00002		201,444	0,626	0,014	1,451	0,531
														Σ Harvest	5813,551	26,279	1,434	98,904	70,903
														ΣΣ After harvest	7464,803	32,889	2,469	117,096	107,804
														Σ/m3	10,664	0,047	0,004	0,167	0,154

Stage	Process	Action	Machine	Machine weight	Working hours	Number of workers for operation	km to forest site	Person*km						
Workers	Workers	Planting, site preparatio	Pick-up truck	2	14,05434783	2	142,2	284,4		90,801	0,364	0,013	0,937	0,320
	Workers	Thinning and Pruning	Pick-up truck	2	74,7	12	142,2	1706,4		544,804	2,181	0,081	5,620	1,921
	Workers	Harvest	Pickup truck	2	169,4660839	24	142,2	3412,8		1089,608	4,362	0,162	11,240	3,842
									Σ Workers	1725,213	6,907	0,256	17,797	6,084

Stage	Process	Action	Machine	Meters of road b	tkm machine	Person km workers	Amount/m	Fuel/m						
Road	Road construction & maintenance	Road construction and maintenance	Gravel	14,7			3,675			28,58	0,21	0,01	0,81	0,20
			Passenger car	14,7		6,9825		61,74		2,23	0,01	0,00	0,02	0,01
			Lorry 16-32t	14,7	720,3					117,21	0,33	0,01	0,74	0,28
									Σ Road	148,02	0,54	0,01	1,58	0,49
									ΣΣ Forest Road	9338,038	40,336	2,739	136,468	114,381
									Σ/m3 Forest road	13,340	0,058	0,004	0,195	0,163

Stage	Process	Action	Machine	Truck net weigh	Share of wood ty	m3 harvested/ha	Kilometers to plant	tons transported	Number of tours driven	Tonkilometers wood trans	km of truck driving back						
Transpor	Transport	Logs to sawmill	Truck <40t	14	0,77	700	47,9	539	18	25818,1	862,2		3016,869	9,409	0,203	23,351	9,169
		Logs to industrial plant	Truck <40t	14	0,13	700	455	91	4	41405	1820		5231,759	16,284	0,351	40,414	15,869
												Σ Transport	8248,628	25,693	0,554	63,765	25,039
													11,784	0,037	0,001	0,091	0,036

Age	Diameter	Treevolume	Piecevolume	Bunch	Distance	Productivity Feller-Buncher	Producitvity FB min	Productivity FB max	Productivity Skidder	Productivity Processor	Productivity Loader	Prodchainsaw
28	60	1,8	1,566	5	200	119,12	76,24	162	31,27	62	102,3211748	
28	60	1,8	1,566		200							7,15607

ΣΣ Gate	17586,666	66,029	3,294	200,233	139,420
Σ/m3 Gate	25,124	0,094	0,0047	0,286	0,199

Machine	Unit	EF 2.0 Global Warming Potential	EF 2.0 Freshwater and terrestrial acidification	EF 2.0 Freshwater eutrophication	EF 2.0 Terrestrial eutrophication	EF 2.0 Photochemical ozone formation
Seedling	1	0,04528075	0,000239226	3,067E-05	0,000533549	0,000142998
Klein LKW (3.5-7.5t)	tkm	0,51049583	0,001418476	4,93794E-05	0,00295174	0,00113567
Lorry 16-32 t	tkm	0,16272556	0,000452366	1,11131E-05	0,001024278	0,000392248
Freischneider	ha					
Forwarding ecoinvent	h	45,794837	0,24539468	0,002775432	1,0030899	0,2898627
Forwarder production	1	72202,119	337,88521	31,91007	697,4145	231,75844
Forwarding 1110D	h	52,0395875	0,278857591	0,0031539	1,139874886	0,329389432
Forwarder prod 1110D (12,8t)	1	83644,4134	391,4318661	36,96704643	807,9378767	268,4865628
Forwarding 1510G (16,33t)	h	58,284338	0,312320502	0,003532368	1,276659873	0,368916164
Forwarder prod 1510G	1	106711,974	499,3814354	47,1618647	1030,751994	342,5301227
Transport ferry	tkm	0,10941447	0,003595323	3,2677E-06	0,009973118	0,002570954
Transport ship	tkm	0,00937574	0,000305676	3,01348E-07	0,000836064	0,000216324
Production passenger car	1	6,9505985	0,043160751	0,003467485	0,080802835	0,030710717
Passenger car	Pkm	0,31927101	0,001278145	4,7366E-05	0,003293569	0,001125872
Lorry >32t	tkm	0,08679529	0,000273195	5,89305E-06	0,000678024	0,000266241
Lorry >32t	km	0,9	0,002731946	5,89305E-05	0,006780242	0,002662415
Lorry 16-32 t	tkm	0,16272556	0,000452366	1,11131E-05	0,001024278	0,000392248
Lorry 16 t Production	1	21571,601	109,65854	11,537845	249,26594	99,090745
Harvesting ecoinvent	h	58,256784	0,33240949	0,012641666	1,3619783	0,38444685
Harvester prod ecoinvent	1	102673,66	501,25734	48,220225	1024,0871	320,3733
Harvesting 1070G (17,8)	h	57,1678721	0,326196229	0,012405373	1,336520762	0,377260928
Harvester prod 1070G	1	130542,225	637,3129037	61,30857179	1302,053599	407,3317671
Harvesting 1270G (20,65t)	h	80,035021	0,45667472	0,017367522	1,871129066	0,528165299
Harvester prod 1270G (20,65t)	1	151443,649	739,3545765	71,12483188	1510,528473	472,5506175
Power saw (chainsaw) production	1	163,63907	1,0121448	0,055060038	2,0204425	0,57798691
Power sawing	h	9,440671	0,028513756	0,012392917	0,086686168	0,45590442
Cable yarder trailer mounted Koller K300	1	31160,0638	189,3022627	15,27222868	497,9853441	108,2477794
Tractor machine operation diesel high load18-74 kW	h	49,7530752	0,218064584	0,001489024	0,886338064	0,25347788
Cable yarder truck mounted Mounty 4000	1	163743,23	815,65358	75,015315	1827,1874	538,89069
Cable yarding and processing, mounted on truck	h	122,60706	0,61198661	0,005793596	2,4687398	0,70784577
Transport by helicopter	h	539,773603	2,443914716	0,006952104	1,292630718	0,617080416
Helicopter AS-350 B3 (1,018t)	1	8143,24291	51,05838248	2,75891346	90,42758097	27,89867888
Hydraulic digger production	1	40490,289	179,3114	17,684927	408,73955	161,16439
Production Excavator Komatsu PC55MR-5 (5,26t)	1	14171,6012	62,75899	6,18972445	143,0588425	56,4075365
Excavating Komatsu PC55MR-5 (28,3kW)	h	30,957469	0,13568463	0,000926504	0,55149924	0,15771957
Ecoinvent machine operation <74,57kW	h	148,25591	0,62952677	0,004445278	2,5224126	0,71521103
Production CAT D7-Bulldozer 29,776t	1	80375,923	355,9450831	35,10575909	811,3752561	319,9220584
Bulldozing CAT D7 (201kW)	h	83,0233096	0,352534991	0,002489356	1,412551056	0,400518177
Production CAT 326 Excavator	1	69913,2323	309,6110173	30,53597395	705,7569563	278,2771801
Excavating CAT326 (152kW)	h	59,7767829	0,253825194	0,001792336	1,01703676	0,288373087
Production CAT 825 roller 35,528t	1	95902,5992	424,7050279	7,130562566	164,8037866	381,7232299
Rolling CAT 825 (302kW)	h	142,301953	0,604244975	0,004266756	2,42111251	0,686488155
Production JD 959M Feller Buncher (37,79t)	1	101927,554	451,3865643	44,51885623	1028,933694	405,7044911
Felling Bunching John Deere 959M (246kW)	h	109,989281	0,467038356	0,003297898	1,871347639	0,530606481
Production SkidderJD 648L (19t)	1	55874,3424	382,763246	39,25746307	786,277456	246,9391113
Skidding JD 648L	h	84,5548783	0,367152453	0,005751797	1,345565307	0,405696946
Production Processor CAT548 (35,354t)	1	95432,9118	422,6250157	41,68219394	963,37187	379,8537229
Processing von ecoinvent!	h	83,5292975	0,379666504	0,003670492	1,480015453	0,440566319
Production CAT 982M Loader (35,56t)	1	95988,9785	425,0875589	41,92506694	968,9852265	382,0670472
Loading CAT 982M (120kW)	h	39,8511886	0,169216796	0,001194891	0,678024507	0,192248725
Swing yarder Madill 124 (56,7t)	1	270098,93	1640,893254	132,3813918	4316,59284	938,303898
Swing yarder Madill 124	h	61,882362	0,37766124	0,003440444	1,6250358	0,45882426
Market for glyphosate	kg	10,465413	0,050521605	0,01557854	0,1031171	0,033087339
Market metsulfuron (unspecified herbicide)	kg	10,026746	0,10428845	0,005358302	0,1257413	0,039677735
Market Hexazinone (triazine unspecified)	kg	9,5443711	0,046727889	0,003088094	0,098912113	0,025483183
Market Terbuthylazine	kg	9,5443711	0,046727889	0,003088094	0,098912113	0,025483183
Gravel crushed (CH) Ecoinvent	kg	0,00622179	4,47722E-05	1,22418E-06	0,000177324	4,4193E-05
Gravel crushed (CH) Forststraße	m3	7,77723125	0,055965289	0,001530229	0,221655275	0,055241203